27
12/21/78
25 w8
NT-15
SAND78-0556
Unlimited Release

An Investigation of the Adequacy of the Composite Population Distributions Used in the Reactor Safety Study

Jeremy L. Sprung

Printed October 1978

Sandia Laboratories

Prepared for

U. S. NUCLEAR REGULATORY COMMISSION

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, or any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for any third party's use, or the results of such use, or any information, apparatus, product or process disclosed in this report, or represents that its use by such third party would not infringe privately owned rights.

The views expressed in this report are not necessarily those of the U.S. Nuclear Regulatory Commission.

Available from
National Technical Information Service
Springfield, Virginia 22161

SAND78-0556
Unlimited Release

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

AN INVESTIGATION OF THE ADEQUACY OF THE COMPOSITE
POPULATION DISTRIBUTIONS USED IN THE REACTOR SAFETY STUDY

Jeremy L. Sprung
Fuel Cycle Risk Analysis Division

October 1978

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 Interagency Agreement DOE 40-550-75
NRC FIN No. A1042

8B
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

Results from risk calculations repeated using disparate meteorological files suggest that adequate risk estimates can be obtained for sites, for which wind speed, atmospheric stability, and precipitation data are unavailable, by substituting data from another site, which has similar topography and meteorology. Substitute meteorology calculations suggest that the composite populations used in the Reactor Safety Study caused the probabilities of early fatalities for low consequence events to be overestimated by about a factor of 3 and to be underestimated by about the same factor for higher consequence events. Site specific calculations for Indian Point and Zion suggest that, if all of the 68 sites examined by the Reactor Safety Study had nearby populations as large and as unfavorably situated as those of these two sites, the early fatality risk estimates of the Reactor Safety Study would be increased by no more than a factor of ~10.

TABLE OF CONTENTS

Introduction	<u>Page</u> 9
Construction of Composite Populations	11
Substitute Meteorology	12
Composite Site Calculations	32
Risk Estimates for Specific Sites	38
Conclusions	48
References	49

Introduction. A computer model (CRAC) was developed for the Reactor Safety Study (WASH-1400) [1] to estimate the consequences of postulated accidents at U.S. commercial light water nuclear power plants. One hundred reactors at 68 sites were considered in the study. The 68 sites were assigned to one of six representative site classes on the basis of their geographic location, topography, and meteorology. For each site class, a composite population distribution was constructed from the actual population distributions about each of the sites comprising that class, and a reference site was chosen for which a full year of meteorological data (wind speed, atmospheric stability, precipitation) was obtained. Given data about a postulated reactor accident (probability, amounts of the released radionuclides, release time and duration) and the reference site (meteorology, composite population, land usage), CRAC was used to calculate the atmospheric dispersion and ground deposition of the released radionuclides and the health effects and cleanup costs resulting from their release.

The risk estimates presented in the Reactor Safety Study were developed by aggregating the results of a set of calculations, which included all possible combinations of (1) a representative set of power plant accidents, which defined the amounts of radioactivity released by each representative accident; (2) a representative set of meteorological sequences from which radionuclide dispersion and deposition were calculated; (3) a representative set of exposed populations, the six composite population distributions. Verification of the

adequacy of this approach requires determination of the adequacy (representativeness) of the six composite population distributions. This can be done by determining

- 1) whether aggregation of the results of individual consequence calculations made using the actual population distributions about each of the 68 sites would yield risk estimates that closely approximate those obtained by the Reactor Safety Study using composite populations; and
- 2) whether the uncertainties in the risk estimates presented in the Reactor Safety Study encompass the range of risks that might be encountered at any of the 68 specific sites considered by that study.

The first of these two questions can be addressed most simply by comparing the results of risk estimates made using a composite population to those obtained by aggregating the results of calculations made using all of the individual reactor site populations combined during the construction of that composite population. Since the requisite meteorological data will not be available for most of the sites combined to form any one of the six composites, this approach will be viable only if the use of some substitute meteorological record can be shown not to alter risk estimates substantially.

The second question can be answered by delineating the range of risks which might occur at specific sites. This will be most easily done by developing risk estimates for a set of

sites, whose risks effectively bound the range of risks presented by the operation of reactors at all of the 68 sites considered by the Reactor Safety Study.

This paper examines these questions in four steps. First, the method of constructing composite population distributions used by the Reactor Safety Study is described. Second, the use in risk calculations of a suitably chosen substitute meteorological record is shown to yield satisfactory risk estimates. Third, the risk estimates calculated using a composite population distribution are compared to those obtained by aggregation of the results calculated using a substitute meteorological record with each of the specific site population distributions combined to construct that composite distribution. And finally, a number of risk estimates for specific sites are made in order to bound the range of risks likely to be encountered at specific sites.

Construction of Composite Populations. The method of constructing composite populations used in the Reactor Safety Study was intended to produce a representative set of 16-sector, composite population distributions, whose peak and mean sector populations closely approximated the peak and mean populations of the set of population sectors from which the composite population was constructed. The construction method had four steps. First, from 1970 U.S. Census Bureau data, population distributions about each of the 68 reactor sites considered by the Reactor Safety Study were constructed upon a polar coordinate

grid having sixteen, 22.5° sectors centered on the compass directions and 34 unequal radial spatial intervals, whose outer radii are listed in Table 1. Second, for each of the six reference site classes, all sectors of all of the sites assigned to that class were ranked (largest population first) according to their cumulative population out to 50 miles (spatial intervals 1 thru 24). Third, a composite population distribution was then constructed for each site class by retaining unchanged the first few sectors in the sector ranking and then by filling the remaining sectors of the composite with populations obtained by averaging, spatial interval by spatial interval, successively larger groups of sectors taken sequentially from the sector ranking. In this manner all of the sectors in the sector ranking were used to fill the 16 sectors in the composite. Finally, the exposure probability of each sector in the composite was defined to be the number of sectors from the ranking, which were averaged to produce the composite sector, divided by the total number of sectors in the ranking. Table 2 illustrates this construction procedure using the Northeast River Valley site class as an example.

Substitute Meteorology. The effect on risk estimates of using substitute meteorological records was investigated by two sets of calculations. For the first set of calculations 12 trial population sectors were constructed and then consequence calculations were made for each trial sector using the one-year meteorological record of each of the seven representative reactor

TABLE 1: Radii of Spatial Intervals

<u>Spatial Interval</u>	<u>Outer Radius (miles)</u>	<u>Midpoint (miles)</u>	<u>Spatial Interval</u>	<u>Outer Radius (miles)</u>	<u>Midpoint (miles)</u>
1	0.5	0.25	18	20	18.75
2	1.0	0.75	19	25	22.5
3	1.5	1.25	20	30	27.5
4	2.0	1.75	21	35	32.5
5	2.5	2.25	22	40	37.5
6	3.0	2.75	23	45	42.5
7	3.5	3.25	24	50	47.5
8	4.0	3.75	25	55	52.5
9	4.5	4.25	26	60	57.5
10	5.0	4.75	27	65	62.5
11	6.0	5.50	28	70	67.5
12	7.0	6.50	29	85	77.5
13	8.5	7.75	30	100	92.5
14	10.0	9.25	31	150	125.0
15	12.5	11.25	32	200	175.0
16	15.0	13.75	33	350	275.0
17	17.5	16.25	34	500	425.0

TABLE 2

Construction of Composite Population for
Northeast River Valley Site Class

Characteristics of Site Class: 14 reactors at 10 sites, therefore 224 sectors in the sector ranking (sectors at sites having more than one reactor are included in the sector ranking a number of times equal to the number of reactors at that site).

Numbering of Composite Sectors: N = 1, NNE = 2, ...NNW = 16.

<u>Composite Sector</u>	<u>Ranked Sectors Averaged to Produce Composite Sector</u>	<u>Conditional Exposure Probability of Composite Sector</u>
1	1	1/224
2	2	1/224
16	3,4	2/224
3	5,6	2/224
15	Average of next 6	6/224
4	Average of next 6	6/224
14	Average of next 12	12/224
5	Average of next 22	22/224
13	Average of next 22	22/224
6	Average of next 23	23/224
12	Average of next 22	22/224
7	Average of next 22	22/224
11	Average of next 20	20/224
8	Average of next 20	20/224
10	Average of next 21	21/224
9	Average of next 22	22/224

sites listed in Table 3. For the second set of calculations this same procedure was repeated but the trial population sectors were replaced by the real, 16-sector, population distributions about the Braidwood, Indian Point, and Millstone reactor sites.

Three of the 12 trial population sectors had uniform population distributions (population densities of 150, 15, and 5 people mi^{-2} , respectively). The remaining nine population sectors were constructed by superimposing a single population spike at a distance of 9.25, 37.5, or 62.5 miles (the midpoints of spatial intervals 14, 22, and 27; see Table 1) upon each of the three sectors having uniform population distributions. Each population spike spanned five consecutive spatial intervals (intervals 12-16, 20-24, or 25-29). Table 4 presents for each of the 12 trial population sectors the baseline density of that sector and the sector's total population within each of four distance ranges (0-25 mi, 25-50 mi, 50-500 mi, and 0-500 mi). As an example Table 5 presents the outer radius, population density (people mi^{-2}), and population for each of the 34 spatial intervals of the second trial population sector (Sector 1.1).

Figure 1 presents four sets of seven early fatality complementary cumulative distribution functions (Log-Log plots of the probability that a consequence of a given magnitude will be equalled or exceeded). All of these complementary cumulative distribution functions (CCDF's) were calculated for a nonbuoyant plume from a PWPls release [2]. Each set of seven CCDF's was

TABLE 3

Occurrence of Rain and Stable Atmospheric
Conditions at Seven Representative Reactor Sites

<u>Site</u>	Percentage of Time Indicated Condition Occurs		
	<u>Rain</u>	<u>E Stability</u>	<u>F Stability</u>
1. Northeast river valley	5.5	30	18
2. Great lakes shore	9.9	24	12
3. Dry western desert ^(a)	0.6	23	36
4. Central midwest plain	6.0	26	16
5. Pacific coast	1.0	36	22
6. Atlantic coast	4.9	32	18
7. Southeast river valley	7.5	47	19

(a) The Reactor Safety Study did not construct a composite population for the third representative site, the dry western desert site, because this site class contained too few reactors to justify the construction of a composite population. Instead, this site was added to the fourth representative site class, the central midwest plains site.

TABLE 4
Properties of Trial Population Sectors

<u>Trial Sector</u>	<u>Baseline Population Density (people mi⁻²)</u>	<u>Population within 25 mi</u>	<u>Population Between 25 mi and 50 mi</u>	<u>Population Between 50 mi and 500 mi</u>	<u>Total Population Within 500 mi</u>
1.0	150	3.48E+4 ^a	1.35E+5	9.09E+6	9.26E+6
1.1	150	5.80E+4	1.35E+5	9.09E+6	9.80E+6
1.2	150	3.48E+4	7.81E+6	9.09E+6	1.69E+7
1.3	150	3.48E+4	1.35E+5	3.81E+7	3.82E+7
2.0	15	3.48E+3	1.35E+4	9.09E+5	9.26E+5
2.1	15	1.23E+4	1.35E+4	9.09E+5	9.34E+5
2.2	15	3.48E+4	3.87E+4	9.09E+5	9.51E+5
2.3	15	3.48E+4	1.35E+4	3.81E+6	3.82E+6
3.0	5	1.16E+3	4.51E+3	3.03E+5	3.09E+5
3.1	5	3.41E+3	4.51E+3	3.03E+5	3.11E+5
3.2	5	1.16E+3	1.13E+4	3.03E+5	3.15E+5
3.3	5	1.16E+3	4.51E+3	8.99E+5	9.05E+5

^a3.48E+4 = 3.48 x 10⁴.

TABLE 5

Characteristics of the Second Trial Population Sector (Sector 1.1)

<u>Spatial Interval</u>	<u>Outer Radius (miles)</u>	<u>Population Density (people mi⁻²)</u>	<u>Population</u>
1	0.5	0	0
2	1.0	0	0
3	1.5	0	0
4	2.0	0	0
5	2.5	0	0
6	3.0	0	0
7	3.5	0	0
8	4.0	0	0
9	4.5	0	0
10	5.0	0	0
11	6.0	150	655
12	7.0	400	2101
13	8.5	4000	35736
14	10.0	40000	428042
15	12.5	4000	79914
16	15.0	400	9680
17	17.5	150	5390
18	20.0	150	6391
19	25.0	150	12017
20	30.0	150	14491
21	35.0	150	21589
22	40.0	150	25535
23	45.0	150	34106
24	50.0	150	39525
25	55.0	150	49568
26	60.0	150	56460
27	65.0	150	67976
28	70.0	150	76341
29	85.0	150	136453
30	100.0	150	158071
31	150.0	150	504608
32	200.0	150	673488
33	350.0	150	2934432
34	500.0	150	4428670

1a. 150 people per square mile.

1b. With a town (2.3×10^4 people) added at 9.25 miles.

1c. With a city (7.7×10^6 people) added at 37.5 miles.

1d. With a metropolitan region (2.9×10^7 people) added at 62.5 miles.

Figure 1: Log-Log plots of conditional probability (per reactor-year) versus early fatalities (conditional on a PWR1a release) showing the effect of 7 disparate meteorological records on the CCDF's for the first 4 trial population sectors (Sectors 1.0, 1.1, 1.2, and 1.3)

1 = Northeast River Valley
3 = Dry Western Desert
5 = Pacific Coast
7 = Southeast River Valley

2 = Great Lakes Shore
4 = Central Midwest Plain
6 = Atlantic Coast

calculated using one of the four trial population sectors (Sectors 1.0, 1.1, 1.2, and 1.3, see Table 4), which were constructed using a baseline population density of 150 people mi^{-2} . Finally, each CCDF in a set of seven CCDF's was calculated using the meteorological record of one of the seven representative sites listed in Table 3.

Sector 1.0 has a uniform population distribution (150 people mi^{-2}), while Sectors 1.1, 1.2, and 1.3 contain population spikes of 2.3×10^4 , 7.7×10^6 , and 2.9×10^7 people, respectively, superimposed on a baseline population density of 150 people mi^{-2} at distances (spike midpoint) of 9.25, 37.5, and 62.5 mi, respectively. Figure 1 shows that the dispersion about the mean result (square root of the range of probabilities at a given consequence magnitude) of the seven early fatality CCDF's obtained using each of these four trial population sectors increases from a factor of ~ 1.3 at low consequences (~ 1 early fatality) to a factor of ~ 3.2 at high consequences ($\sim 10^4$ early fatalities). The two CCDF's which lie highest in all four of these plots are those obtained using the meteorological records of the Pacific Coast and Dry Western Desert sites. Table 3 shows that very stable atmospheric conditions (F stability), which inhibit dispersal of the radioactive plume, occur at these two sites significantly more often than at the remaining five sites. The CCDF's for Sector 1.2 are nearly identical to those of Sector 1.3, which are identical to those of Sector 1.0 but are markedly different

from those of Sector 1.1. Since the population spike in Sector 1.2 begins at 25 miles and since a PWR1a release is a relatively large release, these CRAC calculations suggest that populations more than 25 miles distant from a reactor are only minimally subject to early fatalities.

Early fatality CCDF's for Sectors 2.0 thru 3.3 and total latent cancer fatality CCDF's for all 12 trial sectors are presented in Figures 2 through 6. Figures 2 and 3 echo the conclusions reached by examining the early fatality CCDF's presented in Figure 1. Figures 4, 5, and 6 show that CCDF's for total latent cancer fatalities are largely insensitive to the meteorological record used to calculate them (the dispersion about the mean result is less than a factor of 1.3 for all consequence magnitudes except the very highest) and that, as they should, total latent cancer fatalities are directly proportional to total people exposed.

Figure 7 presents the CCDF's for total latent cancer fatalities and for early fatalities obtained from calculations using each of the seven representative meteorological records, a PWR1a release (non-buoyant plume), and the actual population distributions (16 real population sectors instead of one trial population sector) about the Indian Point and Braidwood reactor sites. Again the dispersion about the mean results of the total latent cancer fatality CCDF's is less than a factor of 1.3 at all but the highest consequence magnitudes. However, now the dispersion about the mean result of the early fatality CCDF's is also less than a factor of 1.3 at

2a. 15 people per square mile.

2b. With a village (8.8×10^3 people) added at 9.25 miles.

2c. With a town (2.5×10^4 people) added at 37.5 miles.

2d. With a city (2.9×10^6 people) added at 62.5 miles.

Figure 2: Log-Log plots of conditional probability (per reactor-year) versus early fatalities (conditional on a PWR1a release) showing the effect of 7 disparate meteorological records on the CCDF's for the second 4 trial population sectors (Sectors 2.0, 2.1, 2.2, and 2.3).

1 = Northeast River Valley	2 = Great Lakes Shore
3 = Dry Western Desert	4 = Central Midwest Plain
5 = Pacific Coast	6 = Atlantic Coast
7 = Southeast River Valley	

3a. 5 people per square mile.

3b. With a village (2.3×10^3 people) added at 9.25 miles.

3c. With a town (6.8×10^3 people) added at 37.5 miles.

3d. With a city (6.0×10^5 people) added at 62.5 miles.

Figure 3: Log-Log plots of conditional probability (per reactor-year) versus early fatalities (conditional on a PWR1a release) showing the effect of 7 disparate meteorological records on the CCDF's for the last 4 trial population sectors (Sectors 3.0, 3.1, 3.2, and 3.3).

1 = Northeast River Valley	2 = Great Lakes Shore
3 = Dry Western Desert	4 = Central Midwest Plain
5 = Pacific Coast	6 = Atlantic Coast
7 = Southeast River Valley	

4a. 150 people per square mile.

4b. With a town (2.3×10^4 people) added at 9.25 miles.

4c. With a city (7.7×10^6 people) added at 37.5 miles.

4d. With a metropolitan region (2.9×10^7 people) added at 62.5 miles.

Figure 4: Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities (conditional on a PWRLa release) showing the effect of the 7 disparate meteorological records listed in Table 3 on the CCDF's for the first 4 trial population sectors (Sectors 1.0, 1.1, 1.2, and 1.3).

5a. 15 people per square mile.

5b. With a village (8.8×10^3 people) added at 9.25 miles.

5c. With a town (2.5×10^4 people) added at 37.5 miles.

5d. With a city (2.9×10^6 people) added at 62.5 miles.

Figure 5: Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities (conditional on a PWR1a release) showing the effect of the 7 disparate meteorological records listed in Table 3 on the CCDF's for the second 4 trial population sectors (Sectors 2.0, 2.1, 2.2, and 2.3).

6a. 5 people per square mile.

6b. With a village (2.3×10^3 people) added at 9.25 miles.

6c. With a town (6.8×10^3 people) added at 37.5 miles.

6d. With a city (6.0×10^5 people) added at 62.5 miles.

Figure 6: Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities (conditional on a PWR1a release) showing the effect of 7 disparate meteorological records listed in Table 3 on the CCDF's for the last 4 trial population sectors (Sectors 3.0, 3.1, 3.2, and 3.3).

7a. Indian Point population distribution.

7b. Indian Point population distribution.

7c. Braidwood population distribution.

7d. Braidwood population distribution.

Figure 7: Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities or early fatalities (conditional on a PWR1a release) showing the effect of the 7 disparate meteorological records listed in Table 2 on CCDF's calculated using 2 real, 16 sector, population distributions and a non-buoyant plume.

all consequence magnitudes and is thus markedly decreased from the results obtained using the trial population sectors (see Figures 1-3). Apparently, the use in each calculation of 16 different real population sectors instead of only one trial sector sufficiently increases the number of ways of obtaining a consequence of any given probability, so that all seven meteorological files yield essentially the same CCDF's for early fatalities. Clearly, if this result holds for all accident types (other release categories, particularly those which produce buoyant plumes), then calculations made using an appropriately chosen substitute meteorological record are likely to yield risk estimates that closely approximate those that would be obtained using a meteorological record measured at the site being examined.

Figures 8 and 9 present CCDF's for substitute meteorology calculations for the Millstone and Indian Point reactor sites, using accidents which produce buoyant plumes (release categories PWR1b and PWR2 [2]). Despite the considerable differences among the 7 meteorological records used in these calculations, Figure 8 shows that, as was the case for nonbuoyant plumes, buoyant plumes yield CCDF's for total latent cancer fatalities which are all quite similar (dispersion about the mean result of ~ 1.7 except at the highest consequence magnitudes). However, Figure 9 shows that the 7 early fatality CCDF's, obtained from calculations which used the 7 different meteorological records and buoyant plumes, differ significantly from each other (dispersion about the mean result of ~ 3 at low consequence magnitudes; dispersion

8a. Indian Point population distribution, PWR1b release.

8b. Millstone population distribution, PWR1b release.

8c. Millstone population distribution, PWR2 release.

Figure 8. Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities (conditional on a PWR1b or a PWR2 release) showing the effect of the 7 disparate meteorological records listed in Table 2 on CCDF's calculated using 2 real, 16 sector, population distributions and a buoyant plume.

9a. Indian Point population distribution, PWR1b release.

9b. Millstone population distribution, PWR1b release.

9c. Millstone population distribution, PWR2 release.

Figure 9: Log-Log plots of conditional probability (per reactor-year) versus early fatalities (conditional on a PWR1b or a PWR2 release) showing the effect of 7 disparate meteorological records on CCDF's calculated using 2 real, 16 sector, population distributions and a buoyant plume.

1 = Northeast River Valley
3 = Dry Wester Desert
5 = Pacific Coast
7 = Southeast River Valley

2 = Great Lakes Shore
4 = Central Midwest Plain
6 = Atlantic Coast

of ~6 at high consequence magnitudes). The lessened smoothness (compared to the CCDF's in Figure 7) of the early fatality CCDF's in Figure 9 is a result of the decreased number of meteorological sequences which lead to early fatalities. Fewer sequences produce early fatalities because the radioactive material in buoyant plumes can be deposited upon the ground in concentrations high enough to cause fatalities only by precipitation. This conclusion is supported by the data on rainfall presented in Table 5 which shows that, of the seven representative sites, the CCDF's which lie lowest are for the two sites which have the least rainfall (the Pacific Coast and Dry Western Desert sites), while the CCDF which lies highest is for the Great Lakes site where rainfall occurs with a significantly enhanced frequency.

The preceding results show that risk estimates made using a substitute meteorological record, measured at a site having meteorology unlike that of the actual site being examined, are not likely to differ by more than a factor of 6 from those which would result from the use of a true meteorological record, measured at the actual site. Therefore, risk estimates made using a substitute meteorological record, measured at a site similar to the actual site (one from the same site class as the site being examined) would be expected to differ minimally (dispersion factor of <2 about the mean result) from those which would be obtained from calculations using a true meteorological record. Accordingly, if risk estimates are made

for all of the sites in a site class using the meteorological record of the reference site of that class, aggregation of the results obtained for each site should yield CCDF's which do not differ substantially from those that would have been obtained had the calculations been made using a true meteorological record for each site.

Composite Site Calculations. The representativeness of the composite populations constructed by the Reactor Safety Study for the Atlantic Coast and Southeast River Valley site classes has been examined by comparing the results of risk estimates made using those composite populations to the risk estimates obtained by aggregating the results of substitute meteorology calculations made for all of the individual reactor site populations in each site class. A PWR1a release (non-buoyant plume) from a 3200 MWt reactor was used for all sites in the Atlantic Coast site class and a PWR2 release (buoyant plume), also from a 3200 MWt reactor, was used for all Southeast River Valley sites. For each site class all calculations used the one-year meteorological record of the reference site of that site class.

Figure 10 presents the results obtained for total latent cancer fatalities. For the Atlantic Coast site class the CCDF obtained by aggregation of the results calculated using substitute meteorology for each of the individual sites in this site class does not differ significantly from the CCDF obtained using the composite population constructed for this

10a. Atlantic Coast Site Class, PWR1a Release (non-buoyant plume).

10b. Southeast River Valley Site Class, PWR2 Release (buoyant plume).

Figure 10: Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities (conditional on a PWR1a or a PWR2 release) comparing the CCDF obtained using the composite population distribution of a site class to that obtained by aggregating the results of substitute meteorology calculations made using the actual population distribution of each site in that site class.

site class by the Reactor Safety Study. For the Southeast River Valley site class the aggregate and composite CCDF's for total latent cancer fatalities differ insignificantly at low consequence magnitudes but diverge for consequence magnitudes $>10^3$.

Results for early fatalities are presented in Figure 11. For the Atlantic Coast site class the CCDF for the composite population exceeds the aggregate CCDF by a factor of ~ 2.5 at low consequence magnitudes and is exceeded by the aggregate CCDF by a factor of ~ 8 at high consequence magnitudes. Similar but more pronounced results were obtained for the Southeast River Valley site class. For that site class the composite CCDF for early fatalities exceeds the aggregate CCDF by a factor of ~ 20 at low consequence magnitudes, while at high consequence magnitudes the converse is true.

Because accidents which produce buoyant and non-buoyant plumes contribute about equally to the risk of early fatalities [3], a measure of the total risk of early fatalities for all of the 14 accidental release categories of the Reactor Safety Study can be obtained by combining the results obtained for the Atlantic Coast site class and for the Southeast River Valley site class. To do this the results for each calculation were weighted by the probability of the accidental release used in that calculation (probability of a PWR1a release = 4×10^{-7} per reactor-year; probability of a PWR2 release = 8×10^{-6} per reactor-year). Summation of the weighted results yields the CCDF's presented in Figure 12. Figure 12 suggests that

11a. Atlantic Coast Site Class, PWR1a Release (non-buoyant plume).

11b. Southeast River Valley Site Class, PWR2 Release (buoyant plume).

Figure 11: Log-Log plots of conditional probability (per reactor-year) versus early fatalities (conditional on a PWR1a or a PWR2 release) comparing the CCDF obtained using the composite population distribution of a site class to that obtained by aggregating the results of substitute meteorology calculations made using the actual distribution of each site in that site class.

Figure 12. Log-Log plots of conditional probability (per reactor-year) versus total latent cancer fatalities or early fatalities presenting the results of combining the CCDF's presented in Figures 10 and 11.

the early fatality CCDF of the Reactor Safety Study may be overestimating the probability of low consequence events by about a factor of 3 and may be underestimating by about the same factor the probability of high consequence events (those having a probability of occurrence of $\sim 10^{-9}$ per reactor-year [4]).

It is easy to understand why the method of constructing composite populations used by the Reactor Safety Study causes the probabilities of early fatalities to be overestimated at low consequence magnitudes and underestimated at higher consequence magnitudes. The averaging of population sectors performed during the construction of the composite population sectors insured that almost every spatial interval of every composite sector contained some people. Most empty spatial intervals disappeared due to averaging with spatial intervals that contained population. Thus, the averaging process produced an increased number of spatial intervals with small numbers of people and, accordingly, more ways to obtain a small number of early fatalities. Conversely, spatial intervals having high populations were reduced in number by being averaged with spatial intervals having lower populations. The only spatial intervals having high populations, which escaped population reduction due to averaging, were those contained in the few sectors which were used in the composite without averaging. But the calculations using the trial population sectors suggested that populations at downwind distances in excess of 25 miles are only minimally subject to early

fatalities. Therefore, the ranking of sectors by cumulative population within 50 miles biased the selection of the sectors used without averaging towards sectors, whose highly populated spatial intervals lay at distances greater than 25 miles and which were therefore only minimally subject to early fatalities. Thus, the ranking of sectors by cumulative population within 50 miles combined with sector averaging tended to decrease the number of spatial intervals at risk that had high populations and thus led to underestimation of the probabilities of events with high numbers of early fatalities.

Risk Estimates for Specific Sites. In order to estimate the dispersion of site specific CCDF's about the aggregate CCDF's developed by the Reactor Safety Study, a number of site specific risk calculations were performed [5]. For each of the 11 site-specific CRAC calculations made for this study, the actual population distribution about the reactor site was used; the exposure probabilities of the 16 sectors of that population distribution were set equal to the fraction of time the wind blows into each sector as specified by the annual wind rose at the reactor site; calculations for pressurized water reactors used only accidents possible at pressurized water reactors and boiling water reactors used only accidents possible at boiling water reactors; and lastly, the amounts of the radio-nuclides released by each hypothetical accident were scaled in proportion to the power level of the site's reactor (scale factor = reactor power level/3200 MWt, where 3200 MWt is the reactor power level used by the Reactor Safety Study).

Risk estimates were made for a PWR1a release [2] at eleven reactors at eight specific sites (Braidwood, Indian Point, Millstone, Palo Verde, San Onofre, Sequoyah, Sterling, and Zion). For each of these eight sites a complete one-year meteorological record (hourly average values for wind speed, and atmospheric stability, and hourly occurrence of precipitation) was obtained. At least one of these eight reactor sites is contained in each of the six reactor site classes (Table 3) of the Reactor Safety Study. Figures 13 through 17 present the results of these calculations.

Figures 13 and 14 illustrate the effect of reactor size upon risk estimates for total latent cancer fatalities and for early fatalities. For both total latent cancer fatalities (Fig. 13) and early fatalities (Fig. 14) the two Indian Point reactors (2619 MWt and 2895 MWt) have almost identical CCDF's. Thus, 10 percent differences in reactor size ($2895/2619 = 1.1$) are of little significance. However, the CCDF's for the two San Onofre reactors (1290 MWt and 3420 MWt) differ significantly for total latent cancer fatalities (probability ratios for a given consequence magnitude of 1.1 to 55) and substantially for early fatalities (probability ratios of 11 to >65). Therefore, reactors which differ in size by factors of 2 to 3 ($3420/1290 = 2.6$) will have CCDF's which differ appreciably, especially for early fatalities. These results suggest that the use by the Reactor Safety Study of a power level of 3200 MWt in all calculations, when the average power level of the

Figure 13: Log-Log plot of probability (per reactor-year) versus total latent cancer fatalities showing the effect of reactor size on CCDF's for two specific sites.

1 = Indian Point (2895 MWt)

2 = Indian Point (2619 MWt)

3 = San Onofre (3420 MWt)

4 = San Onofre (1290 MWt)

Figure 14: Log-Log plot of probability (per reactor-year) versus early fatalities showing the effect of reactor size on CCDF's for two specific sites.

1 = Indian Point (2895 MWt)

2 = Indian Point (2619 MWt)

3 = San Onofre (3420 MWt)

4 = San Onofre (1290 MWt)

100 reactors included in that study was 2680 MWt (range 1290 MWt to 3750 MWt), should not have led to a significant overestimate of consequences.

Figures 15 and 16 present CCDF's for early fatalities and for total latent cancer fatalities for reactors at Indian Point (2895 MWt), Zion (3150 MWt), Millstone (1956 MWt), Palo Verde (3713 MWt), and San Onofre (1290 MWt). Also plotted in these figures are the aggregate CCDF's obtained by the Reactor Safety Study for the 100 reactors included in that study, scaled down by a factor of 100. Thus, the Reactor Safety Study CCDF's present that study's estimates of the risks attendant upon the operation of a typical light water power reactor at a typical reactor site. Of the eleven reactors for which site specific risk estimates have been made, the CCDF's plotted in Figures 3 and 4 for Indian Point and Zion are the highest and those for Palo Verde and San Onofre are the lowest. Thus, Figures 3 and 4 give an indication of the dispersion of site specific results about the results obtained by the Reactor Safety Study. The Millstone 1956 MWt reactor is included in these figures because it is the only boiling water reactor in this set of eleven reactors. CCDF's for the pressurized water reactors located at Braidwood (3360 MWt), Millstone (2484 MWt), Sequoyah (3420 MWt) and Sterling (3450 MWt) are presented in Figures 17 and 18.

Figure 15 suggests that the dispersion (ratio of probabilities at a given consequence magnitude for the site specific

Figure 15: Log-Log plot of probability (per reactor-year) versus total latent cancer fatalities showing the dispersion of site specific CCDF's about the Reactor Safety Study CCDF.

1 = Indian Point (2895 MWt)	2 = Zion (3150 MWt)
3 = Palo Verde (3713 MWt)	4 = Millstone BWR (1956 MWt)
5 = San Onofre (1290 MWt)	* = Reactor Safety Study

Figure 16: Log-Log plot of probability (per reactor-year versus early fatalities showing the dispersion of site specific CCDF's about the Reactor Safety Study CCDF.

1 = Indian Point (2985 MWt)

3 = Palo Verde (3713 MWt)

5 = San Onofre (1290 MWt)

2 = Zion (3150 MWt)

4 = Millstone BWR (1956 MWt)

* = Reactor Safety Study

Figure 17: Log-Log plot of probability (per reactor-year) versus total latent cancer fatalities comparing the CCDF's for 4 specific sites to the Reactor Safety Study CCDF.

1 = Braidwood (3360 MWt) 2 = Sequoyah (3420 MWt)
 3 = Millstone (2484 MWt) 4 = Sterling (3450 MWt)
 * = Reactor Safety Study

Figure 18: Log-Log plot of probability (per reactor-year) versus early fatalities comparing the CCDF's for 4 specific sites to the Reactor Safety Study CCDF.

1 = Braidwood (3360 MWt)	2 = Sequoyah (3420 MWt)
3 = Millstone (2484 MWt)	4 = Sterling (3450 MWt)
* = Reactor Safety Study	

CCDF to the Reactor Safety Study CCDF) of the total latent cancer fatality CCDF's for specific sites about the Reactor Safety Study CCDF is small (dispersion factors of 0.7 to 1.5) for lower consequence events ($\sim 10^3$ latent fatalities). For high consequences events (10^4 to 10^5 latent fatalities) the dispersion about the Reactor Safety Study CCDF of the site specific results is larger (factors of 0.07 to 40). In terms of total risk (the area under a CCDF) the dispersion of the site specific CCDF's about the Reactor Safety Study CCDF is minimal (factors of 0.6 to 2.5). Thus, Figure 15 suggests that the total latent cancer fatality CCDF of most specific sites will not differ greatly from the Reactor Safety Study total latent-cancer fatality CCDF. This result is not surprising, since CRAC calculations of total latent cancer fatalities are largely insensitive to all CRAC parameters except the total amount of radioactive material released and the total population exposed.

Figure 16 shows that at all consequence levels the early fatality CCDF's for Indian Point (2895 MWt) and Zion (3150 MWt) exceed the Reactor Safety Study early fatality CCDF (dispersion factors of 1.1 to 54, average factor of 13), while the Reactor Safety Study CCDF exceeds that for the 1290 MWt reactor at San Onofre by factors of 71 to 253. Clearly, the dispersion of specific site early fatality CCDF's about the Reactor Safety Study CCDF is substantial. Total risk (area under the CCDF) for the Indian Point 2895 MWt reactor is 12 times that predicted

by the Reactor Safety Study CCDF. Thus, if all of the 68 sites examined by the Reactor Safety Study had nearby populations as large and as unfavorably situated as are those of Indian Point and Zion, the early fatality risk estimates of the Reactor Safety Study would be increased by no more than a factor of ~ 10 .

Conclusions

- (1) Results from risk calculations repeated using disparate meteorological records suggest that adequate risk estimates can be obtained for sites, for which wind speed, atmospheric stability, and rain data are unavailable, by substituting data from another site, which has similar topography and meteorology.
- (2) Substitute meteorology calculations suggest that the composite populations used in the Reactor Safety Study caused the probabilities of early fatalities to be overestimated by about a factor of 3 for low consequence events and to be underestimated by about the same factor for higher consequence events.
- (3) Site specific calculations for Indian Point and Zion suggest that, if all of the 68 sites examined by the Reactor Safety Study had nearby populations as large and as unfavorably situated as those of these two sites, the early fatality risk estimates of the Reactor Safety Study would be increased by no more than a factor of ~ 10 .

References

1. Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants, Appendix VI: Calculation of Reactor Accident Consequences, WASH-1400 (NUREG-75/014), U.S. Nuclear Regulatory Commission, Washington, DC (1975).
2. Event sequences for releases categories PWR1a, PWR1b, and PWR2 are as follows: PWR1a (core meltdown, failure of containment spray and heat removal systems, overpressure failure of the containment followed by a steam explosion, release of a relatively non-buoyant plume); PWR1b (core meltdown, failure of containment spray and heat removal systems, containment overpressurization by hot gases followed by a steam explosion which ruptures the containment and releases a buoyant plume); PWR2 (core meltdown, concurrent failure of core cooling, containment spray, and containment heat removal systems, overpressure failure of the containment releasing a buoyant plume).
3. I. B. Wall, P. E. McGrath, H. W. Church, R. M. Blond, and J. R. Wayland, Overview of the Reactor Safety Consequence Model, NUREG-0349, U.S. Nuclear Regulatory Commission, Washington, DC, October 1977.
4. Accident consequences, having a probability of occurrence of less than 10^{-9} per year of reactor operation, are of little practical significance because their chance of occurring is essentially zero. For example, if 300 reactors are eventually built within the continental

United States (current trends suggest fewer than 350 will be built) and each is operated for 30 years, then an accident consequence having a probability of occurrence of 10^{-9} per reactor-year has a 10^{-5} chance of occurring once sometime during the period of operation of nuclear power plants within the United States. Hence, in this paper all CCDF's have been truncated at a probability of 10^{-9} .

5. The absolute precision of CRAC calculations of aggregate risk at specific sites is uncertain. More detailed description of processes and properties, which are site dependent, is most likely necessary to attain meaningful estimates of risks at a specific site. However, comparisons of risks between specific sites should be less subject to error since cancellation of errors is likely.

Distribution:

United States Nuclear Regulatory Commission (2)
Probabilistic Analysis Staff
Office of Nuclear Regulatory Research
Washington, DC 20555

Attn: A. R. Buhl
R. M. Blond

4400 A. W. Snyder
4410 D. J. McCloskey
Attn: J. W. Hickman, 4412
G. B. Varnado, 4414
4413 N. R. Ortiz
Attn: J. E. Campbell
R. M. Cranwell
B. S. Langkopf
4413 D. C. Aldrich
4413 S. J. Niemczyk
4413 L. T. Ritchie (5)
4415 D. A. Dahlgren
Attn: A. R. DuCharme
M. Rios
4415 J. L. Sprung (30)
3141 T. L. Werner (5)
3151 W. L. Garner (3)
for DOE/TIC (Unlimited Release)
3171-1 R. P. Campbell (25)
for DOE/TIC
8266 E. A. Aas