80051202/9

NUREG/CR-1244
SAND79-0376
Unlimited Release
R-1

IMPACT OF RAINSTORM AND RUNOFF MODELING ON PREDICTED CONSEQUENCES OF ATMOSPHERIC RELEASES FROM NUCLEAR REACTOR ACCIDENTS

Lynn T. Ritchie, Warren D. Brown and
J. Robert Wayland

February 1980

Sandia National Laboratories

SF 2900-Q(3-80)

Prepared for
U.S. NUCLEAR REGULATORY COMMISSION

NOTICE

Available from

GPO Sales Program
Division of Technical Information and Document Control
U.S. Nuclear Regulatory Commission
Washington, DC 20555

and

National Technical Information Service
Springfield, Virginia 22161

NUREG/CR-1244
SAND79-0376
Unlimited Release
R1

IMPACT OF RAINSTORM AND RUNOFF MODELING ON PREDICTED CONSEQUENCES OF ATMOSPHERIC RELEASES FROM NUCLEAR REACTOR ACCIDENTS

L. T. Ritchie, W. D. Brown, and J. R. Wayland

February 1980

Sandia Laboratories
Albuquerque, New Mexico 87185
operated by
Sandia Corporation
for the
U.S. Department of Energy

Prepared for
Office of Nuclear Regulatory Research
Probabilistic Analysis Staff
U.S. Nuclear Regulatory Commission
Washington, DC 20555
Under Memorandum of Understanding DOE 40-550-75
NRC FIN No. A1042

ABSTRACT

A general temperate latitude cyclonic rainstorm model is presented which describes the effects of washout and runoff on consequences of atmospheric releases of radioactive material from potential nuclear reactor accidents. The model treats the temporal and spatial variability of precipitation processes. Predicted air and ground concentrations of radioactive material and resultant health consequences for the new model are compared to those of the original WASH-1400 model under invariant meteorological conditions and for realistic weather events using observed meteorological sequences. For a specific accident under a particular set of meteorological conditions, the new model can give significantly different results from those predicted by the WASH-1400 model. However, the aggregate consequences produced for a large number of meteorological conditions are similar between the two models.

TABLE OF CONTENTS

I. Introduction

The consequence model, CRAC, developed for the Reactor Safety Study (WASH-1400) [1], was developed to assess the risk to society from major accidents at commercial nuclear power plants. The CRAC model consists of four basic components: release and atmospheric dispersion, dosimetry, health effects, and property damage [2,3].

In CRAC, the atmospheric dispersion of released radioactive material is modeled using a Gaussian plume dispersion model. The Gaussian model is utilized in a manner different from usual applications in that the plume may change characteristics throughout its lifetime. The meteorological data used by the model consists of hourly observations from a single weather station located at the reactor site. The hourly readings of thermal stability, wind speed, and precipitation occurrence measured at the site are assumed to apply at all downwind locations. The model is used to calculate ground level air concentrations and ground concentrations of radioactive material out to 800 kilometers from the reactor. When precipitation occurs at the reactor site during any portion of an hour, it is assumed to occur for exactly one half of that hour at all locations downwind of the site at a rate of 1 mm/hr. In addition, no runoff is assumed to occur. Thus, the temporal and spatial variability of rainstorms and runoff is neglected.

In order to assess the impact of this simple precipitation model on the accuracy of CRAC's consequence calculations, a more realistic model of rainstorms, precipitation scavenging, and surface runoff was developed. This modified rainstorm/runoff model [4,5] incorporated the spatial/temporal variation in rain rates, the correlation between rain rate and depletion rate and the differences between rural and urban runoff. Four levels of storm intensity were modeled, with each level occurring over a fixed portion of the total storm area. This model continued to use single-station meteorology to describe both the occurrence of precipitation and the hourly rain rates associated with different intensity storm systems.

Criticisms [6] of the original CRAC model and of the structured rain model described in reference [4], have primarily been directed at the use at all downwind distances of rain occurrence and rain rates measured by a single rain gauge at the reactor site. The modeling of the interaction of the model geometry and the behavior of the expanding plume as it moves downwind from the accident site was also criticized.

Because rainstorms are exceedingly complex and variable in structure, realistic characterization of a storm requires considerably more data than a single meteorological station can supply. Estimates of the distribution of precipitation require information on the storm character and the average rainfall rate of the entire storm. The new structured rain model requires the average rainfall rate for the entire storm to provide a distribution of rain activity and spatial/temporal variability that approximates an actual storm [6].

The geometry utilized in the consequence model is illustrated in Figure 1. A polar coordinate grid is used with sixteen sectors centered on the compass directions and thirty-four unequal radial intervals. Each division of the radial interval is called a grid

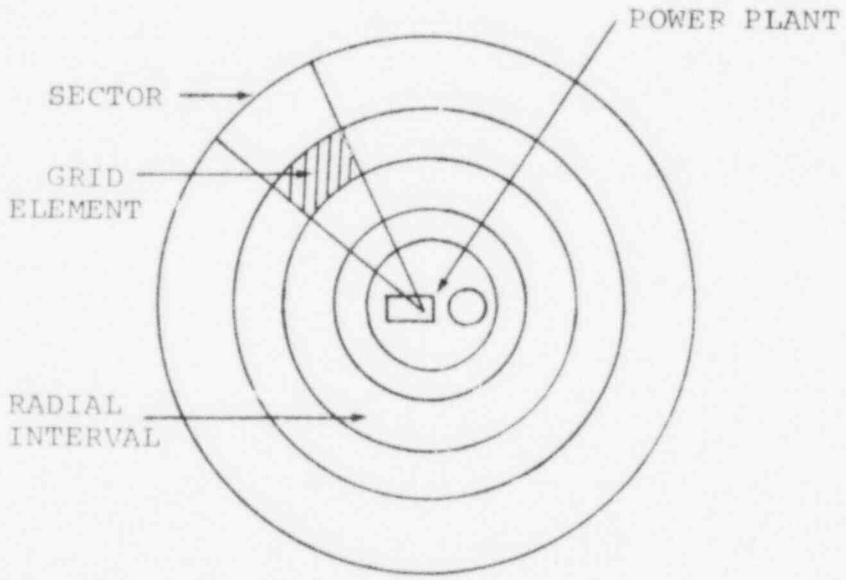

Figure 1. Representation of CRAC Geometry.

element. The meteorological conditions encountered by a plume as it traverses a grid element are represented by the average of the meteorological data for the time the plume is in that grid element.

The variation in grid element sizes presents a special problem for modeling rain activity because at close ranges the dimensions of the grid elements are small compared to the scales associated with rain rate variability, whereas at long ranges the grid elements are large compared to these scales. In addition, the time required for the plume to traverse the small grid elements at close range is small compared to the observed duration of time for rainfall variability. At long ranges, the time required for the plume to traverse the large grid elements permits observation of these variations but it is too long to allow the different areas of rainfall activity to be considered as stationary. The division of each grid element into areas corresponding to the various levels of rainstorm activity is therefore not realistic when the grid elements are either very small or very large. Thus, another approach was adopted for the new precipitation model with different techniques for handling the effects of rain at distances from the reactor site corresponding to small, medium, and large grid elements.

Finally, it must be recognized that rainstorms should not be modeled in too great detail in the CRAC computer code. Improvements and refinements that reduce uncertainties in CRAC and represent the present state of knowledge of storms and other meteorological phenomena must be consistent with the overall detail of the CRAC model. This has been the objective in the design and implementation of the new rain/runoff model.

To determine the impact of the new rain/runoff model on the air and ground concentrations and the consequences predicted for individual meteorological sequences involving rain, and on the risk estimates presented in WASH-1400, a series of calculations was performed using CRAC with the new and original rain models. The results of these calculations are presented in this report.

II. Rainstorm Model

The new model uses the polar coordinate grid of CRAC to represent a general temperate latitude cyclonic storm. A storm is characterized by the hourly rain rate at the reactor site, the average hourly rain rate for the entire storm, and the starting and ending times of the storm. The model partitions the region downwind of the reactor site into three areas and uses different models in each of these areas. In the neighborhood of the reactor site, out to a maximum distance of 10 km, the hourly rain rate measured at the reactor site is taken as the rainfall rate. For distances from 10 km to 240 km, a structured rain model is utilized. In this region, five levels of rain activity are derived from the average rain rate of the entire storm. Beyond distances of 240 km, the storm average hourly rain rate is used without structuring. Representative rain data for the individual reactor sites is required for this model. In the neighborhood of the reactor actual hourly rainfall rates are sufficient, but at all greater distances, storm average hourly rain rates derived from regional data are required. This regional information was acquired by inspecting the records of weather stations at and surrounding each site.

The rain storm data was collected from the tables of hourly precipitation data published by NOAA [7]. The storm average hourly rates were assembled for each of three individual reactor sites. The hourly weather data was examined for each site and for a minimum of six weather stations in the region surrounding the reactor site. For each observed storm, the hourly rain rates from the regional data, representing all of the selected weather stations, were averaged to represent the storm average rain rate, $\overline{R}$. The beginning time and duration of the storm were estimated. Rain rate data representing this information was incorporated into the CRAC weather data files for each site. The average characteristics of each storm are thus represented in the rain data in addition to the hourly rain rates at the reactor site. Although considerable care was taken to represent the storm data accurately, estimates of starting time, and of storm duration and extent, and calculations of $\overline{R}$ involved analysis and interpretation of the precipitation data.

A structured rain model similar to the model described in reference [4] is the heart of the new rain model. The structured model is applied in the region extending from 10 km to 240 km from the reactor. Within this region, grid elements are of the appropriate size to realistically allow one to assume that proportionate areas are covered by different intensities of precipitation and that traversal times for the storm across a grid element are of the order of the lifetime of cellular or small mesoscale rain areas.

The structured model is similar to the general model developed for flood forecasting by Grayman and Eagleson [8]. The general model is based primarily on the studies by Austin and Houze [10] and by Houze [9] of storm characteristics determined from radar soundings. Zawadski, et al., [11,12] used a statistical approach based on rain data from Canada to extend the work begun at MIT by Austin and her students [6,10,13]. From the studies of diverse storms, Houze [10] and Austin [13,6] identified the distinct levels of rain activity shown in Figure 2: synoptic, banded structure, large mesoscale, small mesoscale, and cellular. Each is distinguished by its duration, scale size, and rainfall intensity. Duration is directly correlated with scale size, and rainfall intensity is inversely correlated with scale size. Several smaller scale areas are usually embedded in the next larger scale size area. Table 1 lists the characteristics of the five levels of rainstorms as they appear in Austin's [6] revision of the general model. A comparison with the results of the studies of Austin and Houze [10] can be made by consulting Grayman and Eagleson [8].

Units of each scale size are randomly located within each unit of the next larger scale size at the average density shown in Table 1. The rain intensity in each cell is exponentially distributed, as is the cell duration. The average value of a rainfall rate throughout the storm is

$$\overline{R} = \frac{1}{2}R + \left(\frac{1}{2} - \frac{1}{4}\right)2R + \left(\frac{1}{4} - \frac{1}{16}\right)4R + \left(\frac{1}{16} - \frac{1}{128}\right)8R + \left(\frac{1}{128}\right)32R = 2.44R,$$

where R is the rainfall rate in the synoptic area [6]. The synoptic level has the largest area followed by the banded structure level. In the mesoscale area, first identified by

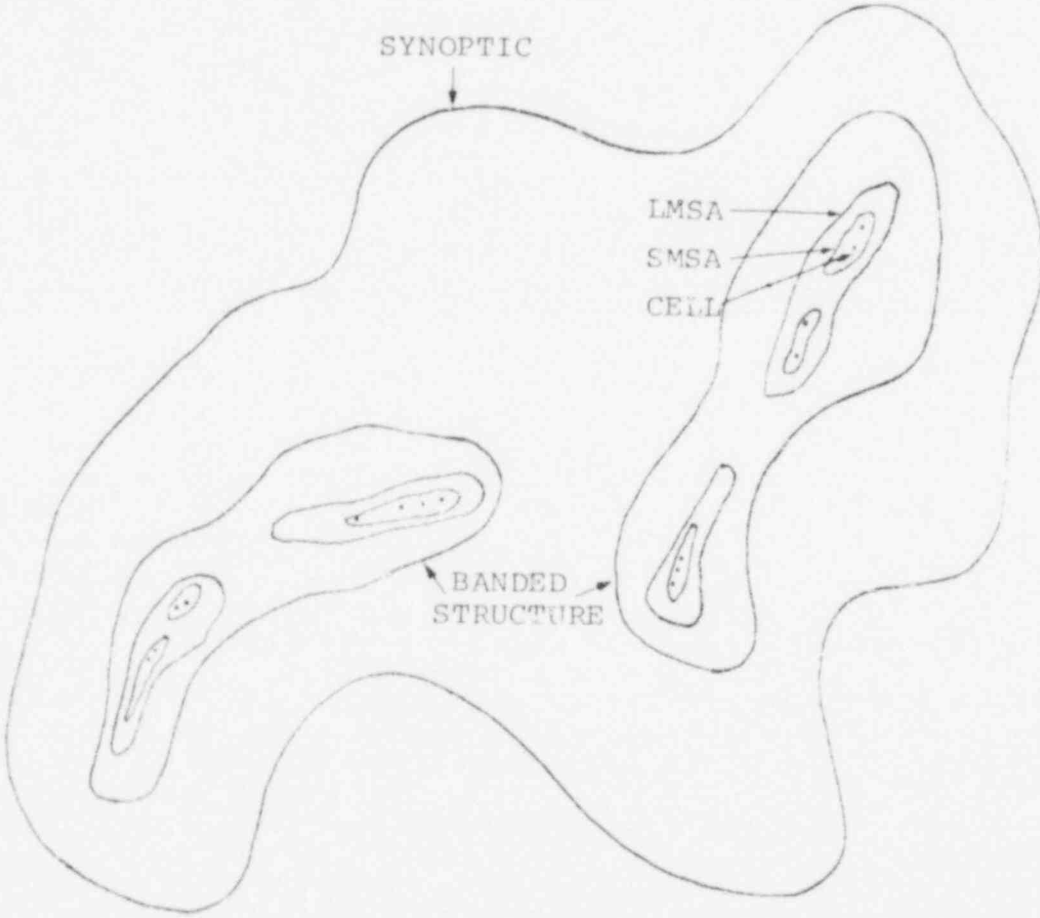

Figure 2. Spatial schematic of typical cyclonic rainstorm. LMSA, large mesoscale area. SMSA, small mesoscale area.

TABLE 1

Characteristics of Model for General Cyclonic Rainstorms

Rain Area Designation	Size of Each Area	Average Rainfall Intensity	Fraction of Storm Covered At Any One Time	Duration	Average Density of Units
Synoptic	10^5 km^2	R	Entire Storm	1-3 days	
Banded Structure (BS)	2.8×10^4 km^2 (70 x 400 km)	$R_B = 2R$	1/2	4 hours	3.3 per 1.6×10^5 km^2
Large Mesoscale Area (LMSA)	4000 km^2	$R_L = 4R$	1/4	2 hours	3.3 per band
Small Mesoscale Area (SMSA)	250 km^2	R_S = [illegible]R	1/16	1 hour	4 per LMSA
Cell	10 km^2	$R_C = 32R$	1/128	t_c - 1/2 I_c	3 per SMSA

---

*t_c - duration of rain in minutes

I_c - rainfall rate in cell in mm/hr

Austin [13], there are two distinct levels of intensity. Houze called these the large mesoscale area, LMSA, and the small mesoscale area, SMSA. These areas are not fixed but instead undergo continuous periods of growth and decay. The mesoscale areas range from about 65 to 13,000 km^2; this size is the same order of magnitude as dense population centers. Areas of high precipitation intensities a few kilometers wide are contained within the SMSA. These areas are the intense cells within storms that were first studied in detail in the Thunderstorm Project [14]. Houze [9] has shown that the statistical characteristics within the mesoscale and cellular levels are relatively homogeneous. The statistical characteristics of synoptic levels, however, can be diverse.

In the spatial intervals immediately surrounding the reactor site, the area of the grid element is small. The plume itself is normally small, and the time of interaction between the rainstorm and plume in any grid element is short, only a few minutes. Therefore, it is not appropriate to assume proportionate areas are covered by different intensities of precipitation. It is more likely that the grid element is covered by rain of a single intensity [6]. Studies by Rogers and Zawadzki of one hour point rainfall records show that the dominant tendency is for rain over small distances to be uniform [15]. The rates utilized in this model for grid elements close to the reactor coincide with the hourly rainfall rates recorded at the reactor site. This treatment is applied out to the downwind distance where the width of the radioactive plume first becomes equal to twice the characteristic diameter of a rain cell, or to a maximum distance of 10 km.

For downwind distances greater than 240 km, the area of the grid elements is large. The plume itself is large and is greatly diluted and depleted. The time of interaction between the rainstorm and plume is long, several hours or more. Even though proportionate distribution of precipitation intensities is appropriate, the assumption that the distribution is stationary is inappropriate for the long time periods involved. Therefore, for those hours in which rainfall occurs it is assumed to occur at the hourly average rate for the entire storm. Experience with the structured rain model has shown this adaptation to give the model great economy without degrading the quality of the dosimetry and health effects results.

The application of the new rain model is directed at temperate latitude regions. Because of the great variety of geographic locations and the subsequent effects of these locations on types of rainstorms, more detailed models may be required for better estimates of specific effects, such as formation of "hot spots" from cellular rain or modeling of specific meteorological events. The information obtained by inspecting the records of regional weather stations has helped to characterize each storm, but some storm types have not been treated.* Preliminary investigations [16] also suggest that for convective storms, even where no rain is involved, there exists the potential for the

*Scattered showers, thunderstorms, snowstorms, or squall line storms have not specifically been addressed.

radioactive plume to be widely dispersed by entrainment into the storm. These storms can occur frequently during the late spring and summer, and the occurrence of this dispersion would alter the health consequence predictions.

III. Washout Model

The CRAC model includes precipitation scavenging as a mechanism for depleting the plume. Washout is the assumed mechanism for all precipitation scavenging. A simple exponential formulation is used. The material in the plume is depleted exponentially according to $\exp(-\lambda t)$, where t is the time since the onset of precipitation and λ is the wet removal rate or washout coefficient.

The washout coefficient, λ, is the fraction of material removed from a contaminated plume by washout in unit time and is defined as

$$\lambda = - \frac{1}{\chi} \frac{d\chi}{dt} \sec^{-1}, \qquad (1)$$

where χ is the local particle concentration and $-d\chi/dt$ is the rate of decrease of the particle concentration resulting from precipitation scavenging. Theoretical calculations and experimental measurements of λ have large uncertainties. The value of the washout coefficient increases with increasing rainfall rate, R. The dependence of the washout coefficient on R is expressed by

$$\lambda = CR^{\alpha}. \qquad (2)$$

Experimental data and theoretical considerations indicate that α ranges from about 3/4 to 1. Both theoretically calculated and experimentally measured values of the washout coefficient λ range from about 10^{-5} to 10^{-2} per second [17]. This large range of values is partly a result of the numerous conditions under which washout can occur. It also reflects the uncertainty in predicting precipitation scavenging. Slinn cautions that order of magnitude uncertainties are to be expected in predictions of precipitation scavenging [18].

In the new model it is assumed that the washout coefficient is linearly dependent on rainfall rate [17]:

$$\lambda(\vec{x},t) = CR(\vec{x},t), \tag{3}$$

where

$$C = \begin{cases} 10^{-4}\ \text{sec}^{-1}\ (\text{mm/hr})^{-1} & \text{for stable atmospheric conditions (warm frontal storm)} \\ 10^{-3}\ \text{sec}^{-1}\ (\text{mm/hr})^{-1} & \text{for unstable atmospheric conditions (convective storms).} \end{cases}$$

$R(\vec{x},t)$ is the rainfall rate in mm/hr predicted by the hybrid rain model, at a location $\vec{x}$ relative to the reactor and at time t; $.25\ \text{mm/hr} \leq R(\vec{x},t) \leq 25.0\ \text{mm/hr}$.

The rate of change of air concentration, χ, at $(\vec{x},t)$ is given by

$$\frac{\partial \chi(\vec{x},t)}{\partial t} = -C\left|R(\vec{x},t)\right| \chi(\vec{x},t) - L(\vec{x},t) \tag{4}$$

where $L(\vec{x},t)$ is the rate of decrease of concentration for reasons other than washout. The ground deposition resulting from washout is readily calculated from a knowledge of the air concentration and the rainfall rate. The rainstorm simulation of the new rainstorm model produces representative values for $R(\vec{x},t)$, but uncertainties in washout predictions still remain.

3

IV. Runoff Model

Runoff is that excess of precipitation which does not remain in the area receiving the rainfall. Inasmuch as CRAC assumes no runoff, its predictions of external radiation exposure levels are higher than would be the case if runoff were modeled. The realistic evaluation of the amount of runoff depends on characterization of the surface on which the rain falls and predictions of rainfall amounts and washout.

Depending on the characteristics of the area, the total runoff can consist of surface runoff, subsurface runoff, and groundwater runoff. For a full understanding of all aspects of each component, knowledge is required of the state and of the physical parameters, both past and present, governing the flow of water over or through the media of the affected area. The effect of past rainfall is one of the most difficult phenomenon to estimate. Another phenomenon that has a great impact on the runoff is the removal of the contaminating material from the runoff because of chemical and physical action with the soil and other surface materials. A full treatment of the runoff problem is inconsistent with the accuracy constraints and time limitations of the consequence model. A viable alternative is to estimate the runoff in terms of accumulated storm rainfall on rural and urban areas. This approach is described below.

All storm precipitation is treated as rain in this model. Total rainfall for each storm is divided into three categories, precedent rain, contaminated rain, and successive rain. This model makes no attempt to approximate soil moisture conditions, but total accumulated rainfall immediately preceeding contaminated rainfall is used as a measure of surface wetness in each grid element. The surface rain retention potential or propensity for runoff is represented by this precedent rain.

Contaminated rainfall can only occur in a grid element when a rainstorm and plume overlap in that grid element. The overlap time is the duration of this interaction. Contaminated runoff is that portion of the rainfall which occurs during the overlap time but which is not retained. Accumulated contaminated rain for a rainstorm is calculated for each grid element.

Washoff and wet removal mechanisms are poorly understood and parameterizations are crude [18]. It is therefore assumed that washoff of previously deposited radioactive nuclides by subsequent rainstorms does not occur. Radioactive material deposited by dry deposition is also assumed to be bound to the surface on which it is deposited and not to be subject to removal by subsequent rainfall. Since successive rain is assumed to have no effect in removing previously deposited radionuclides, it is not calculated.

Two classes of surfaces are very crucial in modeling runoff. One is the man-made surfaces that dominate urban areas. The second is the natural and agricultural surfaces that dominate rural areas. It is necessary to characterize these two surfaces in a reasonable way even though the characterization may not be very refined.

The natural and agricultural surfaces that constitute rural areas are certainly subject to runoff. In a rainstorm, the rain which is necessary to replace the soil moisture deficit and the rainfall which enters the surface layer of the soil determine how much runoff will occur. Wide variations in runoff occur due to soil type and ground cover conditions [19]. Maximum runoff will occur with bare soils, minimum runoff will occur with forested land or good pasture.

In this model no attempt has been made to characterize the ground cover and soil type in each grid element, but rather to generalize rural lands. Calculations with this model have shown that runoff from rural surfaces is minimal and that runoff from rural land has little impact on health consequences. Even for rainfall rates on bare soils as large as 25 mm/hr, consequences are little altered by the maximum runoff that can occur. When it is assumed that no runoff of contaminated rain occurs, conservative estimates of the magnitude of consequences resulting from rainfall over rural areas are produced. The option to assume no runoff has been included in the model.

The man-made materials that constitute surfaces in cities and suburban areas are sufficiently impervious to prevent infiltration. In a rainstorm a thin film of water is rapidly formed on these man-made surfaces. After the surface is completely covered by this film, any additional rainfall runs off. The maximum amount of water that can be retained per unit area of flat surface is called the liquid holdup. For most surfaces the liquid holdup is approximately $300 \mu l/cm^2$ (3 mm) [20]. Thus, when the accumulated rainfall exceeds about 3 mm, runoff from city surfaces will occur. Contaminated rainfall that does not exceed the 3 mm surface retention capacity is assumed to be bound to the surface. If there has been precedent rain, runoff will occur when the sum of the precedent rain and contaminated rain is in excess of 3 mm. Runoff of the remaining contaminated rain is not complete, however. A modest reduction in the runoff occurs due to the processes of evaporation, detention, and recession [21].*

Since people live principally in cities and impact on population is of prime importance in evaluating health effects, the runoff model represents runoff to be characteristic of urban areas. Runoff into sewers is assumed, and all radioactive material carried by the runoff is removed from further consideration.

*The fraction of the excess contaminated rain retained due to the processes of evaporation, detention and recession is modeled by the function

$$P_c \max \left\{ \exp\left(-r^{1/2}\right), \frac{.3\ r_{min}}{r} \right\},$$

where P_c is the excess contaminated rain, r is the modeled rain rate and r_{min} is the minimum modeled rain rate.

V. Results for Simple Weather Events

It is difficult to understand the relationship between the spatial and temporal structures of rainstorms and the air and ground concentrations of radioactive material that result from interaction with a radioactive plume. In order to clarify this relationship, a simplified rainstorm with invariant meteorological conditions is considered in this section. Following the onset of rain in this simplified storm, the rain rate is constant in time. In the new rain model, actual recorded rain, structured rain in terms of the five levels of rain activity, and average rain are maintained for the regions described in Section II. The effects of incorporating the runoff into the new model are investigated for simple weather events. All the examples considered in this section are for a reactor located geographically so that the meteorology is typical of the northeastern part of the country. Interventions by man, such as evacuation, are disregarded so that the effects produced by the weather will not be obscured.*

The simplified storm represents conditions that are typical for the month of August in the northeastern part of the country. The windspeed is assumed to be constant at 5 m/s everywhere, and the Pasquill stability class is fixed at E, corresponding to stable conditions. The inversion height is constant at 650 m, and the coefficient in the wet removal rate is $C = 10^{-4}\ s^{-1}\ (mm/hr)^{-1}$. The reactor accident release category is chosen to

*Therefore, as assumed in the consequence model [3], affected persons are effectively exposed to ground contamination for periods of either 1 day or 7 days, depending on the contamination level.

be PWR-1A [3]. All 54 isotopes included in WASH-1400 are considered in the calculation of health effects. For graphical representations of air and ground concentration as a function of distance from the reactor, only the isotope ^{134}Cs is shown. For PWR-1A, 3 x 10^{+6} curies of ^{134}Cs are released from a height of 25 m.

Figures 3 through 6 display the ground and time integrated air concentrations for the case where the simplified rainstorm is in progress at the time of release and continues throughout the dispersion of the plume. These figures assume no runoff. Figure 3 presents the predictions of the original CRAC model with rain. The ground concentration corresponding to rain in Figure 3 decreases with increasing distance from the reactor and is primarily the result of wet deposition.

Figures 4 through 6 contrast the predictions of the original CRAC rain model with those of the new rain model for the simplified storm with values of the average rain rate ($\bar{R}$) of 0.25, 2.5 and 25 mm/hr, respectively. The corresponding effective rain rates* in the regions of structured rain, which essentially determine the air concentrations in these regions, are essentially identical to the average rain rates. In the new model, the average ground concentration over a sector with structured rain is approximately the

---

*The effective rain rate, R_e, is defined by the relation

$$\exp(-CR_e) = \sum_{n=1}^{5} f_n \exp(-CR_n t),$$

where the rain rates corresponding to the five levels of rain intensity are designated by $R_n (n=1,2,3,4,5)$ and f_n is the fraction of the storm with rain rate R_n. The time for the plume to traverse the spatial interval is designated by t. Note that a rapid remixing of the plume is assumed.

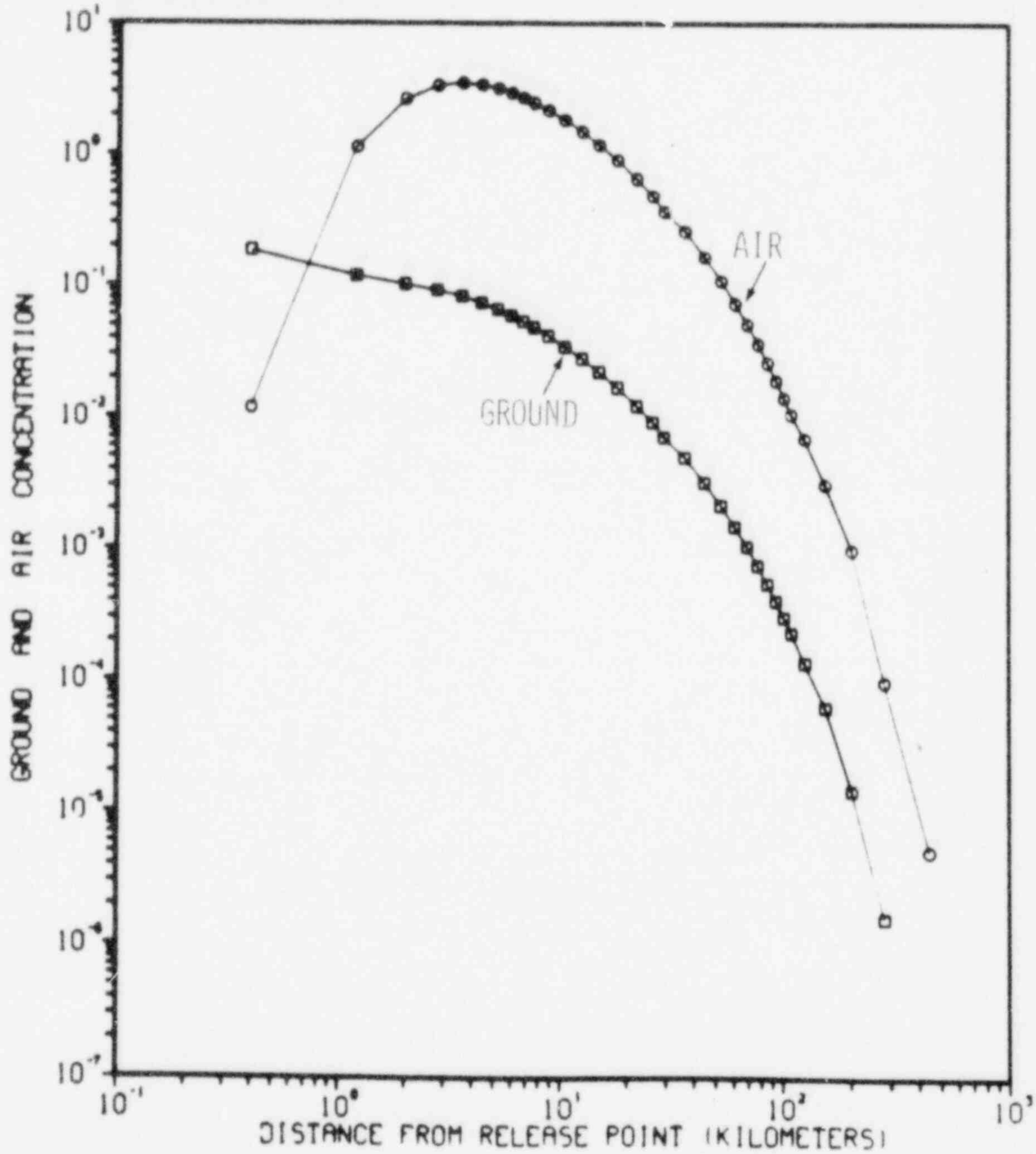

FIGURE 3. Air concentration (Ci-s/m^3) and ground concentration (Ci/m^2) of ^{134}Cs versus downwind distance from release point according to CRAC, for a constant 1 mm/hr rain.

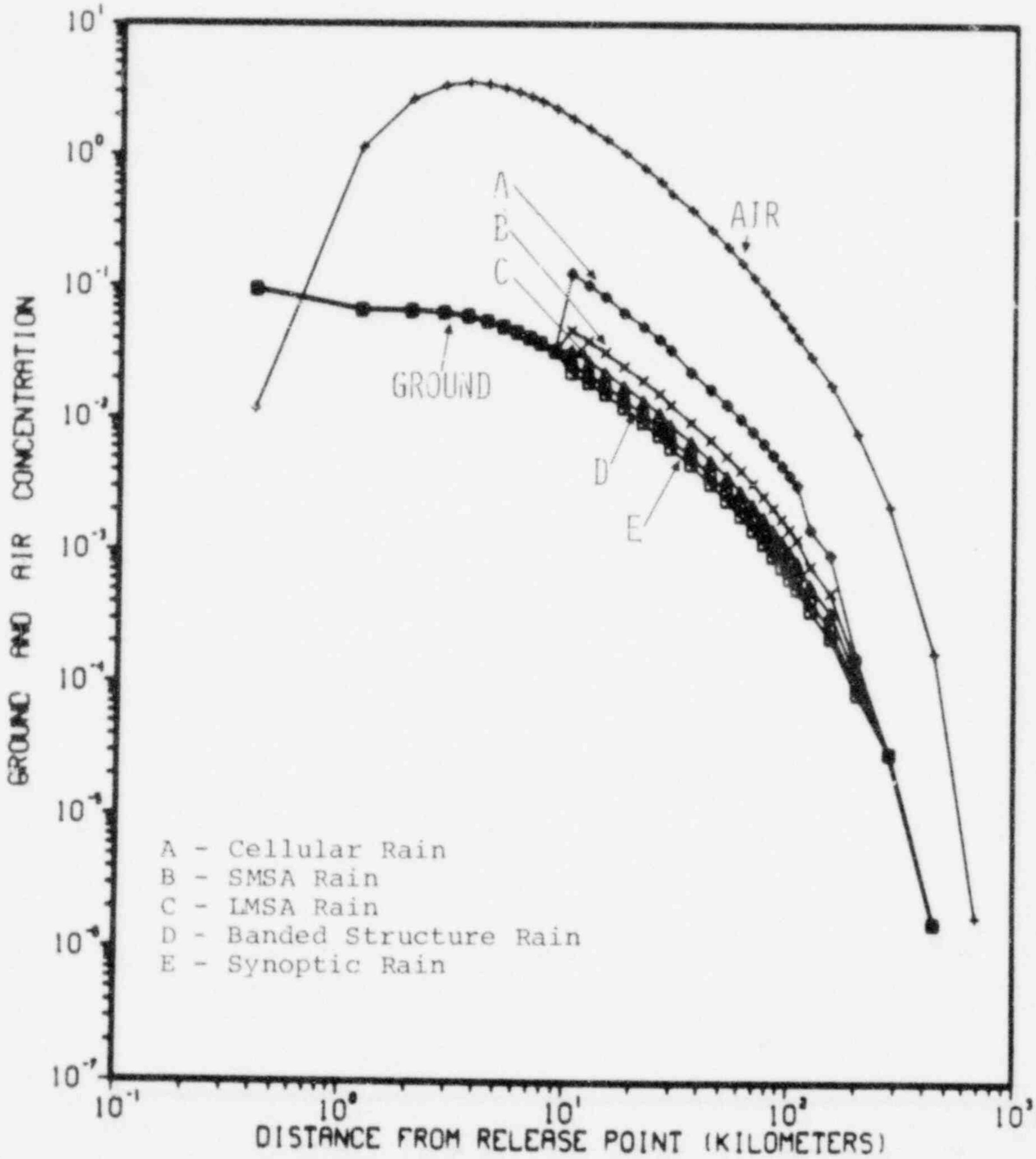

FIGURE 4. Air concentration (Ci-s/m^3) and ground concentration (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA, and cellular levels of rain activity versus downwind distance from release point according to the new rain model where average rain rate is .25 mm/hr.

4

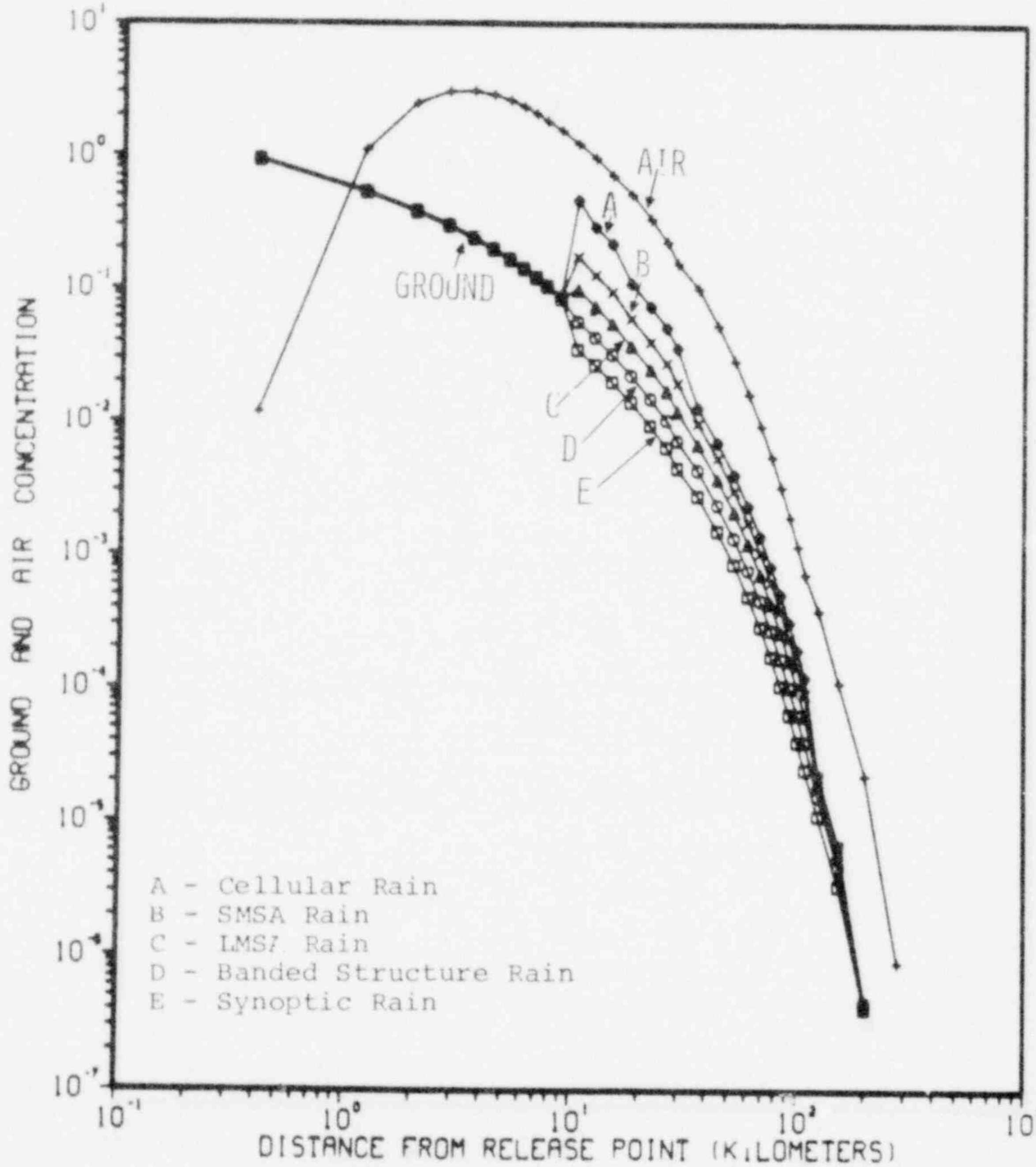

FIGURE 5. Air concentration (Ci-s/m^3) and ground concentration (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA and cellular levels of rain activity versus downwind distance from release point according to the new rain model where average rain rate is 2.5 mm/hr.

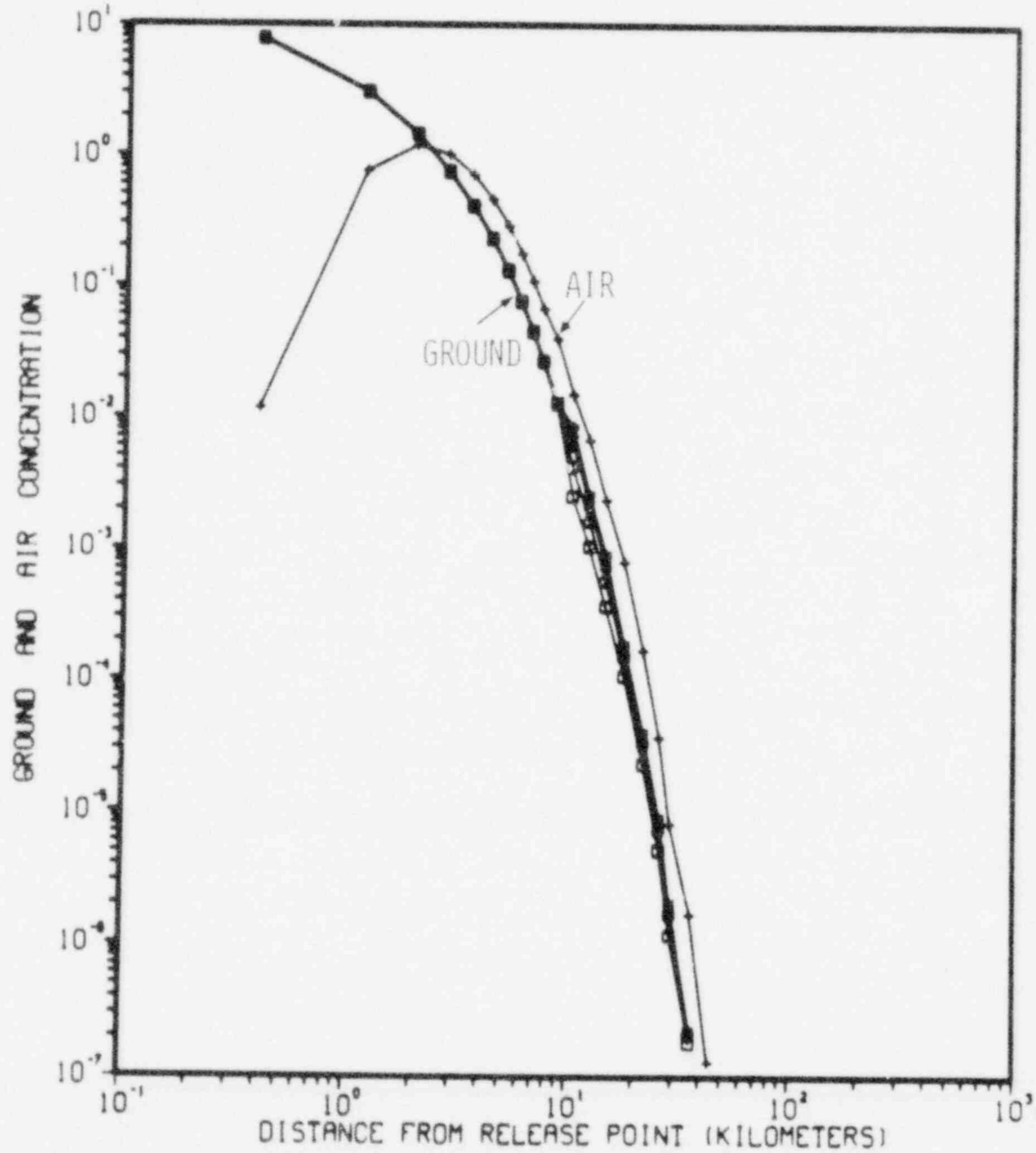

FIGURE 6. Air concentration (Ci-s/m^3) and ground concentration (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA, and cellular levels of rain activity versus downwind distance from release point according to the new rain model where average rain rate is 25 mm/hr.

same as the ground concentration corresponding to the banded structur area rain in that sector. In comparing the ground concentrations of the new model with the ground concentrations of the original model, it is important to be aware of the different average rain rates for the two models.

In Figure 4, $\bar{R}$ = 0.25 mm/hr. The air concentration for the new model is larger than that predicted by the old CRAC model for ranges greater than about 20 kilometers, and the ground concentrations for the old model are lower than the ground concentrations of the new model beyond 100 km. These differences in the air and ground concentrations between the two models are readily understood in terms of the different average rain rates. The hourly averaged rain rate for the old model is always 0.5 mm/hr, whereas the average rain rate for the new model is 0.25 mm/hr, about half that of the old model. The air concentration for the new model is therefore depleted less rapidly than that for the old model.

The average rain rate corresponding to Figure 5, $\bar{R}$ = 2.5 mm/hr, is about five times that of the original model. For ranges greater than a few kilometers the air concentration from the new model in Figure 5 decreases more rapidly than does the air concentration of the old model. This is a result of the larger washout levels produced by the higher rain rate. The ground concentrations corresponding to the new model are all higher than the ground concentrations representing the original model for ranges of less than 10 kilometers. At somewhat larger distances the ground concentrations of the new model decrease to values less than the ground concentration of the old model. These smaller ground concentrations at larger distances are the result of the more severely depleted plume.

The very heavy rain corresponding to Figure 6, $\bar{R}$ = 25 mm/hr, results in the washout of almost all of the radioactive material within 40 kilometers of the reactor. The ground concentrations at distances close to the reactor are higher than for the old model because of the large washout coefficient corresponding to the high rain rate. For larger distances, the ground concentrations shown for the new model decrease rapidly to values much lower than those predicted by the old model because of the much smaller amount of radioactivity remaining in the plume. At a distance of 50 kilometers downwind from the reactor, essentially all of the radioactive material has been removed from the plume. In general then, the ground concentrations for the new rain model with $\bar{R}$ = 25 mm/hr are higher than the predictions of CRAC during the first stages of heavy rain. As the plume is depleted at larger distances, however, these ground concentrations decrease below the results of CRAC.

The uncertainty in the washout coefficient, $\lambda = CR$, largely reflects the great uncertainty of the constant of proportionality, C. This uncertainty is illustrated by two calculations that were performed in which the rainfall occurred continuously from the time of the reactor accident at the rate of 2.5 mm/hr with the constant of proportionality multiplied and divided by ten. Multiplying or dividing the constant of proportionality by ten produces the same ground and air concentrations as increasing or decreasing the rainfall by the same factor.

Figures 7 through 9, generated using the hybrid rain model and an average rain rate of 2.5 mm/hr, display the effects of various degrees of runoff on the ground concentrations. In the case of the very intense cellular rainfall, substantial runoff can occur even when the average rain rate is relatively low and there has been no precedent rain (Figure 7). Notice that the ground concentrations have been reduced, especially in the cellular rainfall areas. In the region where the retention capacity has not been exceeded, the ground concentrations are identical to the case of no runoff. If there has been a considerable amount of rainfall before washout of the plume, there is very little retention by the saturated surface areas. These effects are illustrated in Figure 8 for 1.5 mm of precedent rain. In the case of precedent rainfall exceeding 3 mm, the retention could be as low as 0.1 mm (Figure 9).

Variations in the air and ground concentrations produce changes in health effects and property damage. Two sensitive indicators of changes in health effects are early fatalities (those which occur within one year) and cancer fatalities resulting from latent effects. Early fatalities are the result of exposures to high radiation levels, and are a consequence of the inhalation of radioactive material, external exposure to the passing plume, and external exposure to radioactive material deposited on the ground. For most accidents characterized in the RSS, early fatalities are limited to areas within 50 kilometers of the accident location (in most cases, to areas considerably closer). Latent cancer fatalities result from all exposure modes, with a strong contribution from persistent exposure to ground concentrations.

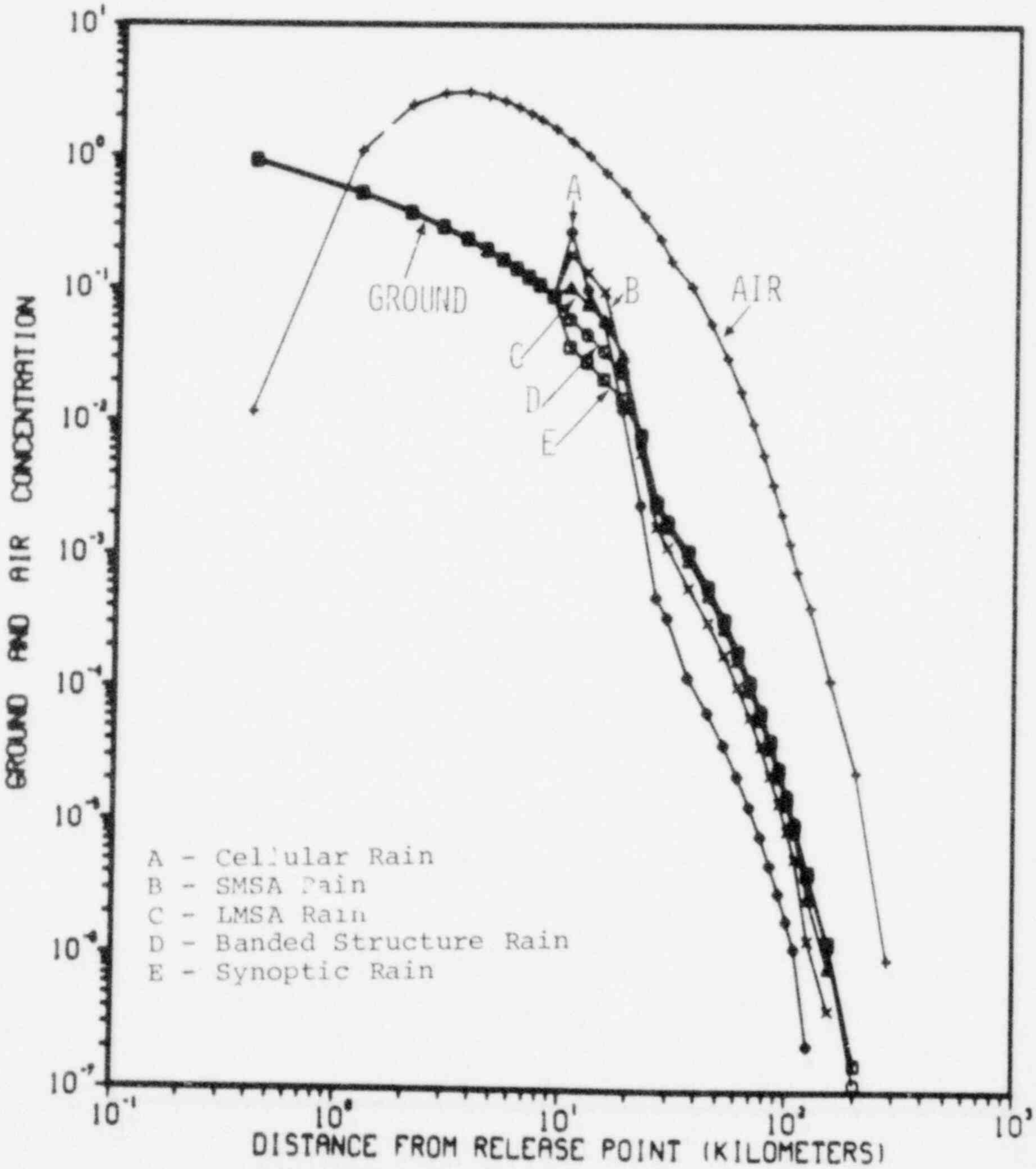

FIGURE 7. Air concentration ($Ci\text{-}s/m^3$) and ground concentration (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA and cellular levels of rain activity versus downwind distance from release point according to the new rain model with urban runoff. Average rain rate is 2.5 mm/hr. Runoff corresponds to no precedent rain on urban surfaces.

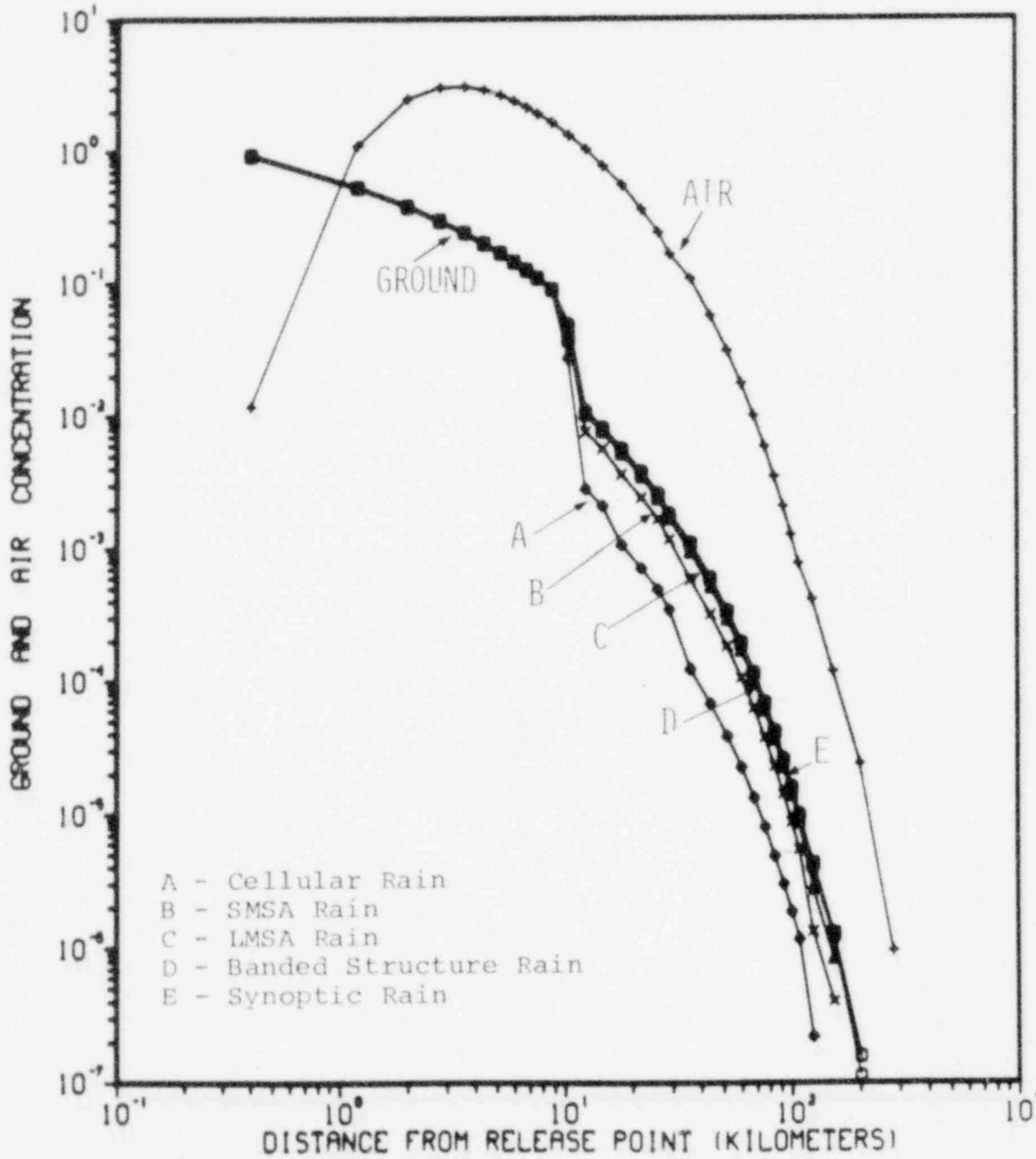

FIGURE 8. Air concentration (Ci-s/m^3) and ground concentrations (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA and cellular levels of rain activity versus downwind distance from release point according to the new rain model with urban runoff. Average rain rate is 2.5 mm/hr. Runoff corresponds to 1.5 mm of precedent rain on urban surfaces.

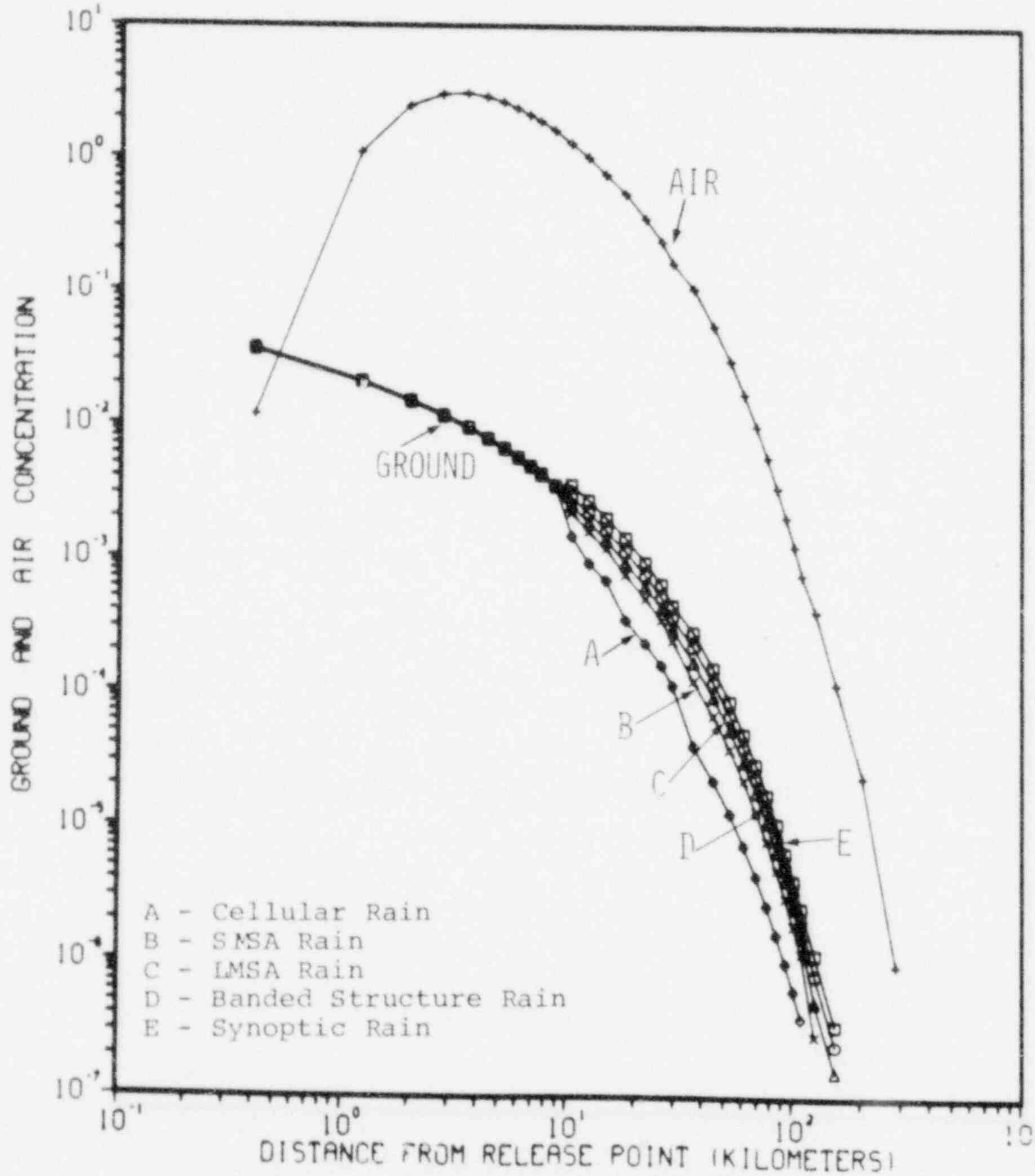

FIGURE 9. Air concentration (Ci-s/m^3) and ground concentrations (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA and cellular levels of rain activity versus downwind distance from release point according to the new rain model with urban runoff. Average rain rate is 2.5 mm/hr. Runoff corresponds to .1 mm rainfall retention.

5

Figures 10 through 13 display the conditional probability of early fatality for an individual as a function of distance from the reactor. The probability is conditional upon the occurrence of the reactor accident and rainfall. As in the case of Figures 3 through 6, the simplified rainstorm is assumed. Curves in Figures 10, 11, and 12 are based on predictions of the original model and the new rain model with urban runoff and without runoff. In the case of runoff, much of the ground contamination resulting from wet deposition is removed. Figures 10, 11, and 12 show rain rates of .25, 2.5, 25 mm/hr, respectively, for the new model. Recall that the hourly averaged rain rate for CRAC is always 0.5 mm/hr. Figure 13 shows, for an average rain rate of .25 mm/hr, the contribution to the probabilities of early fatalities of each of the five levels of rain activity in the structured rain.

The curve in Figure 10 corresponding to the new rain model without runoff has a knee extending between downwind distances of about 20 and 30 kilometers. This knee is caused by the intense rainfall occurring in individual rain cells as shown in Figure 13. A comparison of Figures 10 and 11 shows that increasing the average rain rate from .25 to 2.5 mm/hr does not greatly alter the fatality probabilities. In both cases of no runoff, the early dose exceeds the lethality threshold downwind of the release point to a distance of about 20 km. As illustrated in Figure 12, increasing the average rain rate to 25 mm/hr results in a reduced radius for early fatalities; i.e., the new model without runoff predicts that the conditional probability of early fatality occurring beyond about 10 kilometers for this particular rainfall rate is less than 10^{-6}.

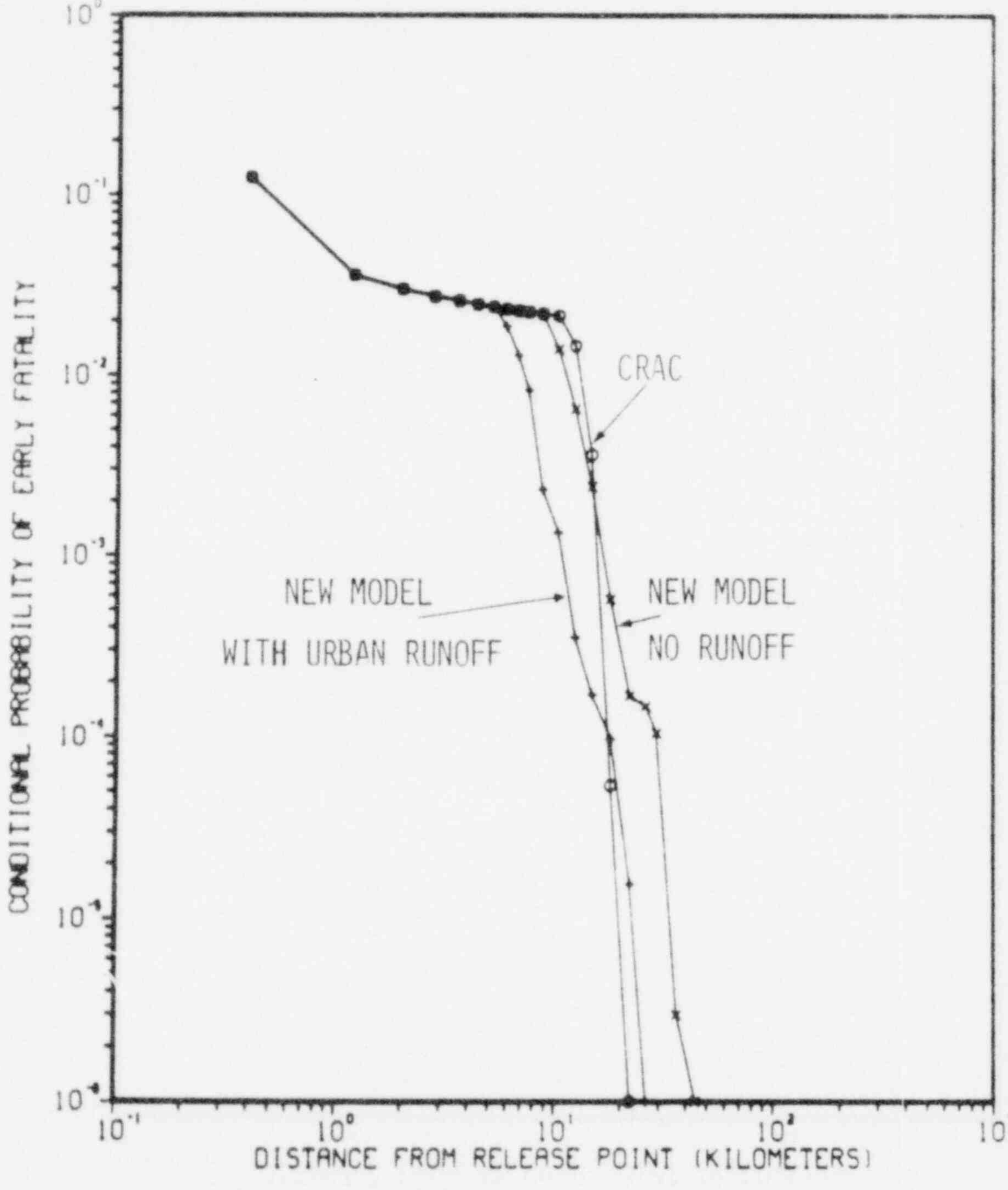

FIGURE 10. Conditional probability per capita of early fatality versus downwind distance from release point. Average rain rate is .25 mm/hr for the new rain model.

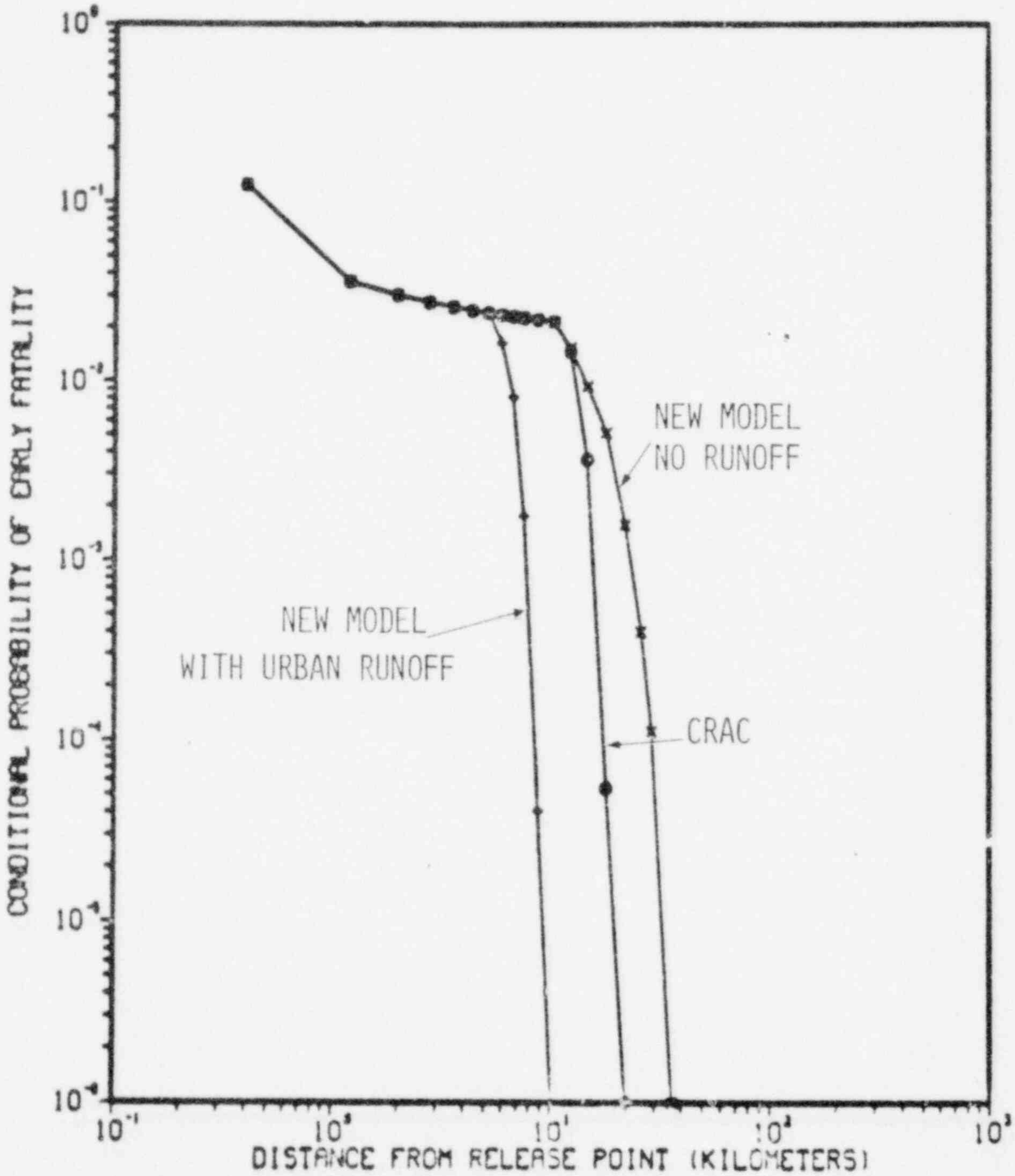

FIGURE 11. Conditional probability per capita of early fatality versus downwind distance from release point. Average rain rate is 2.5 mm/hr for the new rain model.

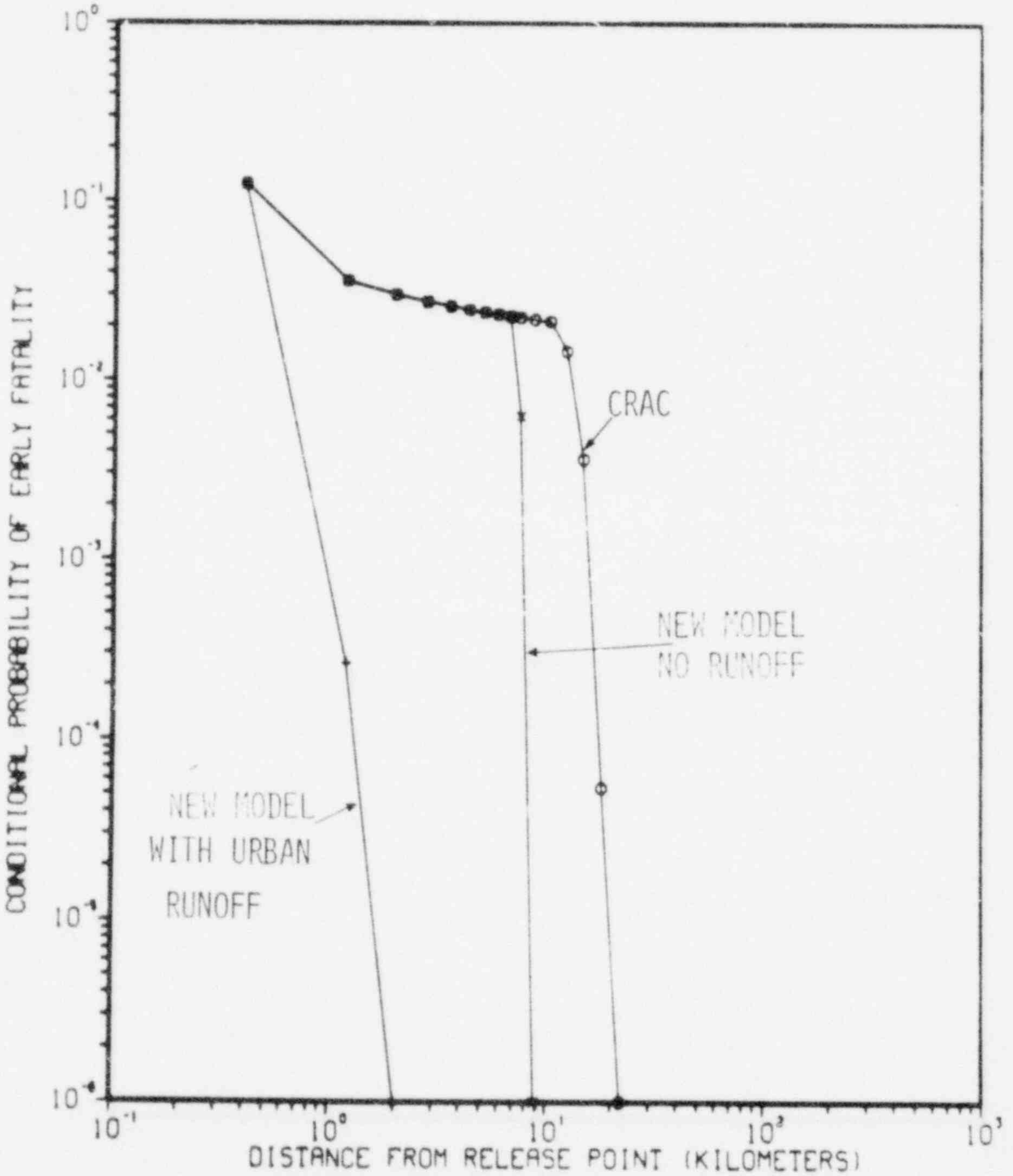

FIGURE 12. Conditional probability per capita of early fatality versus downwind distance from release point. Average rain rate is 25 mm/hr for the new rain model.

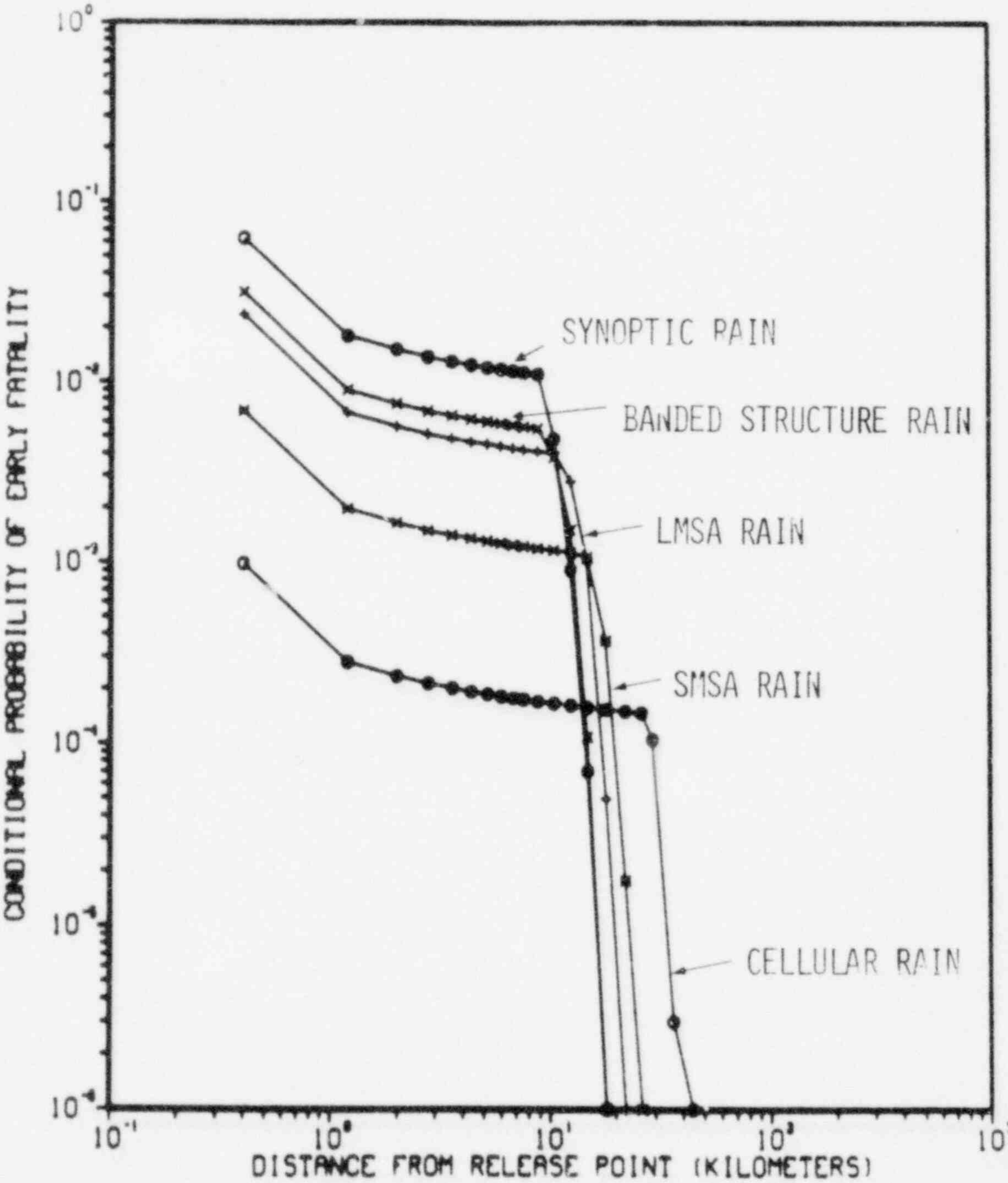

FIGURE 13. Contribution of each of the five levels of rain intensity to the conditional probability per capita of early fatality for the new rain model. Average rain rate is .25 mm/hr.

The very low probability of early fatalities occurring beyond this distance is a result of the large wet removal rate that restricts high air and ground concentrations to small distances from the reacto as shown in Figure 6. For the case of runoff in Figure 12, the conditional probability of early fatalities is small, since the small amount of ground contamination reduces the exposure level to less than the early fatality threshold. For the three cases of no runoff, the conditional probability at distance less than a few kilometers is independent of the rain rate. This is a consequence of exposures that are above the lethality level for early fatalities. The spatial structure of rainstorms produces significant influences in the probability curves for low rain rates. At high rain rates, the structure of the storm is not so important because of the large washout.

The conditional probability of cancer fatalities resulting from latent effects for an individual are displayed in Figures 14 through 17. Figures 14, 15, and 16 correspond to average rain rates of .25, 2.5 and 25 mm/hr, respectively, for the new model. Figure 17 shows, for an average rain rate of .25 mm/hr, the contributions to the conditional probability of cancer fatalities from latent effects of each of the five levels of rain intensity for structured rain. Latent cancer fatalities become dominant when early fatalities decline. As shown in Figure 14, there is no major difference between the predictions of the original model and the new rain model for low rain intensities. If much of the ground contamination produced by wet deposition runs off, there is no longer a large probability for early fatalities. The resulting increased numbers of survivors at close distances, however, receive an exposure that may

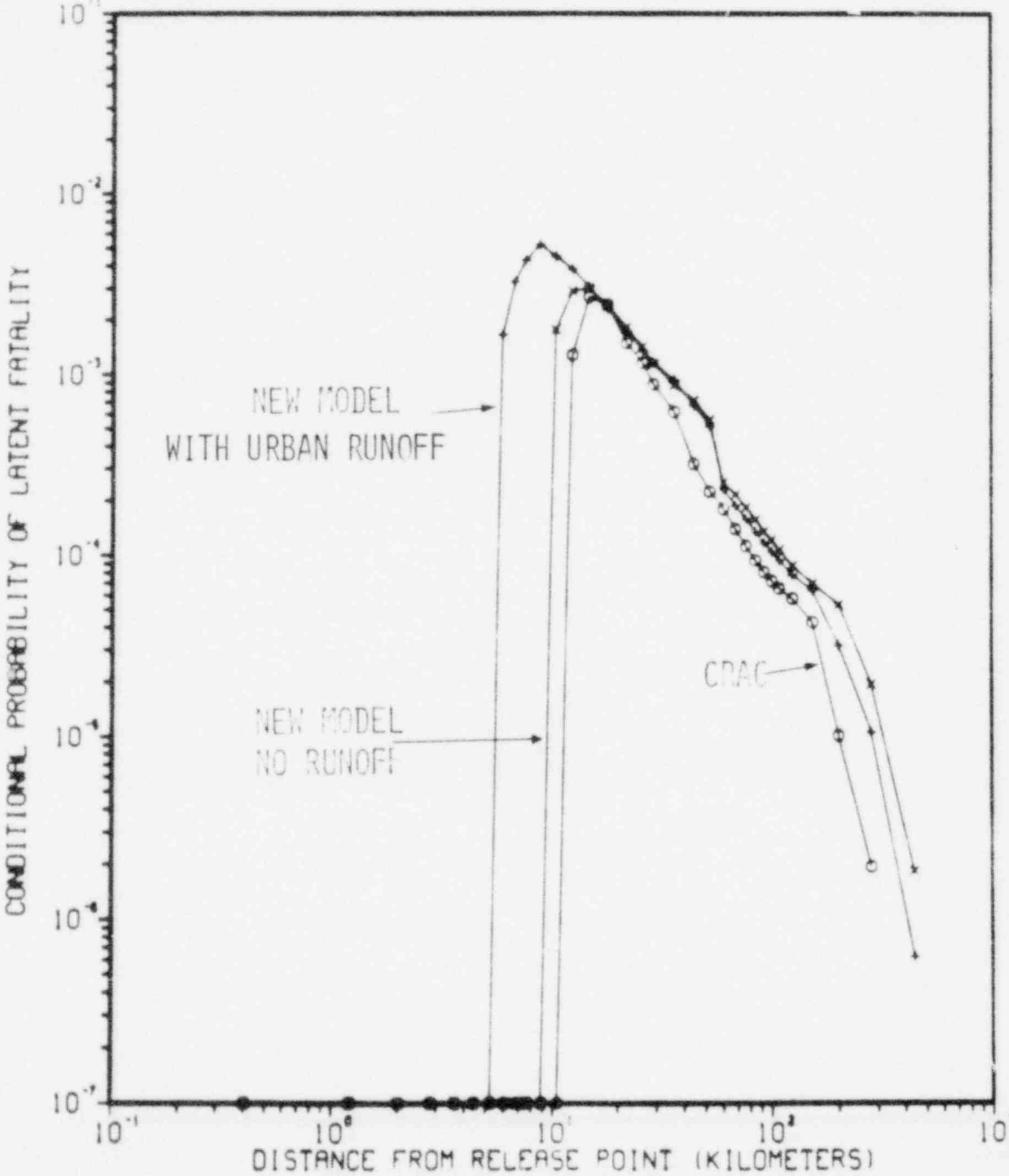

Figure 14. Conditional probability per capita of cancer fatalities resulting from latent effects versus downwind distance from the release point. Averate rain rate is .25 mm/hr for the new rain model.

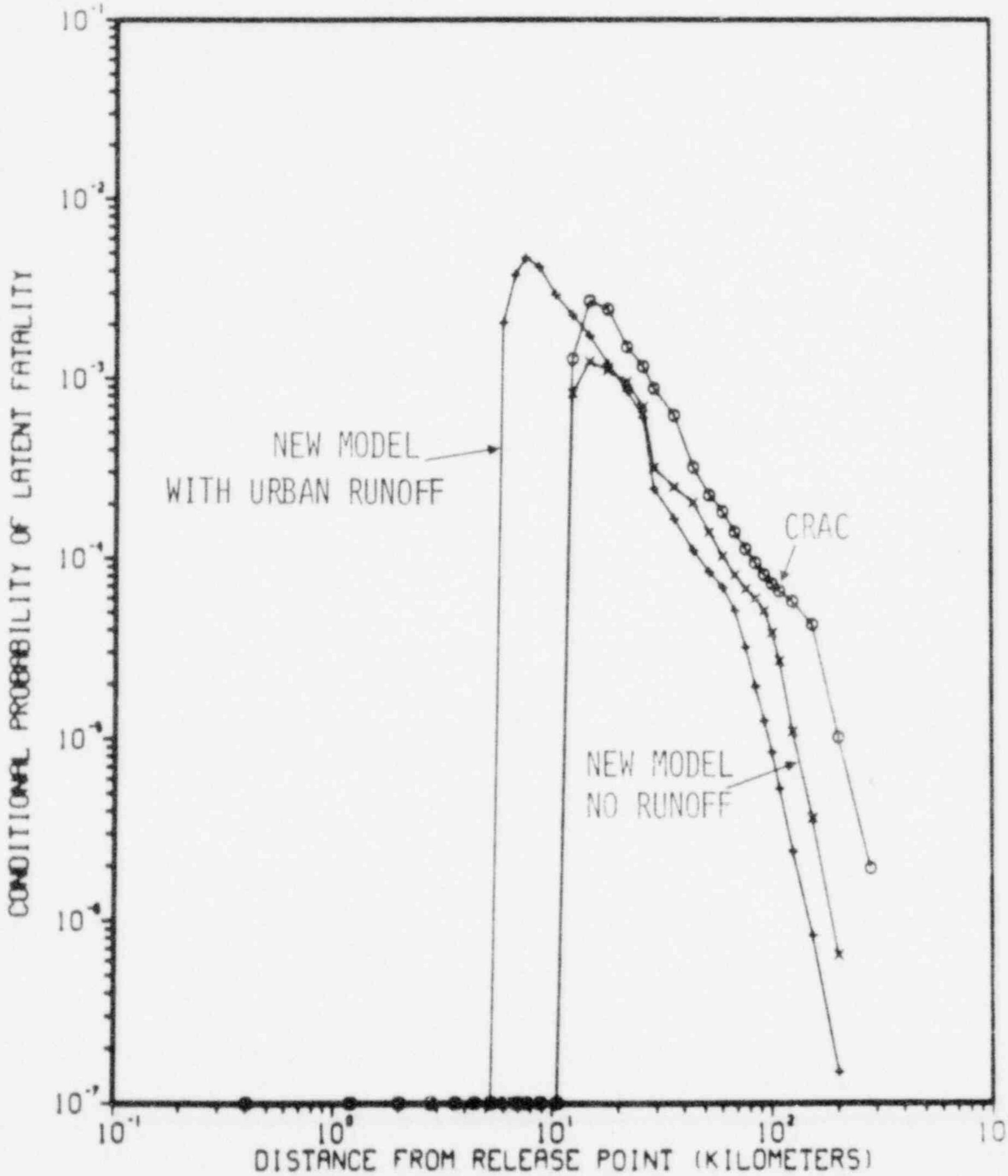

Figure 15. Conditional probability per capita of cancer fatalities resulting from latent effects versus downwind distance from the release point. Average rain rate is 2.5 mm/hr for the new rain model.

6

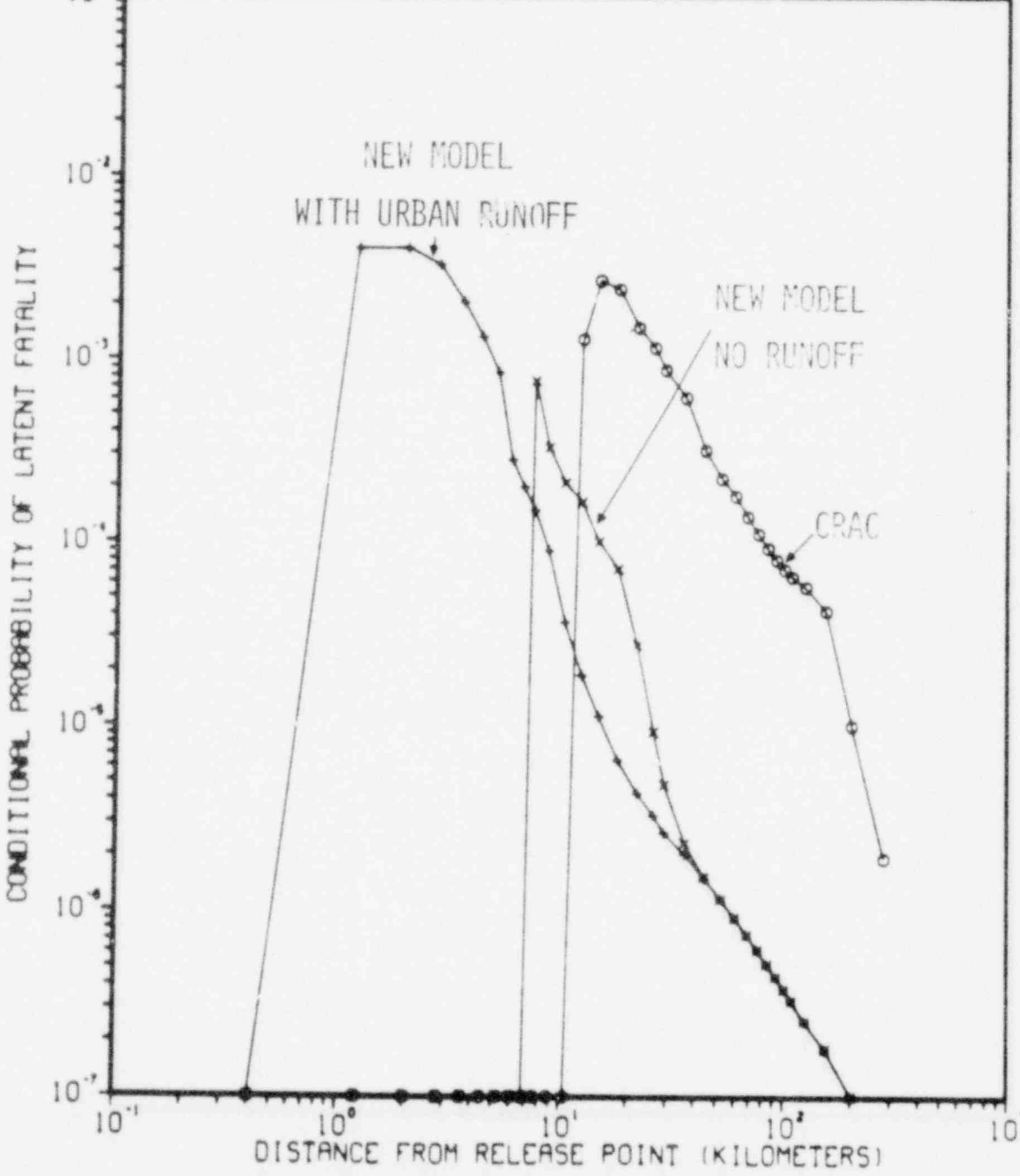

Figure 16. Conditional probability per capita of cancer fatalities resulting from latent effects versus downwind distance from the release point. Average rain rate is 25 mm/hr for the new rain model.

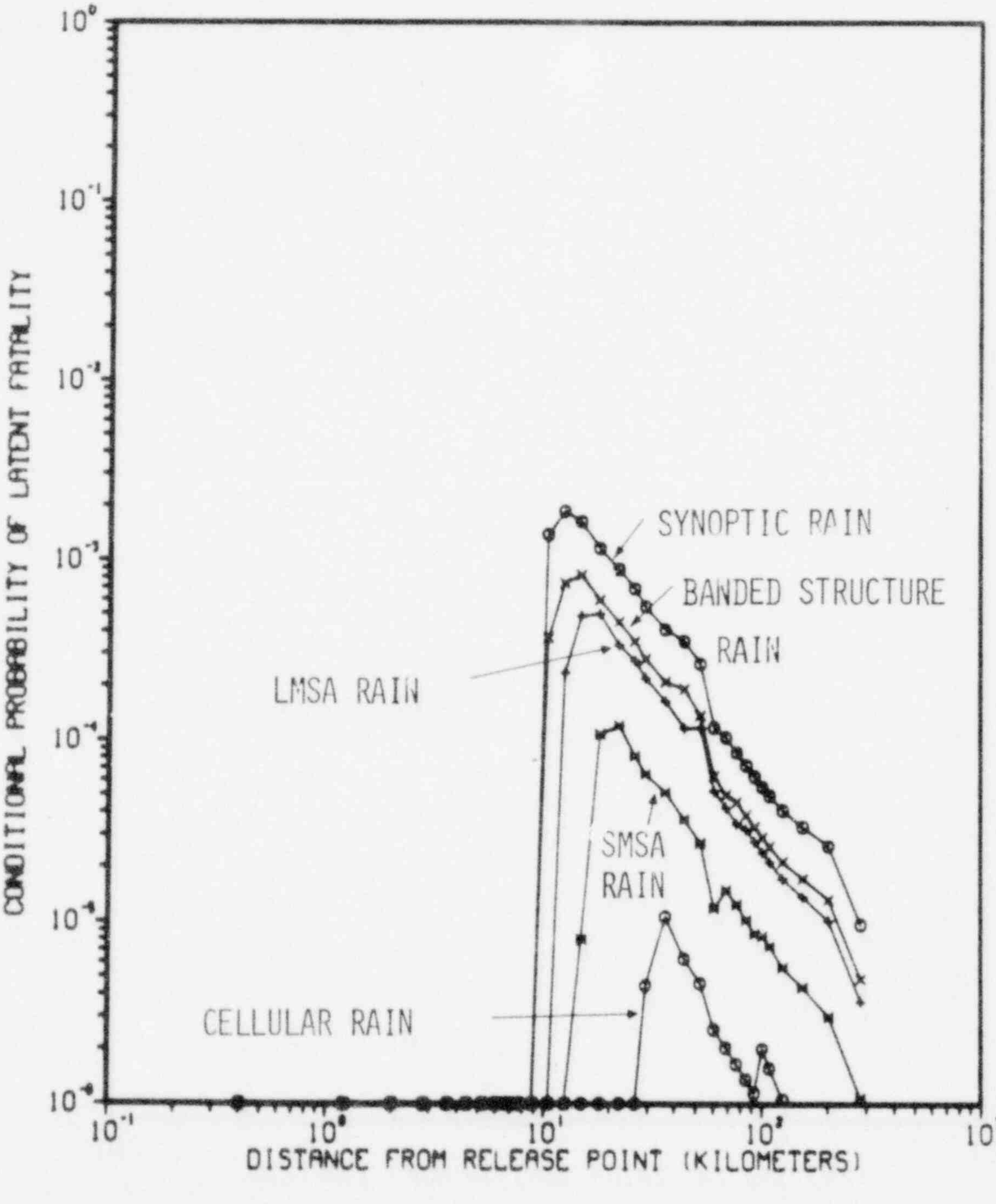

Figure 17. Contributions of each of the five levels of rain intensity to the conditional probability per capita of cancer fatalities resulting from latent effects. Average rain rate is .25 mm/hr.

produce latent cancer fatalities. As the average rainfall intensity increases, the decreased air and ground concentrations beyond the distances where early fatalities occur are less likely to produc latent effects than the original model predicted; see Figures 15 and 16. For runoff, the conditional probability of latent cancer fatalities at distances less than a few kilometers remains large at the high rain rates. Notice, however, that the conditional probability for latent cancer fatalities at these close distances is less than the conditional probability for early fatalities by a factor of about five.

The predictions of the original CRAC model and of the new rain model with urban runoff and without runoff have been presented and compared for cases of simplified storms. The following are some of the important features of the results from the new model for individual storms when rain occurs at the time of release and significant runoff occurs:

1. As the average rain rate increases, larger amounts of radioactivity are deposited closer to the reactor and the air concentration decreases more rapidly with increasing downwind distance. This restricting of the high levels of radioactivity to smaller distances from the reactor can result in a reduced radius for early fatalities and, correspondingly, a larger area over which latent effects dominate.
2. Close to the reactor, where the concentrations of radioactive material are high, the ground concentrations corresponding to the structured rain activity

vary significantly between activity levels. The larger ground concentrations are associated with the levels that have the higher rain rates. As a result, the levels of higher rain rate can contribute more to the production of early fatalities. For example, rain cells can sometimes lead to hot spots that produce early fatalities in regions where storm average rain rates would produce no early fatalities.

3. At distances sufficiently close to the reactor (usually less than a few kilometers) and for the assumed exposure duration, the conditional probability for early fatality for an individual may be independent of rain rate because the exposure levels are above the early fatality lethality level.
4. Runoff reduces the ground concentration of radioactivity. As a result, runoff can decrease the conditional probability for early fatality. For example, runoff can ameliorate, or even eliminate the effects of hot spots formed by rain cells.
5. Although runoff reduces the conditional probability for early fatality, it may increase the conditional probability for latent cancer fatalities in the same region. As the number of early fatalities is reduced, a larger number of people remain to become victims of latent effects.

VI. Results for Observed Weather Events

In a real-accident scenario, rain intensity and atmospheric dispersion characteristics (stability and windspeed) will vary with time. A postulated release that occurs during a selected rainstorm has been chosen to illustrate the effects of an actual storm. The reactor accident release category is chosen to be PWR-1A. The characteristics of the rainstorm were obtained from the meteorological data file in CRAC. The rain, which was of 8-hour duration, occurred during unstable conditions at and downwind from the reactor site. One hour before the time of the accident, the measured rainfall at the reactor began at an intensity of 0.25 mm/hr and increased to 3.8 mm/hr at the start of the release. Two hours after the release the rain rate at the reactor site decreased to 0.25 mm/hr. The average rain rate for this storm was 1 mm/hr. The resulting air and ground concentrations as predicted by CRAC and the new rain model are shown in Figures 18 and 19, respectively. The ground concentration for the first kilometer of plume travel calculated by means of the new model is larger than that calculated with CRAC because of the larger rain rate (3.8 mm/hr for the new model; 0.5 mm/hr for CRAC). The air concentration predicted by the new model beyond the first kilometer of plume travel is lower than the CRAC result because of the large washout produced by the high rain intensity during the release.

The differences in the air and ground concentrations predicted by the two models are reflected in the conditional probabilities of early fatality and of latent effects as displayed

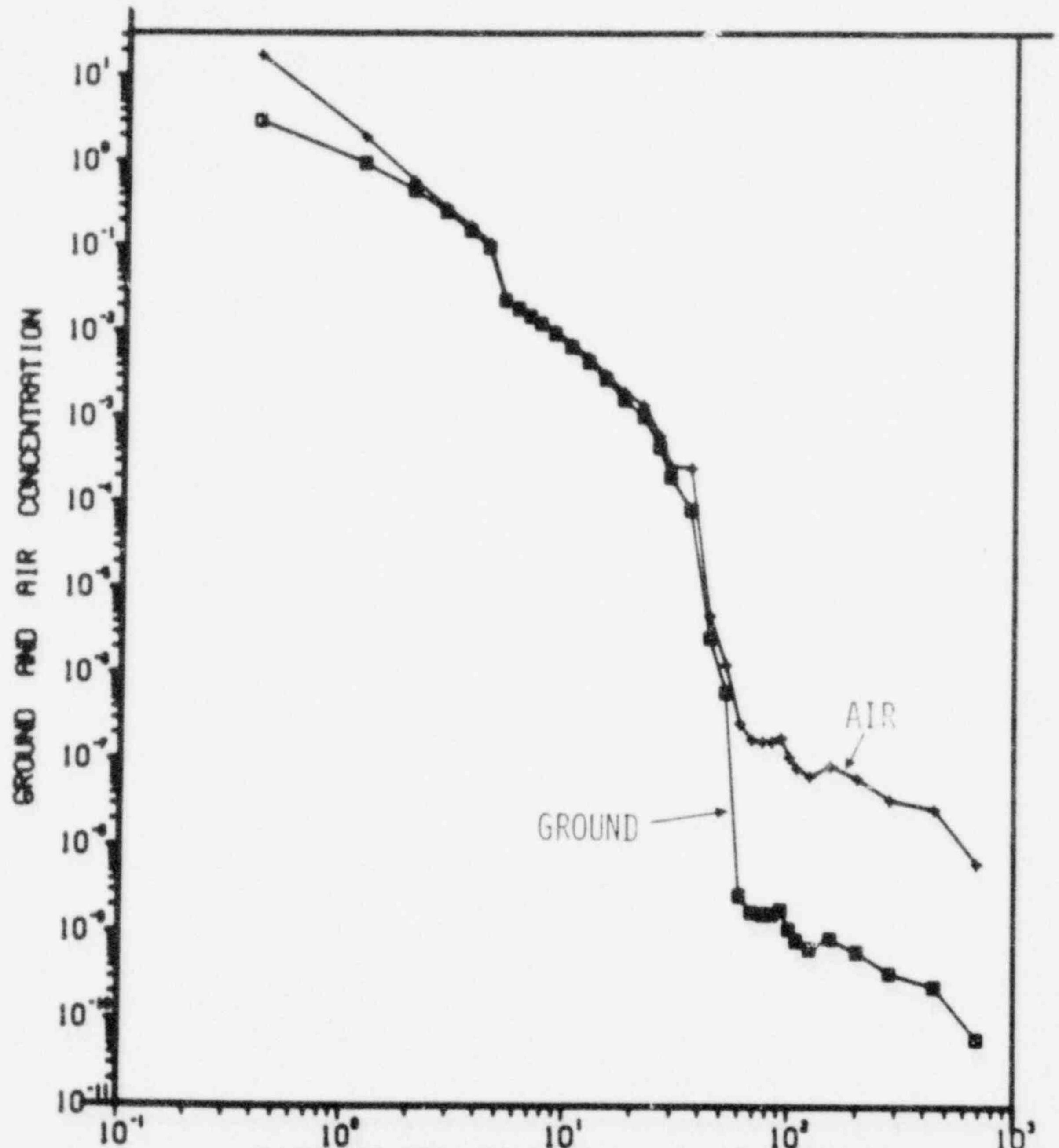

FIGURE 18. Air concentration (Ci-s/m^3) and ground concentration (Ci/m^2) of ^{134}Cs according to CRAC for the sample rainstorm.

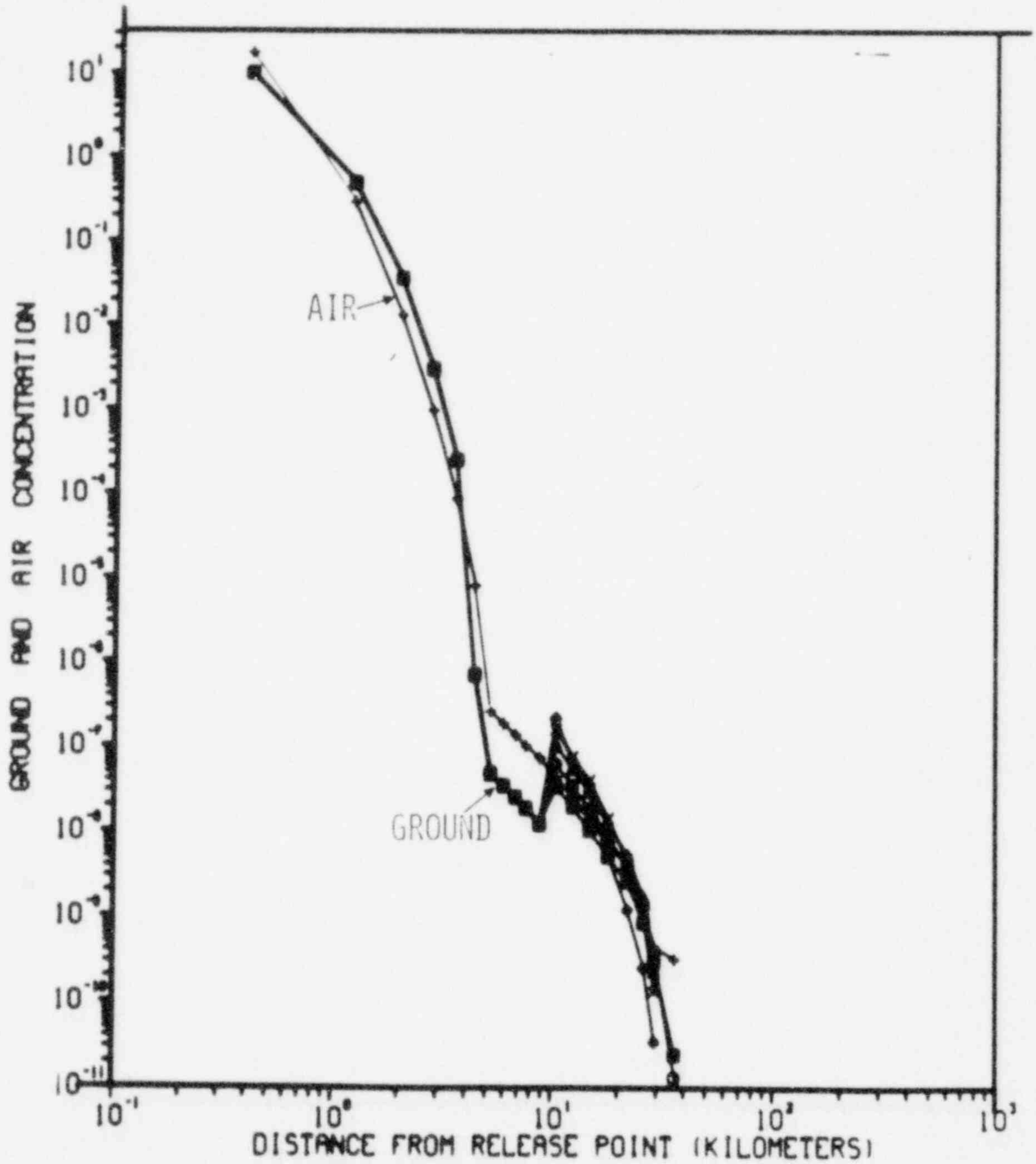

FIGURE 19. Air concentration (Ci-s/m^3) and ground concentrations (Ci/m^2) of ^{134}Cs for synoptic, banded structure, LMSA, SMSA and cellular levels of rain activity versus downwind distance from release point according to the new rain model for the sample rainstorm.

in Figures 20 and 21. The hybrid rain model predicts a range of only 2 kilometers for early fatalities compared to 5 kilometers predicted by CRAC. The range beyond which latent effects are predicted extends from 1 kilometer according to the hybrid model and 5 kilometers according to CRAC. The hybrid rain model predicts lower conditional probabilities for latent effects beyond 5 kilometers because of the large washout produced by the higher rainfall intensity at the reactor site.

The effects of runoff are observable in Figure 19, because the rainfall was sufficiently intense to produce some runoff after the first hour.

Many of the rainstorms that occur in the vicinity of reactors located in the United States have higher rain rates than the storm considered for Figures 19 through 21. Numerous computer calculations comparing the conditional probabilities for early fatalities and latent effects predicted by the hybrid rain model and by CRAC have been performed for a variety of rainstorms. The results of these calculations are consistent with the general trends established in analyzing simplified storms

Rather than examining results for additional individual storms, results for runs with stratified* meteorological conditions, as described in Appendix VI of WASH-1400 [3], are now considered. These results represent stratified meteorological

*The stratified sampling method selects starting times for weather sequences every four days. The starting hours for successive sample days differ by 13 hours. This technique was selected for the CRAC model to ensure complete coverage of the diurnal, seasonal, and four day meteorological cycles without the statistical noise from random numbers.

7

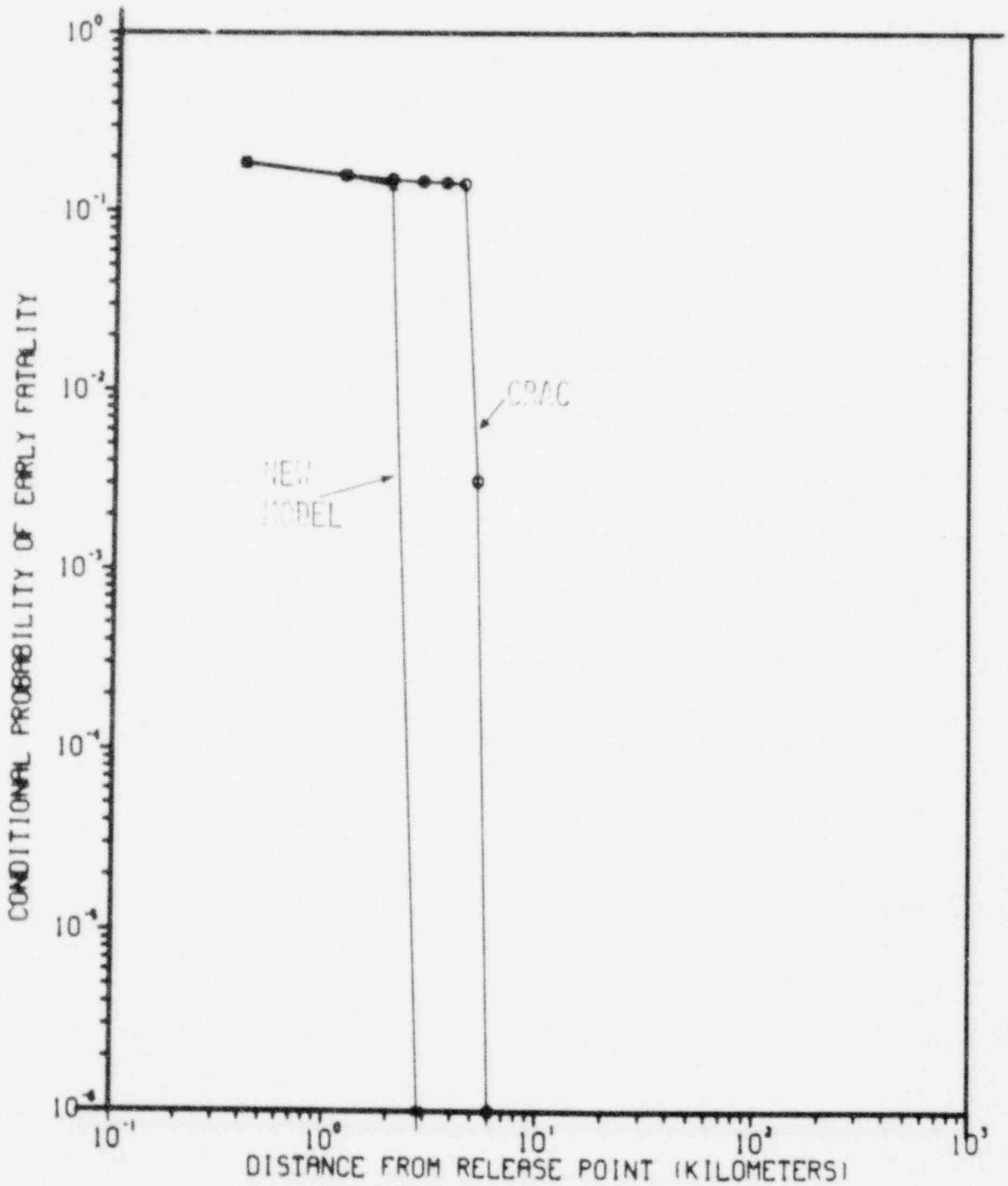

FIGURE 20. Conditional probability per capita of early fatality according to the new rain model and CRAC for the sample rainstorm.

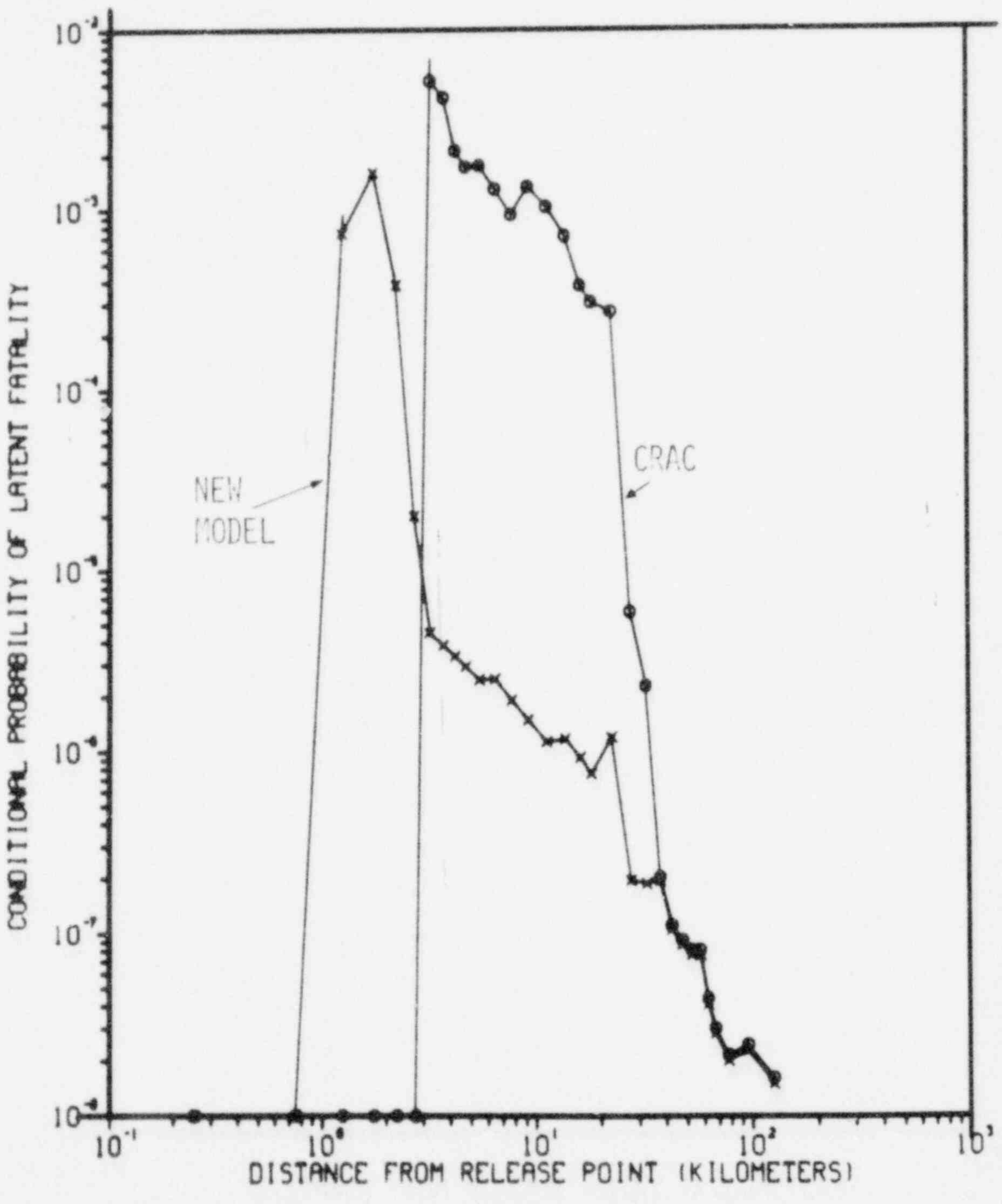

Figure 21. Conditional probability per capita of cancer fatalities resulting from latent effects according to the new rain model and CRAC for the sample rainstorm.

sequences for three sites: a northeast river valley site, Site X; a great lakes shore site, Site Y; and a southeast river valley site, Site Z. Since a stratified run represents 91 separate meteorological sequences obtained from a full year of weather data, it is of considerable interest to examine the frequency of the occurrence of rain at each of the sites during a stratified run. For each of these sites, Table 2 shows the percentage of hours per year during which there is precipitation exceeding .25 mm/hr, and the frequency from 91 stratified weather samples for which rain intersected the plume at some point in its development within 50, 100, 160, 240 and 800 kilometers of the reactor site.

For the stratified runs, the reactor accident release category is chosen to be PWR-1A [3], in which all isotopes are released as specified in Appendix VI of WASH-1400 [3]. The resulting conditional probabilities per capita for early fatality and complementary cumulative distribution functions, CCDF's, for total early fatalities are similar for all three sites. Results for these three sites are shown in Figures 22, 23, and 24. The conditional probability per capita for latent cancer fatalities and CCDF's for total latent cancer fatalities are also very similar for all three sites. Figure 25 illustrates these results. Uniform population densities of 100 people per square mile are assumed for these calculations. Each figure displays the predictions of the original CRAC model, and the new rain model without runoff and with urban runoff. For the three sites, results show no major differences in the predictions of the two models,

TABLE 2

Plume Rain Interaction Frequencies for a Stratified Set of 91 Weather Samples

SITE	X	Y	Z
Percentage of Hours with Measurable Precipitation	5.5	9.9	7.5
Frequency from 91 Weather Samples for Which Rain Intersected the Plume at Some Point in its Development			
Within 50 km of Reactor Site	9	15	19
Within 100 km of Reactor Site	14	20	26
Within 160 km of Reactor Site	20	28	32
Within 240 km of Reactor Site	25	36	35
Within 800 km of Reactor Site	49	68	55

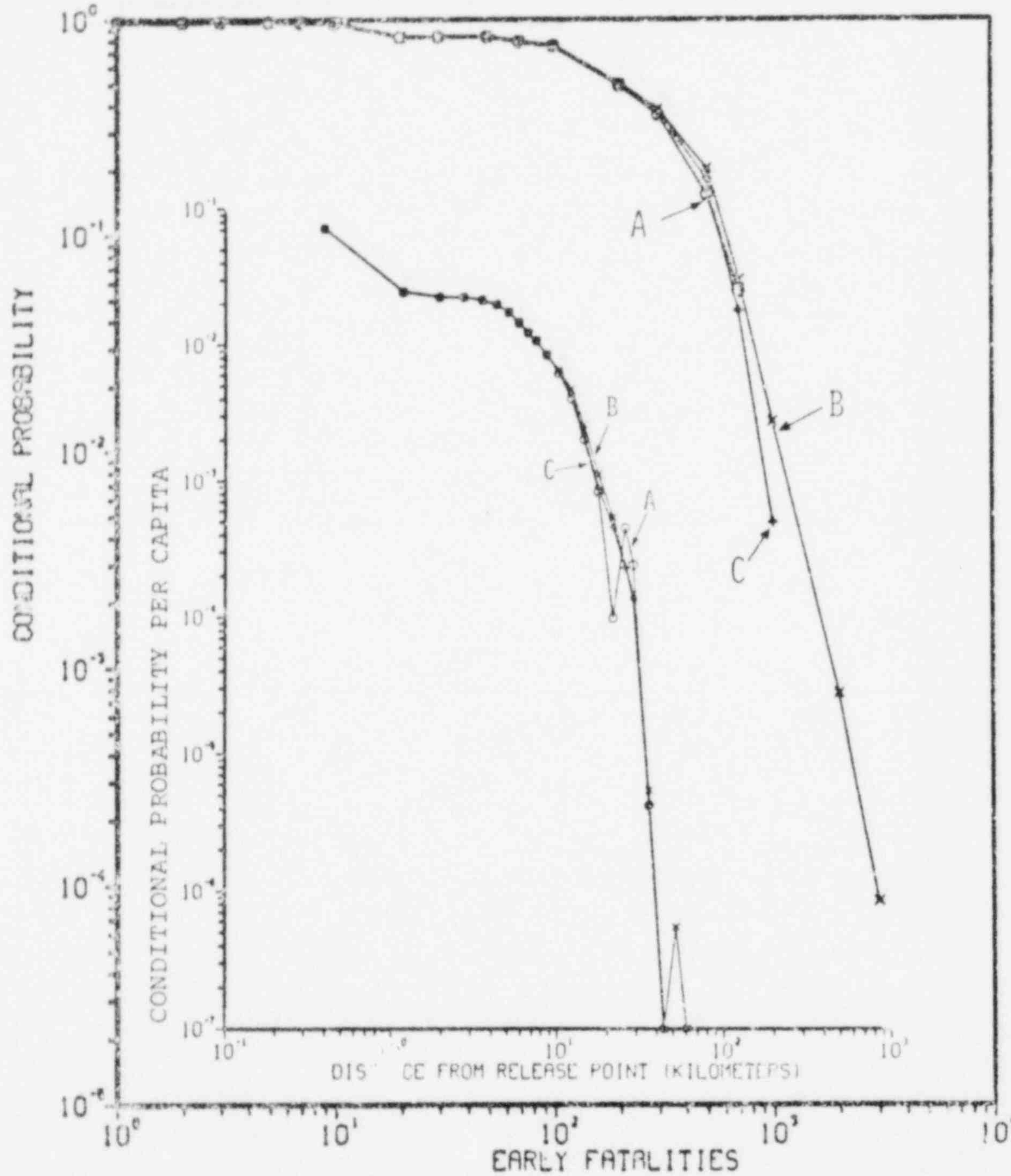

FIGURE 22. Comparison of CCDFs for total early fatalities and of conditional probability per capita of early fatality versus distance at Site X for CRAC and the new model. A - CRAC; B - new model without runoff; and C - new model with urban runoff.

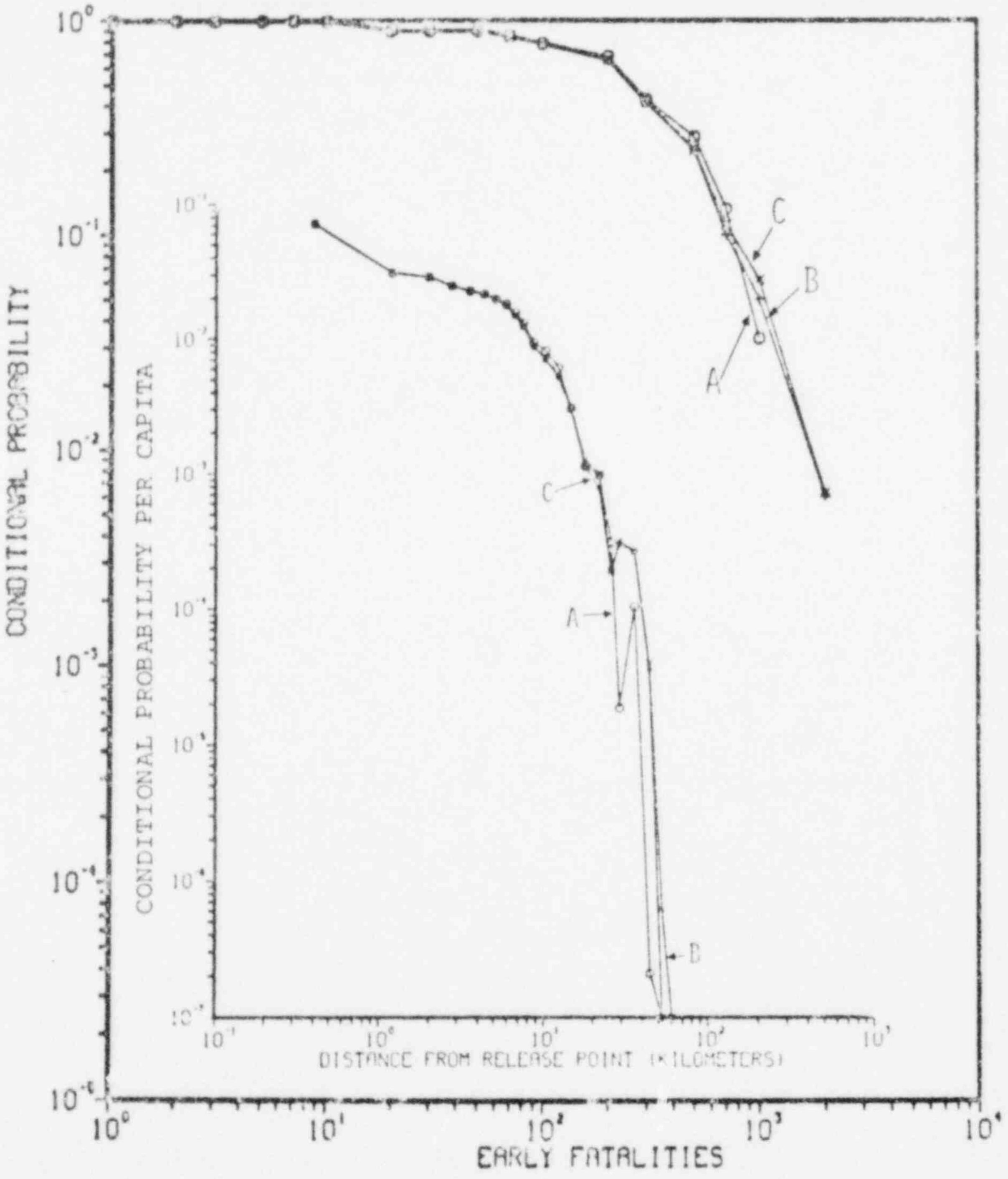

FIGURE 23. Comparison of CCDF's for total early fatalities and conditional probability per capita of early fatality versus distance at Site Y for CRAC and the new model. A - CRAC; B - new model without runoff; C - new model with urban runoff.

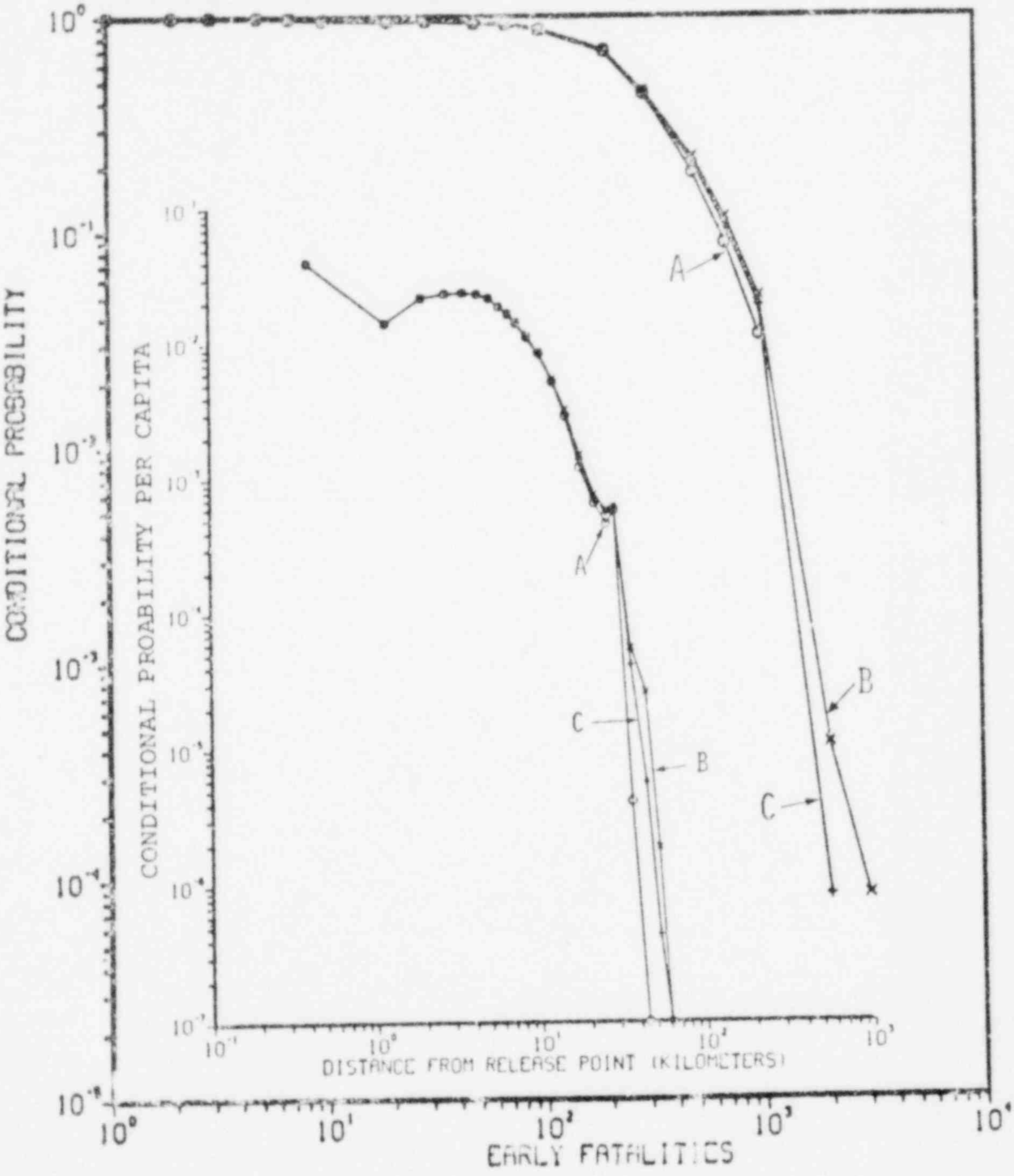

FIGURE 24. Comparison of CCDF's for total early fatalities and conditional probability per capita of early fatality versus distance at Site Z for CRAC and the new model. A - CRAC; B - new model without runoff; C - new model with urban runoff.

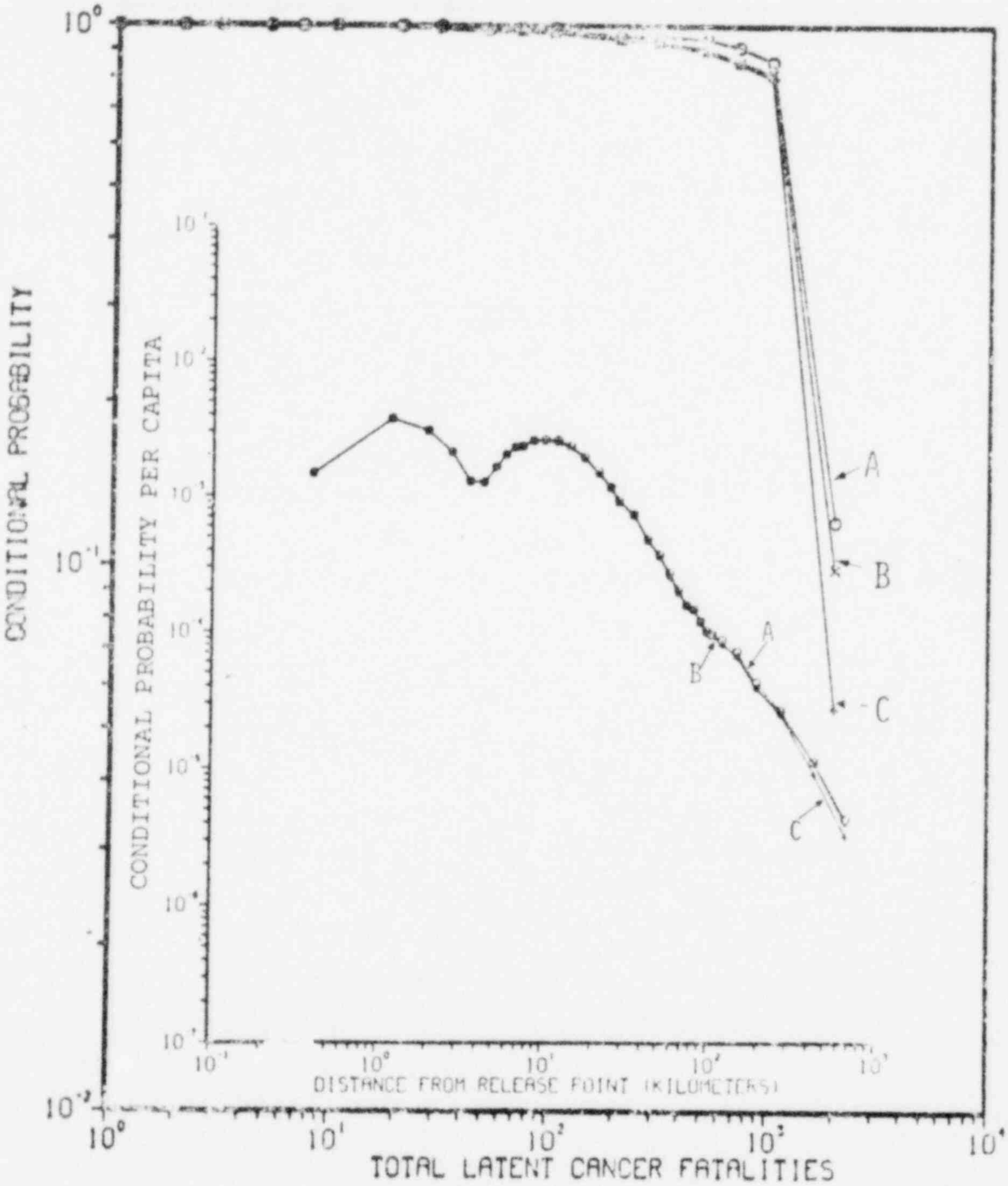

Figure 25. Comparison of CCDF's for latent cancer fatalities and conditional probability per capita of latent cancer fatalities versus distance at Site X for CRAC and the new model. A - CRAC; B - new model without runoff; C - new model with urban runoff.

8

even though the predictions of the new rain model and of CRAC are very different for many individual storms. There are several reasons for this apparent paradox:

1a. Rain is not a frequent event. Rain intercepts the plume within 50 km of the reactor site in not more than 19 of the 91 sequences for these three sites, and in only 9 of the 91 sequences for site A.

b. The differences in predictions of the CRAC rain model and the new rain model tend to dissipate when considered over a number of different rainstorms and accident starting times.

2. For most of the cases in which the plume encountered rain, the interaction was at large distances from the reactor (160 km or more) where the air concentration of the radionuclides was small. At these large distances, few health consequences are predicted by either model.

There is very little variability in the results depicting latent effects. However, it should be observed that comparisons of the results from the new rain model and CRAC show that the most serious accidents are more serious in terms of total early fatalities when the spatial/temporal variations in rain are considered. Although released plumes may encounter rain infrequently, peak accident consequences in terms of total early fatalities are more serious by a factor of approximately two when rainstorm variability is taken into consideration. Runoff acts to reduce the differences in peak consequences between the two models. When actual population densities are used instead of uniform population densities, the predictions by CRAC and the new rain model again show no major differences. An example of these predictions are shown as CCDF's in Figure 26 for total early fatalities for one of the sites. Peak accident consequence predictions are certainly dependent on population densities, but temporal/spatial variations in rain still result in predictions of more serious peak accidents relative to early fatalities, even with runoff considered.

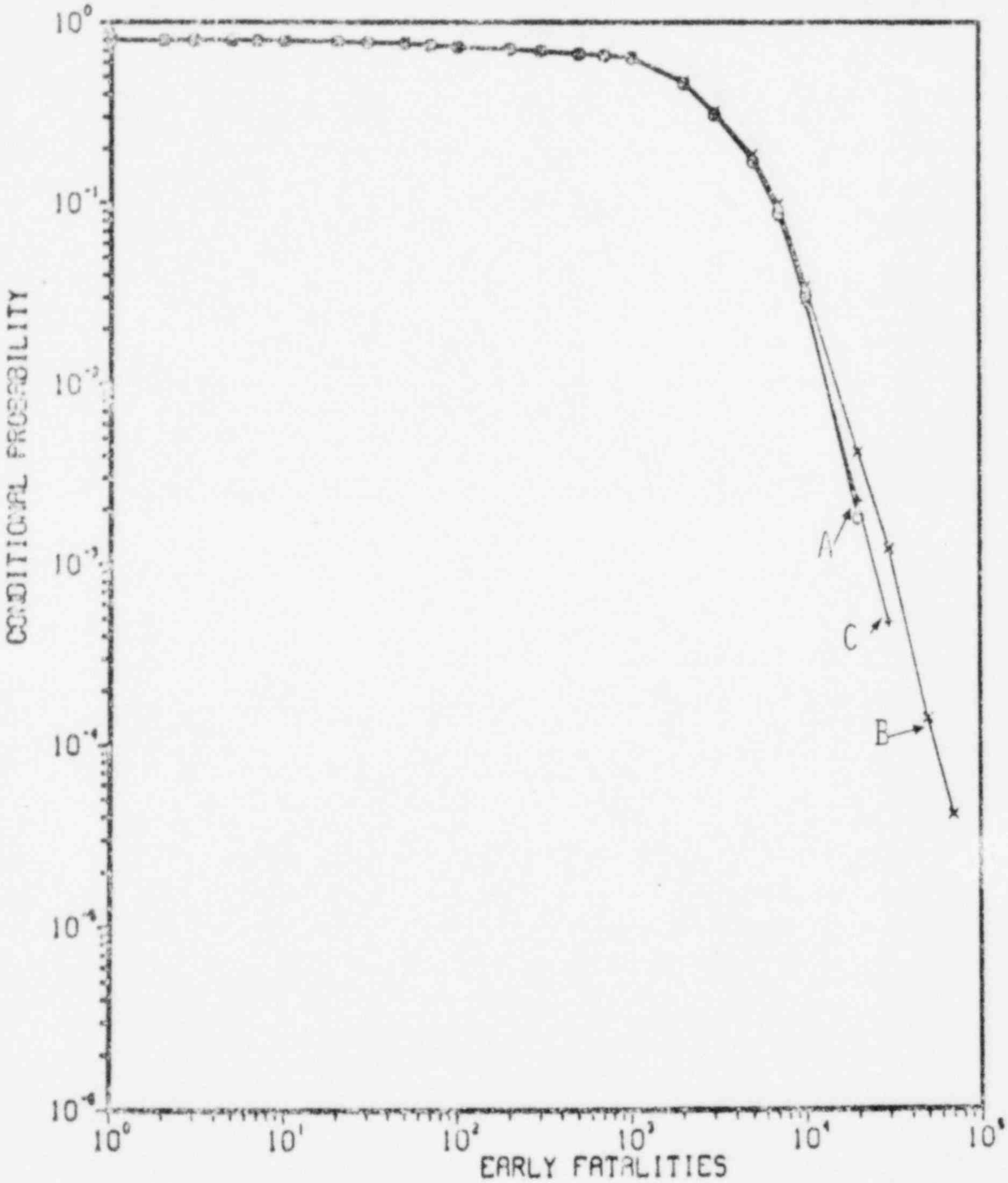

FIGURE 26. Comparison of CCDF's for total early fatalities using the site population data at Site X for CRAC and the new model. A - CRAC; B - new model without runoff; and C - new model with urban runoff.

VII. Observations and Conclusions

The basic features of the new rain/runoff model have been presented. The new model differs from the original CRAC model in three main respects:

1. The average rain rate in the new model is determined from regional rain gage data for each storm, rather than being fixed at 0.5 mm/hr.
2. The rain structure in the new model is represented by actual rain, structured rain in terms of five levels of rain activity, and average rain. In the original model, rain is uniform without any spatial structure.
3. Urban runoff is modeled in the new model and depends on surface retention. No runoff is assumed to occur in the original CRAC.

In addition, the assumptions that have been made in constructing the new model have been described. To summarize, the new model assumes:

1. Storm average rainfall rates for one year and hourly rainfall rates at the reactor for one year are available.
2. The storm average rainfall rate in any grid element is constant for each storm.
3. In the neighborhood of the reactor (out to 10 km), rain rates are uniform and correspond to the int[illegible]ity of the hourly rain rate measured at the reactor site.

4. Beyond 240 km, rain rates are uniform and equal to the storm average rain rate.
5. In the region from 10 km to 240 km rainstorm rates vary spatially and are structured. There are five levels of rainstorm activity in each grid element.
6. Air concentrations of radionuclides are uniform in a grid element.
7. Ground concentrations of deposited radionuclides depend on the level of rainstorm activity.
8. Runoff is dependent on surface retention and is a function of the contaminated rainfall and the precedent rain.

The predictions of the original CRAC model and of the new model with urban runoff and without runoff were presented and compared for cases of simplified storms and for actual storms. One of the most important results of this study has been the indication of the strong interrelationships in the rainstorm/washout/runoff process. For specific accidents, changes in the rainfall rate, washout coefficient, and amount of precedent precipitation can significantly change the accident consequences. A general conclusion of this study is that, when considering specific accidents, the spatial/temporal structure of rainstorms and runoff can have large effects on predictions of consequences of nuclear accidents as compared to predictions using uniform rain without runoff.

Predictions of the original CRAC model and of the new model were presented and compared for cases of stratified meteorological conditions for three sites. Three features of these results should be emphasized. The number of meteorological sequences during which rain encounters the plume close to the reactor is small. Therefore, the conditional probabilities for early fatalities and latent cancer fatalities predicted by the new rain model are close to those predicted by CRAC. Peak health consequences in terms of early fatalities are larger when spatial and temporal variations in rainstorms are considered, but runoff acts to reduce the differences in the peak early fatalities between the two models.

The new rain/runoff model is more representative of the phenomena associated with actual rainstorms and runoff than CRAC and is thus more defensible. However, three observations should be made for the case of stratified sampling:

1. Average health consequences calculated with the new model do not differ significantly from those computed with the original CRAC.
2. The new rain/runoff model requires nearly twice as much computer time as the original CRAC rain model.
3. The rain model in the original CRAC model works extremely well for calculating aggregate health risks.

References

1. Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, NRC Report WASH-1400 (NUREG-75/014), NTIS, 1975.

2. Nuclear Regulatory Commission, Overview of the Reactor Safety Study Consequence Model, NRC Report NUREG-0340, NTIS, 1977.

3. Nuclear Regulatory Commission, Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Appendix VI: Calculation of Reactor Accident Consequences, NRC Report WASH-1400 (NUREG-75/014), NTIS, 1975.

4. L. T. Ritchie, W. D. Brown, and J. R. Wayland, Effects of Rainstorms and Runoff on Consequences of Nuclear Reactor Accidents, SAND76-0429, Sandia Laboratories, Albuquerque, New Mexico, October 1976.

5. L. T. Ritchie, W. D. Brown, J. R. Wayland, "Effects of Rainstorms and Runoff on Consequences of Atmospheric Releases from Nuclear Reactor Accidents," Nuclear Safety, 19(2): 220-238 (1978).

6. P. M. Austin, "Comments on Effects of Rainstorms and Runoff on Nuclear Reactor Accident Consequences," unpublished report, October 1976.

7. National Oceanic and Atmospheric Administration, Hourly Precipitation Data, Vols. 20, 21, 22, (1970, 1971, 1972), Environmental Data Service, U.S. Department of Commerce, Asheville, North Carolina.

8. W. M. Grayman and P. S. Eagleson, Evaluation of Radar and Raingage Systems for Flood Forecasting, Report No. 138, R. M. P. Laboratory, Massachusetts Institute of Technology, 1971.

9. R. A. Houze, Jr., Characteristics of Mesoscale Precipitation Areas, S. M. Thesis, Department of Meteorology, Massachusetts Institute of Technology, 1971.

10. P. M. Austin and R. A. Houze, Jr., "Analysis of the Structure of Precipitation Patterns in New England," Journal of Applied Meteorology, 11(6):926-935 (September 1972).

11. I. I. Zawadzki, "Statistical Properties of Precipitation Patterns," Journal of Applied Meteorology, 12(3):459-472 (April 1973).

12. G. Dsufuca and I. I. Zawadzki, "Statistics of Raingage Data," Journal of Applied Meteorology, 14(8):1419-1429 (December 1975).

13. P. M. Austin, Application of Radar to Measurement of Surface Precipitation, Final Report, Department of Meteorology, Massachusetts Institute of Technology, 1969.

14. H. B. Byers and R. Braham, Jr., The Thunderstorm, U.S. Weather Bureau, 1949.

15. R. R. Rogers and I. I. Zawadzki, "Rainfall Statistics for Application to Plume Rainout Models," unpublished report, February 1977.

16. J. R. Wayland, L. T. Ritchie, Entrainment of a Developing Plume into Convective Cells, SAND77-0736, Sandia Laboratories, Albuquerque, NM, August 1977.

17. W. G. N. Slinn, "Some Approximations for the Wet and Dry Removal of Particles and Gases from the Atmosphere," Water, Air, Soil Pollution, 7(4):513-543 (1977).

18. W. G. N. Slinn, "Parameterizations for Resuspension and for Wet and Dry Deposition of Particles and Gases for Use in Radiation Dose Calculations," Nuclear Safety, 19(2):205-219 (1978).

19. V. T. Chow (editor), Handbook of Applied Hydrology, A Compendium of Water-Resources Technology, McGraw-Hill Book Co., New York, 1964.

20. L. H. Gevantman, et al., Contaminability of Selected Materials - Liquid Hold Up as a Measure of their Contaminability, Report NRDL-TR-11, Naval Radiological Defense Laboratory, 1954.

21. D. M. Gray (editor), Handbook on the Principles of Hydrology, A Water Information Center Publication, Port Washington, NY, 1973.

Distribution:

U.S. Nuclear Regulatory Commission
Division of Technical Information and
Document Control (240 for R-1)
7920 Norfolk Avenue
Bethesda, MD 20014

U. S. Nuclear Regulatory Commission (5)
Probabilistic Analysis Staff
NL 5650
Washington, DC 20555
Attn: F. H. Rowsome
R. Blond

Massachussets Institute of Technology
Department of Meteorology
Cambridge, MA 02139
Attn: P. M. Austin

McGill University
Department of Meteorology
Montreal, Quebec
Canada
Attn: R. R. Rogers

University of Quebec
Department of Physics
Montreal, Quebec
Canada
Attn: I. I. Zawadzki

Environmental Protection Agency
410 Street NW
CM-2, TS-769
Room 821
Washington, DC 20460
Attn: P. S. McGrath

1000 G. A. Fowler
1200 L. D. Smith
1250 R. G. Clem
1254 B. Boverie
1254 W. D. Brown (5)
4000 A. Narath
4400 A. W. Snyder
4410 D. J. McCloskey
Attn: J. W. Hickman
G. B. Varnado
L. D. Chapman
4413 N. R. Ortiz
4413 D. C. Aldrich
4413 L. T. Ritchie (10)
4500 E. H. Beckner
4510 W. D. Weart
4512 T. O. Hunter
4512 J. R. Wayland (5)
4514 M. L. Merritt
4530 R. W. Lynch
4540 M. L. Kramm
4541 L. W. Scully
4542 J. W. McKiernan
4543 J. E. Ney
4550 R. M. Jefferson
Attn: R. E. Luna
3141 T. L. Werner (5)
3151 W. L. Garner (3)
3154-3 R. P. Campbell (25)
for NRC Distribution to NTIS
8266 E. A. Aas

POOR ORIGINAL