OCT 22 1998

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Assessment of the Meteorological Characterization Used in the ADROIT Code

Eric E. Ryder

Prepared by
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ABSTRACT

The ADROIT (Analysis of Dispersal Risk Occurring in Transportation) code is the primary tool used to perform probabilistic risk assessments for the Transportation Safeguards Division of the Department of Energy. The current version of ADROIT uses a Pasquill-Gifford stability-class approach to meteorological characterization. In order to assess the affect that this simplified approach to weather characterization has on ADROIT's predictions of consequence and risk, the Pasquill-Gifford stability-class approach was replaced with a direct use of radiosonde data from the National Climatic Data Center (NCDC). A comparison of results obtained for the two weather characterizations shows that, under certain circumstances, the use of the stability-class approach can result in a significant underprediction of consequence and risk values. Since such an underprediction is non-conservative, it is recommended that the stability-class approach currently used by ADROIT be replaced with a more detailed characterization of meteorological conditions. Specifically, the NCDC database was found to have sufficient temporal and spatial resolution for ADROIT applications. Understanding that an attempt to use of all of the NCDC data in ADROIT would be prohibitive, a sampling scheme is presented as a viable alternative for instituting the recommendation of this study.

Preface

The work documented in this report was funded by the Transportation Safeguards Division (TSD) of the Department of Energy. The recommendations of this investigation will be incorporated into the 1999 update of the Defense Programs Transportation Risk Assessment (DPTRA) sponsored by TSD.

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1.0 Introduction

The ADROIT code (Analysis of Dispersal Risk Occurring In Transportation) has been used in numerous probabilistic risk assessments for the transportation of hazardous cargoes, including nuclear explosives, nuclear explosive components, and special nuclear materials (e.g., [1]). The current version of ADROIT evaluates the risk associated with 1) intrinsic radiation from the cargo, 2) blunt trauma and/or burns resulting from the direct effects of an accident, and 3) dispersal of radioactive material resulting from a severe accident.

In ADROIT, the dispersal risk associated with a severe accident is built upon three elements—the *probabilities* of release and specific consequence scenarios developed from an event tree; *consequences* evaluated for each end event in the tree through an assessment which integrates dispersion calculations, route characterization, population data, and dose-health effects models to provide estimates of excess latent cancer fatalities (LCFs); and *uncertainties* evaluated by incorporating a Latin Hypercube Sampling (LHS) scheme into the calculations of probabilities and consequences.

The focus of this investigation is on how ADROIT's approach to weather characterization affects the calculations of *consequences* and *risk*. *Consequence* evaluations performed in this study focus on the last two questions in ADROIT's truck-accident dispersal event tree shown in Figure 1. These two questions, related to weather characterization, are key to the estimation of the health consequences (i.e., LCFs) and the environmental consequences (i.e., *contaminated area*) associated with either a fire-driven or high-explosive driven dispersal of nuclear material. Comparisons of consequences alone, however, are not sufficient to make conclusions regarding potential modifications to ADROIT's approach to weather characterization. Comparisons of risk are also required. Risk evaluations combine consequence evaluations with per-trip probabilities for initiating events to provide a more complete picture of how changes in meteorological characterization might affect bottom-line risk predictions.

The purpose of this investigation is to examine alternatives to the simplification of weather data represented by Questions 16 and 17 in Figure 1. Presented first is an examination of how ADROIT's predictions of consequence and risk change when the Pasquill-Gifford stability-class approach to weather characterization is replaced with a direct use of radiosonde data from the National Climatic Data Center (NCDC). This is followed by an investigation of how increased spatial and temporal resolution in meteorological data affects consequence and risk calculations. Finally, recommendations for modifications to ADROIT are made based on the study findings. It is noted that consequence comparisons for all aspects of this study are predicated on a truncation of the ADROIT event tree (Figure 1) at Question 15, with the assumption that a high-explosive driven dispersal of nuclear material has a probability of 1 and that every assumed accident location is equally probable.

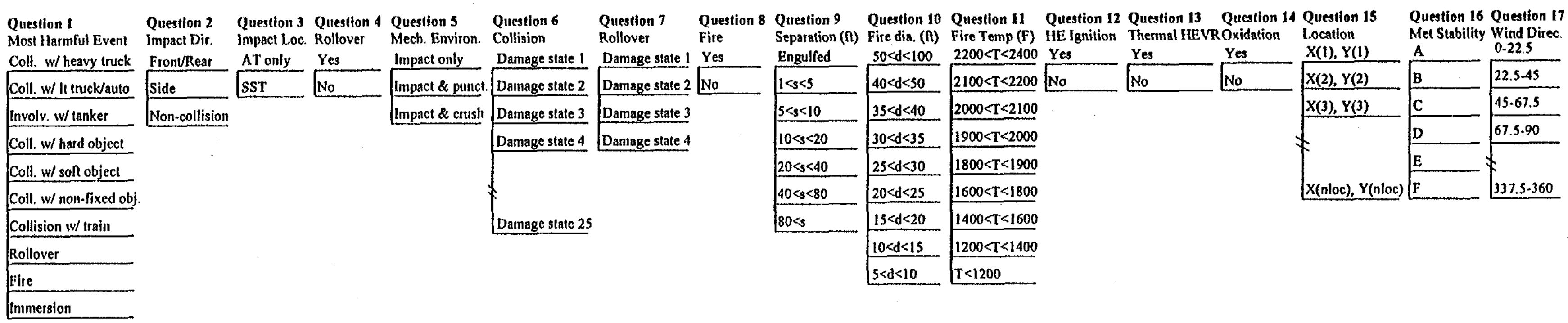

Figure 1. Truck-Accident Dispersal Event Tree from ADROIT [1]

2.0 Alternative Weather Characterization

Meteorological variability in the current version of ADROIT is captured using a Pasquill-Gifford stability-class approach. Each profile is selected to be representative of one of the six Pasquill-Gifford stability-class designations (Table 1). Pasquill-Gifford stability classes are intended to define the near-surface turbulence environment based on limited meteorological measurements and observations. For the purposes of turbulence typing, Pasquill viewed turbulence near the ground as having a mechanical and a thermal component. The mechanical component was conceived as being created by frictional wind shear and the thermal component as arising from vertical heat flux. The relative importance of these two components determines the turbulence type. Table 1 presents the criteria for the six Pasquill-Gifford stability classes, which are based on five classes of surface wind speeds, three classes of daytime insolation, and two classes of nighttime cloudiness [2].

Table 1. Meteorological Conditions Defining Pasquill-Gifford Stability Classes [2]

Pasquill-Gifford Stability Class Designators:

A: *Extremely unstable conditions*	**D:** *Neutral conditions*
B: *Moderately unstable conditions*	**E:** *Slightly stable conditions*
C: *Slightly unstable conditions*	**F:** *Moderately stable conditions*

Surface Wind Speed (m/s)	Daytime Insolation			Nighttime Conditions[†]	
	Strong	Moderate	Slight	Thin Overcast or > 4/8 low cloud	≤3/8 cloudiness
<2	A	A-B	B		
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

[†]The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

Pasquill-Gifford stability-classes are implemented in ADROIT through the definition of six upper-air profiles, each one corresponding to a specific stability class. These upper-air profiles are used as input to the ERAD (Explosive Release Atmospheric Dispersion) dispersion code [3], which in turn provides predictions of dispersal patterns. These dispersion results are manipulated by ADROIT to calculate health and environmental consequences at a given accident location by weighting the consequences obtained for each stability class by the corresponding probability-of-occurrence for that stability class.

The use of the Pasquill-Gifford stability-class approach means that a year's worth of weather data must, in effect, be captured by only six meteorological profiles. Given the known variability in meteorological data, such a simplification may not be appropriate. As an alternative, the stability-class approach in ADROIT can be replaced with a direct use of available NCDC radiosonde data in the dispersion calculations. Radiosonde data of sufficient detail to generate a year's worth of dispersion calculations are available for 88 weather stations across the continental United States (Figure 2) [4]. These data are generally limited to twice-daily measurements, one at 0000 GMT and the other at 1200 GMT. Direct application of NCDC radiosonde data means that the number of ERAD cases increases from 6 to over 700 for a given combination of cargo, meteorological station, and release mechanism.

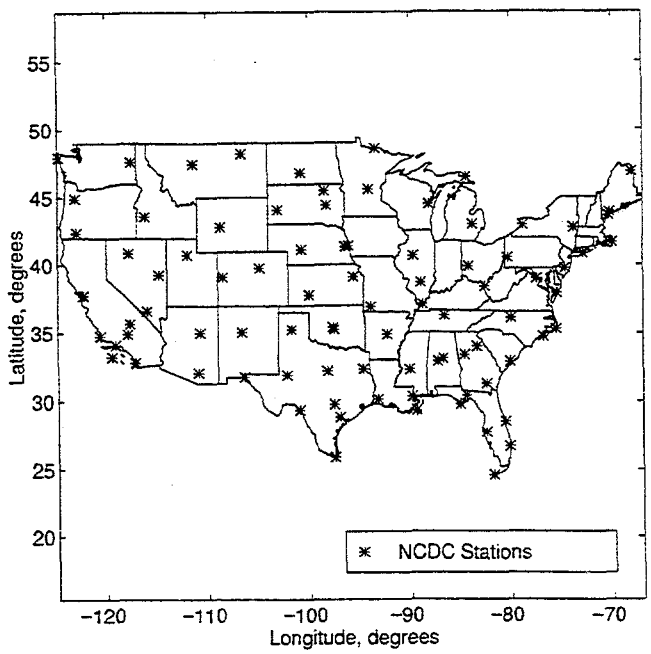

Figure 2. Locations of NCDC Meteorological Stations

2.1 Comparisons of Health Consequences

To assess the stability-class approach to weather representation, detonation-driven dispersal calculations were performed using (1) a Pasquill-Gifford stability-class weather characterization and (2) a direct application of available sounding data for 1989. It is noted that 1989 meteorological data are used to be consistent with the fact that available stability-class probabilities are based on 1989 data [1]. The non-meteorological inputs to ERAD used in this assessment are presented in Appendix A.

In order to quantify the effect that a change in weather characterization has on health consequences, excess latent cancer fatalities were calculated at multiple accident locations along two of the shipping routes defined in Reference [1]—Route 4 and Route 223 (Figures 3 and 4). Twenty accident locations are assumed for Route 4 and 92 accident locations are assumed for Route 223. All accident locations were chosen by ADROIT using the default accident spacing criteria.

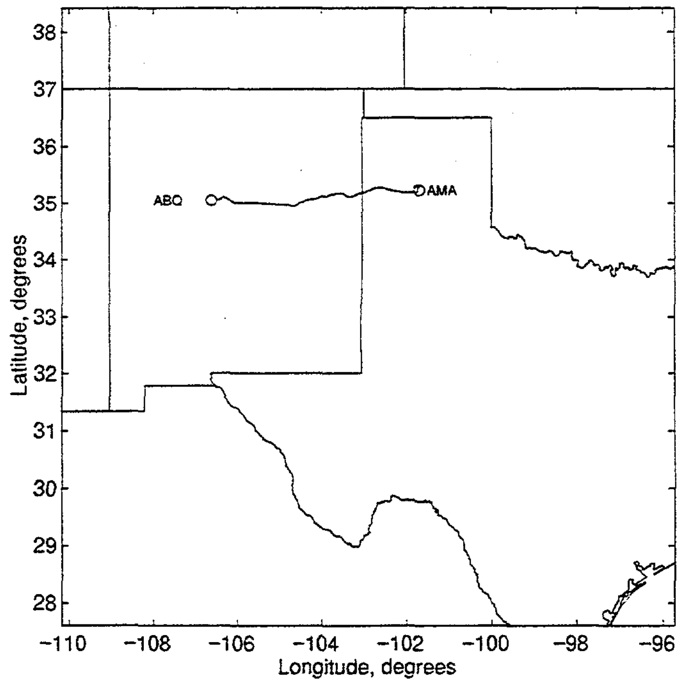

Figure 3. Route 4: Amarillo, TX to Albuquerque, NM

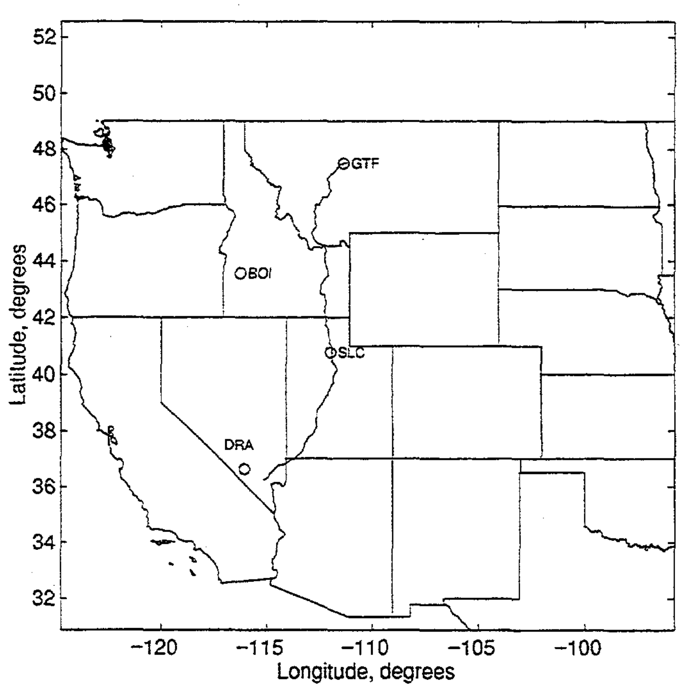

Figure 4. Route 223: Great Falls, MT to Las Vegas, NV

For an individual ERAD run, the calculation of health consequences in ADROIT is performed by overlaying the ERAD dose contours onto Census Bureau population block data [5]. The *at-risk* population is defined as those members of the public subject to a maximum individual risk (given the exposure) of contracting an excess latent cancer, resulting in fatality, greater than some defined risk threshold. Specifically,

$$C_h = S_f K \sum_i E_i N_i \tag{1}$$

where C_h is the health consequence, S_f is the shielding factor, K is the ratio of the *dose health conversion factor for high doses and high dose rates* and the *dose-rate effectiveness factor*, E_i is the calculated dose at a point, and N_i is the population count at the same point. For this study, a risk threshold of 1 in 10,000, a shielding factor of 1, a *dose-health conversion factor for high doses and high dose rates* of 1,000 LCFs per 10^6 person-rem, and a *dose rate effectiveness factor* of 2 are used to define the *at-risk* population. Using these values in Equation 1, the at-risk population is that segment of the populace that resides within the 0.2 rem contour produced by ERAD.

From the individual values for health consequence derived from each ERAD run, distributions of health consequences are constructed for each accident location. For the stability-class approach, a distribution of 96 probability-consequence pairs is assembled. The 96 values for health consequences result from the manner by which ADROIT accounts for changes in wind direction (Question 17 in Figure 1). Specifically, ADROIT applies the ERAD dispersion results for each stability class at 16 different wind directions, each direction randomly chosen from a different 22.5° sector. The probabilities assigned to each of the 96 consequence values are defined as the probability that the given stability class will be observed at the meteorological station assigned to the accident location multiplied by the probability-of-occurrence for the wind direction. Table 2 presents the stability-class probabilities for the six meteorological stations applicable to Routes 4 and 223 [1]. Since all wind directions are assumed equally probable in ADROIT, the second factor in determining the probability of a given health consequence result is simply 1/16.

The generation of health consequence distributions for the approach to meteorological characterization that uses available radiosonde data is accomplished by assuming that each radiosonde profile is equally probable. Thus, the consequence-probability distribution for the NCDC-derived consequences is on the order of 700 points (depending on data availability), with the probability assigned to each point simply being the inverse of the total number of points. Integration of these consequence-probability distributions provides a *mean* value that is the basis of the health consequence comparisons presented in this study.

Table 2. Assumed Stability Class Distributions for 1989 [1]

Station		Stability Class A	B	C	D	E	F
Albuquerque	ABQ	0.04	0.04	0.12	0.50	0.16	0.14
Amarillo	AMA	0.03	0.17	0.00	0.488	0.194	0.118
Boise	BOI	0.02	0.02	0.10	0.50	0.18	0.18
Desert Rock	DRA	0.02	0.02	0.08	0.56	0.12	0.20
Great Falls	GFT	0.02	0.00	0.04	0.70	0.16	0.08
Salt Lake City	SLC	0.02	0.02	0.10	0.56	0.22	0.08

2.1.1 Dose Area

As a preliminary assessment of the differences in health consequences predicted by the two approaches to weather characterization, the areas enclosed by the 0.2 rem dose contour were calculated for the six meteorological stations identified in Table 2. *Dose area* (i.e., the area enclosed by the 0.2 rem contour) provides an indication of the size of the boundary within which health consequences are considered potentially significant. Table 3 presents the integrated *dose areas* for the six meteorological stations for both approaches to weather characterization. A comparison of the mean areas enclosed by the 0.2 rem contour appears to indicate that a change in approach to meteorological characterization could have a significant impact on estimated health consequences. However, because of the nature of population distribution in the United States, the relationship between dose area and health consequence is not linear. Thus, the order-of-magnitude increase in dose area is unlikely to result in an equivalent increase in health consequence. The actual impact of the calculated increase in dose area is discussed in the following sections.

Table 3. Comparison of Mean Areas Enclosed by 0.2 rem Contour for Two Characterizations of 1989 Weather Data

Meteorological Station	Mean Dose Area (km^2) Stability-Class	Mean Dose Area (km^2) Meteorological Data
Albuquerque, NM	271	2940
Amarillo, TX	250	1891
Boise, ID	286	3664
Desert Rock, ID	293	2769
Great Falls, MT	280	1920
Salt Lake City, UT	273	3484

2.1.2 Latent Cancer Fatalities for Route 4

The calculation of health consequences at accident locations along Route 4 requires dispersion predictions for two weather stations, Albuquerque (ABQ) and Amarillo (AMA). Point-by-point comparisons of the integrated values for the LCF-probability curves for Route 4 show that, in general, higher predictions of health consequences result from the use of radiosonde data than from the use of the stability-class approach (Table 4). LCFs for remote, rural accident locations vary by up to two orders-of-magnitude, while health consequences for accident locations closer to population centers vary by up to a factor of 3. Individually, these variations are significant, however, the aggregate health consequence for the route—assuming each accident location is equally probable—varies by less than a factor of two between the two approaches to weather characterization. This overall result is much smaller than what was expected based on the order-of-magnitude increase in dose area shown for both Amarillo and Albuquerque.

The explanation for the reduced impact of dose area on health consequences is straightforward. Population centers in the western United States are highly localized, with population density dropping off rapidly as you proceed away from the major cities. Thus, while the dose area for the more complete characterization of weather increases by an order-of-magnitude over that of the stability-class approach, this increase is not directly reflected in the numbers of people enclosed by the 0.2 rem contour. As an example, Table 5 shows the mean number of people at-risk for each accident location along Route 4 for both approaches. In most cases, the order-of-magnitude increase in dose area does not result in large increases in the at-risk population. The locations that do show equivalent increases are the rural locations where the dose contours generated using the radiosonde data are sufficiently large to extend back to nearby population centers, like Albuquerque or Amarillo. As expected, the overall difference for population-at-risk is only a factor of two.

Table 4. Accident Locations and Mean Health Consequences for Route 4 for Two Characterizations of 1989 Weather Data

Pt	Latitude (°)	Longitude (°)	Station	Health Consequence: Stability Class (LCFs)	Health Consequence: 1989 Met Data (LCFs)
1	35.192	-101.76	AMA	9.54	10.70
2	35.193	-101.80	AMA	18.03	15.20
3	35.191	-101.88	AMA	26.00	19.90
4	35.187	-101.93	AMA	14.38	17.65
5	35.208	-102.16	AMA	0.947	4.86
6	35.269	-102.72	AMA	0.055	2.28
7	35.231	-102.85	AMA	0.040	1.91
8	35.193	-101.75	AMA	6.88	8.93
9	35.221	-101.74	AMA	7.68	8.39
10	35.068	-106.49	ABQ	34.30	47.85
11	35.076	-106.51	ABQ	42.11	66.02
12	35.133	-103.22	ABQ	0.095	2.88
13	35.124	-103.86	ABQ	0.239	2.18
14	35.053	-104.33	ABQ	0.022	1.89
15	35.011	-104.47	ABQ	0.030	1.93
16	34.979	-105.04	ABQ	0.034	2.77
17	34.992	-105.32	ABQ	0.181	3.61
18	35.005	-105.89	ABQ	0.479	6.95
19	35.095	-106.37	ABQ	7.52	22.55
20	35.070	-106.53	ABQ	38.82	64.57
Mean of All Route 4 Accident Locations				10.37	15.63

Table 5. Accident Locations and Mean Population-at-Risk for Route 4 for Two Characterizations of 1989 Weather Data

Pt	Latitude (°)	Longitude (°)	Station	Population at Risk: Stability Class	Population at Risk: 1989 Met Data
1	35.192	-101.76	AMA	14,674	24,290
2	35.193	-101.80	AMA	20,107	29,665
3	35.191	-101.88	AMA	22,330	39,179
4	35.187	-101.93	AMA	17,482	35,189
5	35.208	-102.16	AMA	5,146	17,054
6	35.269	-102.72	AMA	289	10,301
7	35.231	-102.85	AMA	247	8,869
8	35.193	-101.75	AMA	14,638	22,047
9	35.221	-101.74	AMA	16,139	21,629
10	35.068	-106.49	ABQ	46,178	61,634
11	35.076	-106.51	ABQ	47,380	72,802
12	35.133	-103.22	ABQ	506	13,227
13	35.124	-103.86	ABQ	708	10,828
14	35.053	-104.33	ABQ	82	11,023
15	35.011	-104.47	ABQ	149	10,773
16	34.979	-105.04	ABQ	187	15,508
17	34.992	-105.32	ABQ	1,134	17,575
18	35.005	-105.89	ABQ	2,417	25,492
19	35.095	-106.37	ABQ	28,165	52,270
20	35.070	-106.53	ABQ	48,813	70,229
Mean of All Route 4 Accident Locations				14,339	28,462

2.1.3 Latent Cancer Fatalities for Route 223

In order to confirm the findings obtained for Route 4, a second route was selected for examination. Whereas Route 4 is predominantly an east-west route, Route 223 runs primarily north-south from Montana to Nevada (Figure 4). The number of assumed accident locations for Route 223 is 92 and the number of required sources for weather data is four—Great Falls, MT (GTF); Boise, ID (BOI); Salt Lake City, UT (SLC); and Desert Rock, NV (DRA). Again, Route 223 passes through relatively sparsely populated sections of the United States; however, Route 223 does pass through or near a larger number of heavily populated regions than does Route 4. Thus, it is expected that a greater overall difference in health consequences will be seen for Route 223 than the factor of two observed for Route 4.

The health consequence values reported in Table 6 were calculated using the same method applied to Route 4. As with Route 4, the point-by-point results for Route 223 show some significant differences; however, on an overall route basis, the estimated health consequences vary by less than a factor of three. While this is an increase in effect over that obtained for Route 4, it does not begin to approach the order-of-magnitude difference seen in the calculated dose areas (Table 3). Again, this is due to the relatively sparse distribution of population outside of the major cities along Route 223.

Table 6. Accident Locations and Mean Health Consequences for Route 223 for Two Characterizations of 1989 Weather Data

Pt	Latitude (°)	Longitude (°)	Station	Health Consequence (Stability Class) (LCFs)	Health Consequence (1989 Met Data) (LCFs)
1	46.694	-112.01	GTF	2.49	2.60
2	46.659	-112.01	GTF	4.41	4.63
3	46.592	-112.00	GTF	8.91	7.86
4	45.996	-112.47	GTF	5.89	4.34
5	45.991	-112.53	GTF	9.74	12.44
6	45.993	-112.55	GTF	7.61	9.69
7	46.007	-112.61	GTF	2.46	6.05
8	45.972	-112.66	GTF	1.16	3.29
9	45.963	-112.66	GTF	1.30	3.10
10	45.920	-112.67	GTF	0.80	2.42
11	45.857	-112.67	GTF	0.31	1.83
12	45.809	-112.70	GTF	0.15	1.58
13	45.796	-112.71	GTF	0.47	1.50
14	45.739	-112.72	GTF	0.22	1.25
15	45.715	-112.70	GTF	0.17	1.26
16	45.665	-112.68	GTF	0.12	1.29
17	43.222	-112.34	BOI	3.39	12.23
18	43.187	-112.37	BOI	4.69	13.80
19	41.299	-112.03	SLC	9.56	35.69
20	41.260	-112.02	SLC	12.80	41.30
21	41.220	-112.01	SLC	19.43	55.56
22	41.199	-112.00	SLC	23.70	60.91
23	41.137	-112.02	SLC	25.78	58.35
24	41.109	-112.01	SLC	24.29	55.63
25	41.066	-111.97	SLC	24.77	55.92
26	41.021	-111.94	SLC	20.65	56.22
27	40.995	-111.91	SLC	16.16	51.62
28	40.980	-111.90	SLC	15.20	54.45
29	40.948	-111.89	SLC	16.98	65.98
30	40.875	-111.90	SLC	25.29	92.04

Table 6. Accident Locations and Mean Health Consequences for Route 223 for Two Characterizations of 1989 Weather Data (continued)

Pt	Latitude (°)	Longitude (°)	Station	Health Consequence (Stability Class) (LCFs)	Health Consequence (1989 Met Data) (LCFs)
31	40.852	-111.91	SLC	25.31	91.14
32	40.798	-111.92	SLC	32.68	101.04
33	40.753	-111.91	SLC	44.86	102.71
34	40.702	-111.90	SLC	52.87	108.31
35	40.686	-111.90	SLC	55.97	107.88
36	40.649	-111.90	SLC	57.58	102.71
37	40.575	-111.90	SLC	43.27	96.35
38	40.529	-111.89	SLC	28.87	89.15
39	40.485	-111.90	SLC	17.55	78.01
40	40.409	-111.86	SLC	13.73	49.01
41	40.398	-111.84	SLC	16.52	45.61
42	40.306	-111.72	SLC	25.98	39.50
43	40.248	-111.69	SLC	30.52	50.08
44	40.235	-111.68	SLC	28.15	51.04
45	40.179	-111.65	SLC	12.08	32.65
46	40.031	-111.76	SLC	7.16	32.51
47	37.688	-113.08	SLC	5.50	11.87
48	37.656	-113.08	SLC	4.34	14.72
49	37.085	-113.58	SLC	10.17	18.55
50	37.040	-113.60	SLC	4.54	16.32
51	47.441	-111.48	GTF	1.45	2.86
52	47.119	-111.93	GTF	0.083	1.12
53	46.751	-112.01	GTF	1.56	1.65
54	46.320	-112.07	GTF	0.47	1.84
55	46.271	-112.10	GTF	0.41	2.13
56	45.454	-112.71	GTF	0.071	0.97
57	45.255	-112.65	GTF	1.28	1.70
58	44.944	-112.84	GTF	0.044	0.75
59	44.702	-112.68	GTF	0.027	0.82
60	44.336	-112.17	BOI	0.043	2.49
61	44.163	-112.24	BOI	0.31	3.09
62	43.896	-112.21	BOI	0.46	3.51
63	43.632	-112.08	BOI	1.99	8.69
64	42.802	-112.32	BOI	1.82	5.42
65	42.799	-112.26	BOI	1.26	4.56
66	42.328	-112.22	BOI	0.15	2.94
67	42.027	-112.21	BOI	0.35	3.72
68	41.730	-112.20	SLC	2.14	10.97
69	40.346	-111.76	SLC	14.18	27.61
70	39.982	-111.77	SLC	4.84	30.86

Table 6. Accident Locations and Mean Health Consequences for Route 223 for Two Characterizations of 1989 Weather Data (concluded)

Pt	Latitude (°)	Longitude (°)	Station	Health Consequence (Stability Class) (LCFs)	Health Consequence (1989 Met Data) (LCFs)
71	39.676	-111.85	SLC	0.80	21.01
72	39.216	-112.16	SLC	0.15	12.63
73	39.190	-112.19	SLC	0.13	13.03
74	38.667	-112.59	SLC	0.050	6.38
75	38.322	-112.65	SLC	0.30	6.87
76	37.980	-112.74	SLC	0.12	6.41
77	37.884	-112.80	SLC	0.51	6.83
78	37.624	-113.13	SLC	1.01	8.46
79	37.129	-113.52	SLC	5.82	12.46
80	36.753	-114.31	DRA	0.17	7.73
81	36.511	-114.70	DRA	1.76	13.10
82	36.295	-114.99	DRA	10.85	27.59
83	47.494	-111.23	GTF	13.55	11.95
84	47.494	-111.29	GTF	16.62	16.77
85	47.494	-111.31	GTF	15.54	14.56
86	47.469	-111.36	GTF	5.30	6.10
87	43.504	-112.05	BOI	13.02	21.29
88	42.946	-112.44	BOI	5.36	13.26
89	42.902	-112.44	BOI	12.89	21.51
90	42.855	-112.42	BOI	9.21	11.33
91	42.833	-112.41	BOI	6.45	11.05
92	36.241	-115.07	DRA	34.85	56.65
Mean of All Route 223 Accident Locations				10.80	26.72

2.2 Comparison of Environmental Consequences

For environmental consequences, the ERAD deposition contours are used directly by ADROIT to define *contaminated area*. For this study, the 0.2 $\mu Ci/m^2$ deposition contour is used as the defining boundary for contaminated area. While it is expected that the actual screening criteria would be developed on a case-by-case basis, 0.2 $\mu Ci/m^2$ is a common default value used in assessing environmental consequences [6].

Contaminated area distributions for the two approaches to meteorological characterization were calculated for each station identified in Table 2. These values are what would be applied to any accident location assigned to the corresponding meteorological station. Table 7 shows that the use of the radiosonde data produces mean estimates of environmental consequences (i.e., contaminated area) between 2.3 and 3.5 times greater than those predicted using the stability-class approach. These differences are significant, particularly when viewed in terms of added clean-up costs. Depending on land usage, every 100 km^2 in contaminated area translates to anywhere from 7 to 40 billion dollars in environmental remediation costs [6].

Table 7. Comparison of Mean Areas Enclosed by 0.2 $\mu Ci/m^2$ Deposition Contour for Two Characterizations of 1989 Weather Data

Meteorological Station	Mean Deposition Area (km^2)	
	Stability-Class	Meteorological Data
Albuquerque, NM	119	379
Amarillo, TX	112	389
Boise, ID	121	385
Desert Rock, NV	123	367
Great Falls, MT	115	268
Salt Lake City, UT	119	389

2.3 Comparisons of Risk

The health and environmental consequence comparisons presented in Sections 2.1 and 2.2 indicate that the simplifications inherent in the stability-class approach to weather characterization can result in a significant underestimation of health and environmental consequences at individual accident locations. A comparison of consequences alone, however, is not sufficient to make recommendations regarding modifications to ADROIT. It is the overall *risk* predicted for a route that is of primary concern. As a means of simplifying the comparison of risk values, only the probability factors that have a dependency upon route are used. As stated in Section 1.0, this means that Questions 1 through 14 in Figure 1 are simplified with the assumption that a detonation-driven release of nuclear material has a probability of 1 (other release mechanisms have an assigned probability of 0). The remaining factor, which represents the weighting factor for this comparison of risk, is the probability of an initiating event occurring in a given *operating environment.*

Operating environment refers to the categorization of a given accident location with respect to road type and population density. Road types are classified as either *limited access* or *other.* Limited access roads have a lower accident rate because lane separation reduces the number of head-on crashes, grade separation at roadway crossings reduces the number of side-on collisions, lack of railroad crossings at the same grade eliminates collisions with trains, and better design (longer sight distances, larger radii on curves, etc.) provides a more forgiving environment for driver error. Conversely *other* roadways have higher accident rates because they lack many of the features of the limited access roadway [7]. Population density is classified as either *rural* or *urban.* Urban operating environments are defined by the Federal Highway Administration as population areas[1] with 5,000 or more inhabitants.

Currently ADROIT considers four operating environments: *Limited/Urban, Limited/Rural, Other/Urban,* and *Other/Rural.* For each operating environment, per-trip initiating event probabilities are calculated as follows:

[1] A *population area* is defined differently for each state. An *area* is roughly equivalent to a *place* as defined in the census data. A *place* is an incorporated place or census designated place which is loosely equivalent to a town or city [7].

$P_{\text{initiaing event}}$ = *(Tow-away accident rate per mile)•(Fraction of Tow-aways with Severities Comparable to Fatals)•(Influence Factor)• (Mileage in Operating Environment)* (2)

Table 8 presents the values used by ADROIT for the first three factors on the right-hand side of Equation 2. Combining these values with the operating environment mileages for Route 4 and Route 223 results in the initiating event probabilities presented in Table 9.

For this comparison, the distributed nature of the health consequences for each operating environment is simplified by assuming that the integrated value of the combined probability-consequence curves for each operating environment adequately reflects the overall consequence for that environment. Multiplying these *mean* health consequences by the appropriate probability for an initiating event calculated from Equation 2 (Table 9) yields the risk numbers reported in Table 10. (Appendix B documents the operating environment assigned to each accident location in Routes 4 and 223.)

Table 8. ADROIT Parameters for Calculating Initiating Event Probabilities

Operating Environment	Mean Tow-away Accident Rate per mile	Mean Fraction of Tow-aways with Severities Comparable to Fatals	Influence Factor
Limited/Urban	6.6×10^{-8}	0.16	0.93
Limited/Rural	6.6×10^{-8}	0.16	0.63
Other/Urban	6.6×10^{-8}	0.16	3.91
Other/Rural	6.6×10^{-8}	0.16	3.83

Table 9. Operating Environment Mileages and Probabilities of Initiating Events for Routes 4 and 223

Operating Environment	Mileage		Probability (trip^{-1})	
	Route 4	Route223	Route 4	Route 223
Limited/Urban	16.54	149.0	1.62×10^{-7}	1.46×10^{-6}
Limited/Rural	265.2	805.5	1.76×10^{-6}	5.36×10^{-6}
Other/Urban	5.28	28.54	2.18×10^{-7}	1.18×10^{-6}
Other/Rural	9.23	0	3.73×10^{-7}	0

Table 10. Mean Health Risk by Operating Environment for the Two Approaches to Weather Characterization

Operating Environment	Route 4 Risk (LCF/trip)		Route 223 Risk (LCF/trip)	
	Stability Class	Met Data	Stability Class	Met Data
Limited/Urban	3.90×10^{-6}	4.80×10^{-6}	2.36×10^{-5}	5.89×10^{-5}
Limited/Rural	1.54×10^{-6}	8.61×10^{-6}	9.15×10^{-6}	4.36×10^{-5}
Other/Urban	4.98×10^{-6}	8.01×10^{-6}	1.57×10^{-5}	2.17×10^{-5}
Other/Rural	1.67×10^{-6}	3.13×10^{-6}	0	0
Total Health Risk	1.21×10^{-5}	2.45×10^{-5}	4.85×10^{-5}	1.24×10^{-4}

A comparison of the operating-environment risk values in Table 10 shows that an increase of 1.2 to 5.6 can be attributed to a change in the approach to weather characterization. Further examination of the health consequences associated with each operating environment shows that this range could be much larger. For example, with the exclusion of accident location 19 from Route 4, the Limited/Rural health risk calculated using radiosonde data would be 23 times greater than that calculated using the stability-class approach. Similarly, if accident locations 69, 79, and 82 are excluded from Route 223, the factor of 5 difference in health risk for the Limited/Rural operating environment increases to an order-of-magnitude. This is not unexpected for rural accident locations, given the scarcity of population directly adjacent to the accident locations and the more limited extent of the stability-class dose contours. In fact, depending on the number of rural accident locations selected for a route, it is conceivable that the risk for the Limited/Rural operating environment calculated using the two weather characterizations could vary by up to two orders-of-magnitude. This points to a sensitivity of the ADROIT calculations to consequence predictions for the Limited/Rural operating environment.

2.4 Summary of Alternative Weather Characterization Comparisons

Comparisons of mean health and environmental consequences were performed at 112 accident locations along two routes for two characterizations of a year's worth of weather data—(1) the Pasquill-Gifford stability-class approach and (2) a direct use of radiosonde data. In all of the cases examined, the radiosonde approach predicts between 2.3 and 3.5 times greater environmental consequences. For health consequences, the radiosonde approach predicts between 0.74 and 128 times the values produced by the stability-class approach. Given that the radiosonde approach is a more detailed representation of weather, it is concluded that the stability-class approach is underpredicting heath and environmental consequences at the majority of the accident locations examined. Furthermore, it was found that the underprediction of health consequences translates into health risks that are approximately one-half of the values predicted using the radiosonde approach. These results indicate that the stability-class approach used in ADROIT should be replaced with a more detailed characterization of a year's worth of weather.

3.0 Required Resolution in Meteorological Data

Although the recommendation from Section 2 is to modify ADROIT's approach to meteorological characterization to one that is more detailed, several questions regarding what constitutes an *appropriate level of detail* must be examined. Two obvious concerns regarding the appropriate level of detail relate to the issues of temporal and spatial resolution. Since the NCDC data examined in the previous sections are limited in both temporal and spatial resolution, the overall issue boils down to whether the recommendation to modify ADROIT's meteorological characterization should shift its focus from applying NCDC data to applying generated data obtained from a mesoscale meteorological model (e.g., MM4 [8]). Generated data from a model like MM4 provides greater resolution; however, the simplifications inherent in any model-generated data make this approach less appealing than using the radiosonde data in ADROIT. For the investigation of temporal and spatial resolution presented in the following sections, Route 4 is chosen as the basis for comparison. Furthermore, it is assumed that the MM4 upper-air profiles are equivalent in the accuracy of their meteorological representation to the radiosonde data recorded by NCDC. (Note that the MM4 simulations use NCDC data to initialize the model).

Figure 5 highlights the six MM4 grid points that were chosen to represent Route 4, along with the meteorological stations that have been historically assigned to Route 4 (i.e., Albuquerque, NM and Amarillo, TX). Table 11 lists the latitude and longitude of both the meteorological stations and the MM4 grid-points shown in Figure 5, along with the Route 4 accident locations assigned to each point.

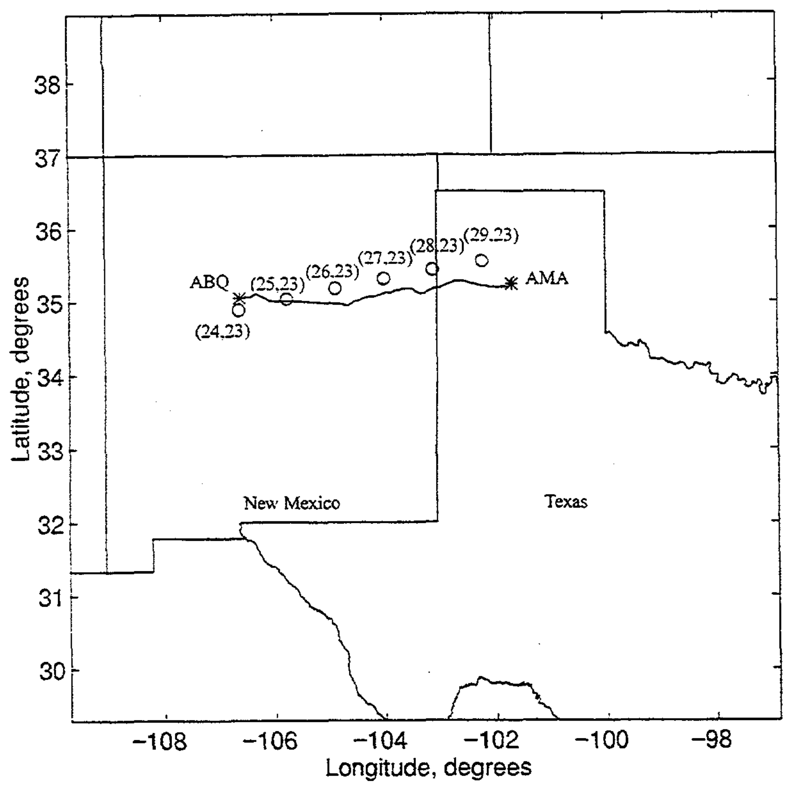

Figure 5. Route 4 with Meteorological Stations and MM4 Grid Points

Table 11. Locations of Meteorological Stations and MM4 Grid Points Assigned to Route 4

Station or MM4 (i, j) Point	Latitude (°)	Longitude (°)	Assigned Accident Locations
Albuquerque, NM (ABQ)	35.05	-106.62	10 through 20
Amarillo, TX (AMA)	35.23	-101.70	1 through 9
(24, 23)	34.89	-106.64	10, 11, 19, 20
(25, 23)	35.04	-105.77	17, 18
(26, 23)	35.18	-104.89	15, 16
(27, 23)	35.31	-104.00	13, 14
(28, 23)	35.43	-103.12	6, 7, 12
(29, 23)	35.55	-102.23	1, 2, 3, 4, 5, 8, 9

3.1 Temporal Resolution

Since ADROIT assumes that an accident can occur at any time, the limitation of the NCDC data to two soundings a day (usually 0000 GMT and 1200 GMT) is a concern. In effect, the limited temporal resolution of the NCDC data means that the health and environmental consequences calculated using the 0000 GMT and 1200 GMT meteorology must be close approximations of those calculated using data for all 24 hours. Otherwise, meteorological data sources that provide additional temporal resolution must be incorporated into ADROIT. In order to assess the *equivalence* of a 2-hour characterization of weather to a 24-hour characterization, surrogate meteorological data must be used. Specifically, generated data from the mesoscale model MM4 for the 1990 calendar year are used [8]. This focus on MM4 eliminates issues related to spatial resolution and provides a consistent basis for comparison. The results obtained from the MM4 data are extrapolated—based on the assumption that the NCDC and MM4 data are of equivalent quality—to determine whether the NCDC data provides sufficient temporal resolution with respect to the generation of representative consequence and risk values in ADROIT.

3.1.1 Health Consequences

Annual distributions of health consequence for the 20 accident locations along Route 4 were calculated using meteorological input from MM4 grid points (24,23) through (29,23), inclusive. Appendix C contains the mean values derived from the probability-consequence distributions assembled for each hour. As the initial basis for addressing the issue of temporal resolution, two annual health consequence distributions were created for each accident location—the first constructed by combining the 0000 GMT and 1200 GMT results and the other constructed by combining the results for all 24 hours. Table 12 shows that the 5th percentile, 95th percentile, median, and mean values for all 20 accident locations are very consistent between the two combinations of hourly meteorological data. It is noted, however, that the mean value from the 0000/1200 GMT combination of results is up to 30% lower than the corresponding 24-hour value. This is due to the fact that peaks in health consequences generally occur between 1600 and 1800 GMT. While the magnitude of the differences in mean values is not seen as significant, it is one *penalty* that must be acknowledged when using 0000/1200 GMT data to represent 24-hour behavior.

Despite the differences in mean health consequences between the two combinations of hourly data, Table 12 demonstrates that the overall correspondence between the 2-hour and 24-hour distributions of LCFs is quite close. As a graphical example of this correspondence, the two distributions for accident location 1 are presented in Figure 6. It is noted that the x-axis for Figure 6 is based on the 0000/1200 GMT range of health consequences. Thus, some of the extreme health consequence values (>95th percentile) for the 24-hour distribution are not shown. (Comparison plots of distributed health consequences for all of the accident locations can be found in Appendix D.) The results in Table 12 and Appendix D indicate that a combination of dispersion results for 0000/1200 GMT are representative and can be used in place of 24-hour data without introducing significant error.

As a final confirmation of this proposed equivalence between the 2-hour and 24-hour combinations of meteorology, the population distribution associated with Route 4 is removed from consideration, and two population-independent features of the dispersion results are examined from a temporal resolution standpoint. Specifically, *dose area* and *effective wind direction*, are compared.

Table 12. 5th Percentile, 95th Percentile, Median, and Mean Values for Health Consequence Distributions

Accident Location	5th Percentile		95th Percentile		Median		Mean	
	All Hours	0000/1200 GMT	All Hours	0000/1200 GMT	All Hours	0000/1200 GMT	All Hours	0000/1200 GMT
1	0.64	0.64	61.86	60.40	3.58	3.85	14.61	13.57
2	6.07	5.63	66.11	62.94	14.45	14.66	22.99	21.41
3	10.75	12.42	68.02	65.72	32.44	31.50	35.95	34.19
4	1.57	1.59	86.21	79.50	29.46	28.40	32.95	30.29
5	0.04	0.04	47.40	43.30	2.32	2.34	8.69	8.05
6	0.009	0.008	30.89	25.47	2.10	1.96	6.63	5.91
7	0.006	0.006	30.34	27.54	2.02	1.77	6.41	5.89
8	0.25	0.26	56.55	55.77	2.33	2.29	12.22	11.26
9	0.36	0.36	56.91	53.84	2.23	2.18	11.14	10.62
10	1.92	1.90	121.60	101.16	10.64	9.69	28.32	23.32
11	3.44	3.07	135.64	110.31	27.78	25.89	44.66	37.47
12	0.02	0.01	24.19	24.00	1.93	1.75	5.59	5.62
13	0.005	0.006	18.74	15.87	1.41	1.33	4.37	3.67
14	0.005	0.006	14.70	12.56	0.60	0.47	3.24	3.17
15	0.006	0.004	16.89	12.53	0.68	0.36	3.74	2.94
16	0.001	0.001	15.61	10.35	0.43	0.22	3.56	2.48
17	0.007	0.006	12.50	10.12	0.23	0.09	3.10	2.30
18	0.004	0.003	16.65	14.27	0.50	0.35	4.90	3.93
19	0.94	0.89	89.40	65.79	4.11	3.46	16.91	13.68
20	2.96	3.00	134.72	112.72	30.37	27.83	47.26	38.80

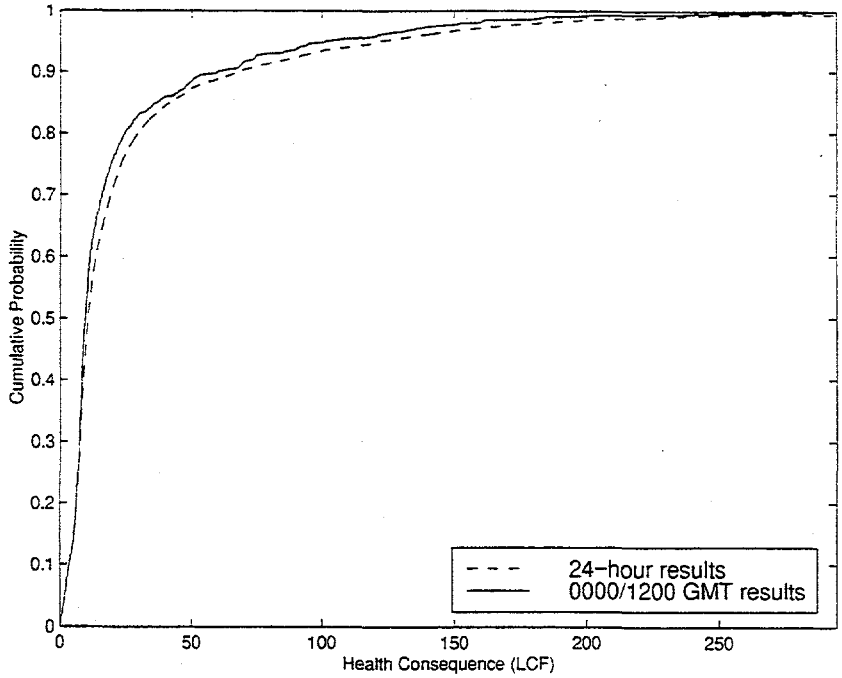

Figure 6. Route 4 Health Consequence Distribution for Accident Location 1

Dose area—introduced in Section 2.1.1—defines the potential area within which the populace is considered *at-risk*. *Wind direction* is determined by the ERAD dispersion model, and is reported as the along-wind rotation angle for the computational grid. It is the combination of the dose area and the effective wind direction that determines the affected region for a given dispersal calculation, which when combined with population distribution yields health consequences. Thus, if the dose area and wind direction results also correspond between the 0000/1200 GMT and 24-hour combinations of MM4 results, the conclusion obtained above regarding the acceptability of the 0000/1200 GMT resolution can be generalized to dismiss the issue of temporal resolution, regardless of the surrounding population distribution (i.e., independent of accident location).

3.1.2 Comparison of 0000/1200 GMT to 24-hour Wind Direction Distributions

The distribution of along-wind rotation angles reported by ERAD were broken down for each MM4 grid point along Route 4 into 45° bins for each hour. Because each meteorological profile is considered equally probable, the percentage of cases falling within each bin represents a weighting factor that can influence the calculation of health consequences. For each of the six MM4 grid points, Tables 13 and 14 present the percentage of ERAD cases falling within the 8 sectors for the 24-hour and the 0000/1200 GMT combinations, respectively. A comparison of Tables 13 and 14 shows that the average difference between the 0000/1200 GMT results and the 24-hour results is only about 1%, with all of the 0000/1200 GMT bins falling within 3.6% of their 24-hour counterparts. This close correspondence indicates that the use of meteorological data from 0000 and 1200 GMT will not introduce any significant error into the calculation of health consequences due to an inaccurate representation of preferred wind directions.

Table 13. Distribution of Rotation Angles for the Combination of all 24-hours

Sector	Percentage of Cases					
	(24, 23)	(25, 23)	(26, 23)	(27, 23)	(28, 23)	(29, 23)
0°≤ θ <45°	24.3	25.9	26.3	25.8	22.5	17.8
45°≤ θ <90°	13.8	14.0	18.2	23.5	28.3	32.0
90°≤ θ <135°	6.1	8.2	9.3	9.0	9.3	11.4
135°≤ θ <180°	10.5	9.0	6.7	5.5	5.4	5.8
-135°> θ ≥-180°	3.6	3.8	5.8	6.9	8.4	8.8
-90°> θ ≥-135°	3.5	3.0	3.7	6.0	9.1	10.0
-45°> θ ≥-90°	15.1	10.8	6.7	5.6	5.8	6.6
0°> θ ≥-45°	23.1	25.3	23.2	17.7	11.2	7.7

Table 14. Distribution of Rotation Angles for the Combined 0000 GMT and 1200 GMT Cases

Sector	Percentage of Cases					
	(24, 23)	(25, 23)	(26, 23)	(27, 23)	(28, 23)	(29, 23)
0°≤ θ <45°	23.7	23.8	22.7	24.5	22.4	19.1
45°≤ θ <90°	15.5	16.3	20.8	23.1	27.4	30.1
90°≤ θ <135°	7.0	9.9	11.0	10.4	11.3	12.4
135°≤ θ <180°	9.3	8.9	7.2	6.5	5.4	5.2
-135°> θ ≥-180°	4.9	3.3	4.6	6.0	7.8	9.3
-90°> θ ≥-135°	3.9	3.3	3.3	5.2	8.5	8.8
-45°> θ ≥-90°	14.2	10.6	8.2	6.3	6.5	7.0
0°> θ ≥-45°	21.6	23.8	22.1	18.0	10.6	8.2

3.1.3 Comparison of 0000/1200 GMT to 24-hour Dose Area Distributions

As with the comparison of wind direction distributions, a comparison of annual mean dose areas does not show a significant difference between the 24-hour and the 0000/1200 GMT combinations of meteorological data (Table 15). The values for overall mean dose area presented in Table 15 are encouraging. However, it is the interrelationship among dose area, wind direction, and population distribution that ultimately determines health consequences. To make the argument that the 0000/1200 GMT dispersion results are representative of the combined 24-hour results, independent of population distribution (i.e., accident location), the *combination* of wind direction and dose area must be similar. Thus, the dose areas predicted for each ERAD calculation were combined based on the 45° sector defined by their associated wind direction, and the results averaged. Tables 16 and 17 show the mean dose area by sector for the 24-hour and the 0000/1200 GMT combinations of results, respectively. The overall range of differences between the values in Table 15 and Table 16 is -38.3% to +21.0% (Table 18). Because of the previously discussed nonlinear relationship between dose area and health consequence, this range is not considered critical, particularly in light of the fact that the average difference, from an absolute value standpoint, is only 12.1%.

The overall dose area results and the dose area results divided by sector are sufficiently similar to confirm that the use of meteorological data from 0000/1200 GMT will yield health consequences that are representative of those that would be predicted from a combination of results for all 24 hours.

Table 15. Overall Comparison of Mean Dose Area

MM4 Grid Point	24-Hour Mean Dose Area (km^2)	0000/1200 GMT Mean Dose Area (km^2)	Percent Difference
(24, 23)	2799	2378	-15.1
(25, 23)	3048	2516	-17.5
(26, 23)	3644	3106	-14.7
(27, 23)	3357	3210	-4.4
(28, 23)	3915	3681	-6.0
(29, 23)	2760	2797	+1.4

Table 16. Mean Dose Area by Sector for the Combination of all 24-hours

Sector	Mean Dose Area (km^2)					
	(24, 23)	(25, 23)	(26, 23)	(27, 23)	(28, 23)	(29, 23)
$0° \leq \theta < 45°$	2325	2780	3928	3426	4090	2827
$45° \leq \theta < 90°$	2239	2121	3403	3338	3948	2437
$90° \leq \theta < 135°$	1716	2257	3273	3380	3991	3026
$135° \leq \theta < 180°$	2265	2521	2895	3208	3770	3281
$-135° > \theta \geq -180°$	3052	3478	3238	2915	3707	2988
$-90° > \theta \geq -135°$	4017	4003	3995	3136	3210	2477
$-45° > \theta \geq -90°$	3846	4228	4133	3693	3511	2819
$0° > \theta \geq -45°$	3254	3602	3777	3458	4421	3216

Table 17. Mean Dose Area by Sector for the Combined 0000 GMT and 1200 GMT Cases

Sector	Mean Dose Area (km^2)					
	(24, 23)	(25, 23)	(26, 23)	(27, 23)	(28, 23)	(29, 23)
$0° \leq \theta < 45°$	2322	2621	3481	3457	3623	2661
$45° \leq \theta < 90°$	1836	1638	2934	3319	4037	2948
$90° \leq \theta < 135°$	1272	1392	2758	2960	3942	2852
$135° \leq \theta < 180°$	1810	1593	2362	2803	3339	3284
$-135° > \theta \geq -180°$	2634	3277	2938	2559	3675	2525
$-90° > \theta \geq -135°$	3849	3885	3435	2554	2735	2257
$-45° > \theta \geq -90°$	3433	3835	3646	3309	3042	2492
$0° > \theta \geq -45°$	2411	2939	3085	3399	3937	3319

Table 18. Percent Difference in Mean Dose Area by Sector

Sector	Percent Difference					
	(24, 23)	(25, 23)	(26, 23)	(27, 23)	(28, 23)	(29, 23)
$0° \le \theta < 45°$	-0.1	-5.8	-11.4	+0.9	-11.4	-5.9
$45° \le \theta < 90°$	-18.0	-22.8	-13.8	-0.6	+2.3	+21.0
$90° \le \theta < 135°$	-25.9	-38.3	-15.7	-12.4	-1.2	-5.8
$135° \le \theta < 180°$	-20.1	-37.0	-18.4	-12.6	-11.4	+1.1
$-135° > \theta \ge -180°$	-13.7	-5.7	-9.3	-12.2	-0.9	-15.5
$-90° > \theta \ge -135°$	-4.2	-3.0	-14.0	-18.5	-14.8	-8.9
$-45° > \theta \ge -90°$	-10.7	-9.3	-11.8	-10.4	-13.3	-11.6
$0° > \theta \ge -45°$	-25.9	-18.4	-18.3	-1.7	-11.0	+3.2

3.1.4 Environmental Consequences

As a final step in the examination of temporal resolution, the environmental consequences for the 0000/1200 GMT and 24-hour combinations of dispersion results are compared in Table 19. As with the case of health consequences, the environmental consequences for the two combinations of hourly data compare favorably. Therefore, restricting the meteorological data to that from 0000 GMT and 1200 GMT should not introduce any significant bias to the calculation of environmental consequences by ADROIT. Thus, the temporal resolution reflected in the NCDC data appears sufficient.

Table 19. Mean Environmental Consequences MM4 Meteorological Data From 0000 and 1200 GMT as well as for All Hours

MM4 Grid Point	Contaminated Area: 0000 and 1200 GMT (km^2)	Contaminated Area: All Hours (km^2)
(24,23)	389	400
(25,23)	381	397
(26,23)	401	409
(27,23)	412	408
(28,23)	417	413
(29,23)	403	397

3.2 Spatial Resolution

As shown in Figure 2, the stations for which sufficient data are available to produce a year's worth of dispersion calculations are generally separated by significant distances. Thus, when calculating consequences at an accident location, it is not uncommon to have to use dispersion results generated using data from a meteorological station 100 or even 200 miles away. The applicability of a meteorological station's data to an accident location several hundred miles away is an obvious concern. As with the case of temporal resolution, no site-specific data are available at sufficient resolution to make meaningful comparisons that will address the issue of spatial resolution.

For the investigation of temporal resolution, attention was focused on a comparison of results obtained strictly for the MM4 surrogate data. This focus on the MM4 data was necessary since no NCDC data source could provide sufficient temporal resolution to make meaningful comparisons. Consequently, implicit in the evaluation of temporal resolution is an assumption that—had temporal effects proven significant—the proposed use of NCDC data would be supplanted by a recommendation to use MM4 simulations of upper-air conditions.

Having discarded temporal resolution as an issue in the previous section, the remaining concern of *spatial resolution* becomes a comparison of results obtained using NCDC data from a limited number of widely spaced stations versus using results obtained using MM4 data, spaced at approximately 80 km between grid points. Recalling the underlying assumption that the MM4 upper-air profiles are equivalent in the accuracy of their meteorological representation to the radiosonde data recorded by NCDC, the *baseline* consequences for this study are assumed to be those produced using meteorological data at the greatest spatial resolution. Thus, consequence predictions derived from MM4 data for the six grid points shown in Figure 5 are used as the basis for comparison in this section. Furthermore, to be consistent with the available NCDC radiosonde data and to restrict our focus to spatial resolution, only MM4 data for 0000 GMT and 1200 GMT are used in the ERAD calculations presented in this section. It is noted that since the MM4 meteorological data are for 1990, the ERAD calculations for the Albuquerque and Amarillo stations presented in Section 2 were re-run using radiosonde data from 1990.

Table 20 shows that the point-by-point differences in mean health consequences between the MM4 and the radiosonde results are minor. The MM4 data tends to produce slightly higher rural health consequences and slightly lower urban health consequences than does the radiosonde data. Overall, however, the estimate of health consequences for the route only varies by 6 percent. Similarly, the mean environmental consequences calculated for the two meteorological stations are within 15% of those calculated for the six MM4 grid points (Table 21). These results indicate that the spatial resolution provided by the NCDC data is sufficient.

3.3 Combined Effect of Spatial and Temporal Resolution

While the effects of increased spatial and temporal resolution appear to be non-issues individually, their combined effect must still be examined. For environmental consequences, a comparison of the last column in Table 19 with the environmental consequences calculated for Albuquerque and Amarillo (Table 21) shows that the combined effect of increased spatial and temporal resolution on environmental consequences is less than 15 %. For health consequences, the last column in Table 20 is compared with the second-to-last column in Table 12. At individual accident locations, mean health consequences estimated using the radiosonde data vary by up to 63% from those calculated using the MM4 data for all hours. On an overall route basis, however, the difference in mean health consequences is less than 7 percent. While this overall result appears to confirm that the combination of spatial and temporal effects is not an issue with respect to ADROIT's calculation of health consequences, the variations at individual accident locations warrants a discussion of health risk prior to making any final recommendations.

Table 20. Mean Health Consequences for Route 4 Using MM4 and Radiosonde for the Hours 0000 GMT and 1200 GMT

Pt	Latitude (°)	Longitude (°)	Met Station	Closest MM4 Grid Point (i, j)	Health Consequence for MM4 Data (LCFs)	Health Consequence for Radiosonde Data (LCFs)
1	35.192	-101.76	AMA	(29, 23)	13.57	9.52
2	35.193	-101.80	AMA	(29, 23)	21.41	19.52
3	35.191	-101.88	AMA	(29, 23)	34.19	32.71
4	35.187	-101.93	AMA	(29, 23)	30.29	27.83
5	35.208	-102.16	AMA	(29, 23)	8.05	4.52
6	35.269	-102.72	AMA	(28, 23)	5.91	2.82
7	35.231	-102.85	AMA	(28, 23)	5.89	2.99
8	35.193	-101.75	AMA	(29, 23)	11.26	7.12
9	35.221	-101.74	AMA	(29, 23)	10.62	6.40
10	35.068	-106.49	ABQ	(24, 23)	23.32	38.51
11	35.076	-106.51	ABQ	(24, 23)	37.47	54.34
12	35.133	-103.22	ABQ	(28, 23)	5.62	2.05
13	35.124	-103.86	ABQ	(27, 23)	3.67	2.24
14	35.053	-104.33	ABQ	(27, 23)	3.17	1.60
15	35.011	-104.47	ABQ	(26, 23)	2.94	1.38
16	34.979	-105.04	ABQ	(26, 23)	2.48	2.29
17	34.992	-105.32	ABQ	(25, 23)	2.30	2.92
18	35.005	-105.89	ABQ	(25, 23)	3.93	5.86
19	35.095	-106.37	ABQ	(24, 23)	13.68	18.47
20	35.070	-106.53	ABQ	(24, 23)	38.80	52.77
Mean for All Route 4 Accident Locations					13.92	14.81

Table 21. Mean Environmental Consequences for MM4 Points and Meteorological Stations Assigned to Route 4 for the hours 0000 and 1200 GMT

MM4 Point or Met Station	Contaminated Area (km^2)
(24,23)	389
(25,23)	381
(26,23)	401
(27,23)	412
(28,23)	417
(29,23)	403
Amarillo, TX	389
Albuquerque, NM	355

Applying the approach presented in Section 2.3 yields the estimates of health risk shown in Table 22. The overall health risk obtained using the twice-daily meteorological data from two stations is only 18% lower than that obtained using 24-hour per day data from six MM4 locations. This difference is not considered significant enough to warrant a modification to the overall recommendation from Section 2. In other words, the limited spatial and temporal resolution of the NCDC data do not appear to affect ADROIT's calculation of risk to an extent that would require the use of more detailed upper-air data obtained from a mesoscale model.

Table 22. Mean Health Risk by Operating Environment

Operating Environment	Radiosonde Data (LCF/trip)	MM4 Data: All Hours (LCF/trip)
Limited/Urban	4.93×10^{-6}	4.85×10^{-6}
Limited/Rural	7.54×10^{-6}	1.07×10^{-5}
Other/Urban	6.45×10^{-6}	6.37×10^{-6}
Other/Rural	1.05×10^{-6}	2.47×10^{-6}
Total Health Risk	2.00×10^{-5}	2.44×10^{-5}

4.0 Recommended Changes to ADROIT

The overall conclusion from the above investigations of meteorological characterization, temporal resolution, and spatial resolution is that the stability-class approach currently used in ADROIT should be replaced with an approach that makes direct use of NCDC radiosonde data. Use of all of the sounding data, however, increases the number of up-front dispersion calculations, as well as the sizes of the arrays needed in the ADROIT calculations. As a point of reference, it is estimated that approximately 10 hours of run time (on a Sun Ultra-2 with a 300 MHz processor) is required for a single combination of cargo, meteorological station, and release mechanism (i.e., detonation or fire-driven). This run time reflects the time required for the completion of all calculations needed to ensure that the dose and deposition contours of interest are closed. The resulting 700^+ ERAD output files require from 50 Mb to 200 Mb of storage (depending on grid resolution). Given the number of cargoes and routes typically investigated for a study like Reference [1], these run times and storage requirements are prohibitive. It would be preferable therefore if a sampling of the meteorological sounding data could be used to generate a representative set of dispersion contours that could then be used as the input to ADROIT's health and environmental consequence calculations.

4.1 Sampling of Meteorological Data

Mean health consequences at individual accident locations were calculated from distributions assembled by using between 20 and 400 randomly selected ERAD dispersion results (as generated in Section 2). One thousand different sets of 20 to 400 random points were selected for each accident location along Route 4 and Route 223. The 1,000 iterations of random sampling were performed to establish an expected range of mean health consequences for each sample set size.

In order to identify an acceptable sample size for estimating health consequences at a single accident location, the results from the 20 accident locations along Route 4 were combined. First, for each sample size, the 1,000 mean health consequence values calculated at each accident location were normalized with respect to their corresponding baseline value (i.e., the appropriate mean health consequence value from the last column of Table 4). The resulting normalized distributions of mean health consequences for each accident location were then combined and sorted to provide the cumulative probability curves shown in Figure 7[2]. This method for combining the Route 4 results allows the number of randomly selected radiosonde profiles needed to adequately represent the annual mean health consequences at an unknown accident location to be estimated without presupposing any additional information about that location (e.g., whether an accident location is in an urban or rural setting). Table 23 presents the 5th and 95th percentile values for each normalized curve in Figure 7, along with the associated medians.

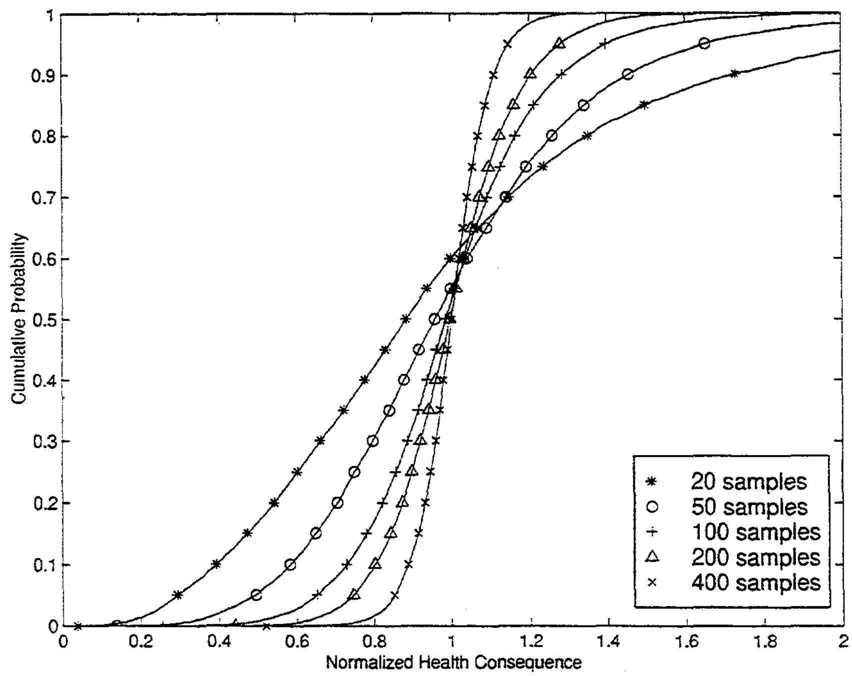

Figure 7. Cumulative Probability Curves for Health Consequences at 20 Accident Locations Along Route 4

Table 23. Median, 5th, and 95th Percentile for Combined Route 4 Accident Locations

Sample Size	5th Percentile	95th Percentile	Median
20	0.29	2.14	0.88
50	0.49	1.65	0.96
100	0.65	1.40	0.99
200	0.75	1.28	1.0
400	0.85	1.15	1.0

[2] Note that the symbols in Figures 7 through 10 are intended to help visually differentiate the curves. The symbols do not represent all of the data used to generate the curves.

To be considered acceptable, the median for a given sample size must be approximately 1. This indicates that the overall distribution of mean health consequences obtained from the 20,000 distributions generated using a given sample set size is centered about the appropriate baseline values from Table 4. As a further screening criterion, it is assumed that the 5th and 95th percentile values must show that the distribution of mean values is likely to be within 30% of the corresponding baseline value.

From Figure 7 and Table 23, it appears that ERAD dispersion results generated for 200 randomly selected radiosonde profiles should be adequate to estimate the mean health consequences for any single accident location. For Route 4, use of this sampling frequency should result in a mean health consequence estimate for a given location that is within 25 to 28% of the corresponding baseline value presented in Table 4.

In order to confirm that a sample set of 200 points is acceptable for single-point estimates (i.e., one accident location) of mean health consequence, the radiosonde profiles for the four meteorological stations assigned to Route 223 were sampled and the corresponding ERAD results used to calculate health consequences for each accident location. As with Route 4, the mean health consequences for the 1,000 distributions generated for each combination of accident location and sample size were normalized and combined into a single cumulative probability curve (Figure 8). Each curve presented in Figure 8 is therefore composed of 92,000 normalized values of mean health consequence. Table 24 presents the 5th and 95th percentile values for these combined results, along with the associated medians. As is the

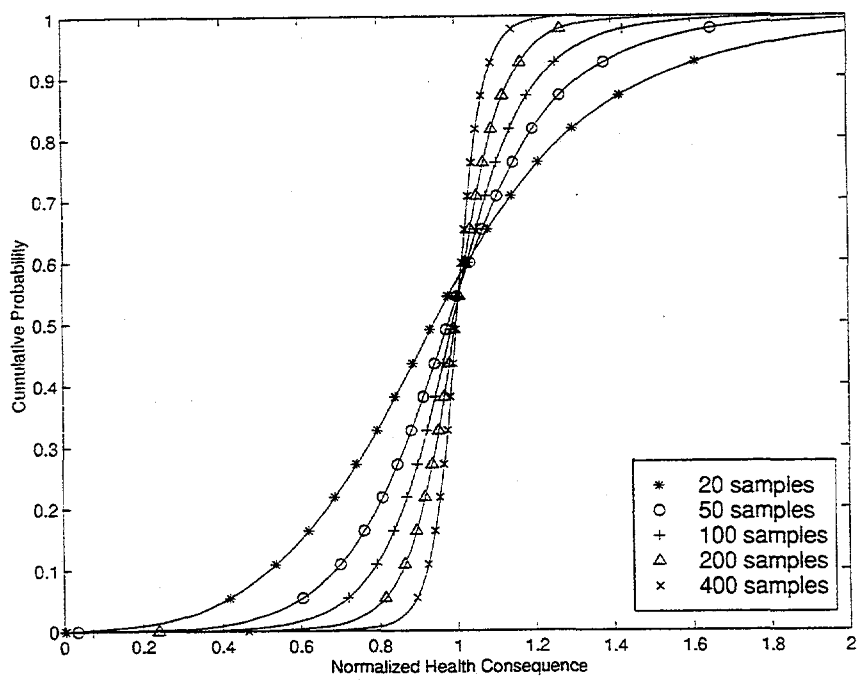

Figure 8. Cumulative Probability Curves for Health Consequences at 92 Accident Locations Along Route 223

Table 24. Median, 5th, and 95th Percentile for Combined Route 223 Accident Locations

Sample Size	5th Percentile	95th Percentile	Median
20	0.40	1.77	0.94
50	0.59	1.47	0.98
100	0.71	1.31	0.99
200	0.81	1.20	1.0
400	0.89	1.11	1.0

case for Route 4, the results for Route 223 support a sample set size of 200 radiosonde profiles. It is noted that the 200-point sample set shows a tighter correspondence to baseline values for Route 223 than it does for Route 4 (±20% for Route 223 as compared to ±28% for Route 4). This is likely due to the increase in the number of accident locations from 20 for Route 4 to 92 for Route 223.

While 200 samples represents a substantial reduction in the required number of dispersion calculations (down from approximately 700), it is only recommended for estimates of health consequences at a *single* accident location. In ADROIT, health consequences are aggregated by operating environments, weighted by probabilities, and finally combined into an overall health risk for the route. Because of this process, it may be possible to recommend a smaller sample set for calculations that are not focused on estimating consequences for a single point, but are instead intended to provide estimates of health-risk for an entire route.

In order to assess sample sizes from a risk perspective, Questions 1 through 14 in Figure 1 are again simplified with the assumption that a detonation-driven release of nuclear material has a probability of 1 (other release mechanisms are assigned a probability of 0). Thus, only the probabilities-of-occurrence for each operating environment (Table 9) are used to weight the health consequences. Mean health consequences for the 1,000 iterations of each sample set size were aggregated by operating environment. These operating-environment health consequences were then multiplied by the appropriate probability-of-occurrence from Table 9, and the resulting products summed to give an overall mean health risk for the route. Figure 9 shows the cumulative-probability curves for Route 4's mean health risk, normalized to the risk value presented in the last row of Table 10. Table 25 presents the 5th and 95th percentile values for each normalized curve in Figure 9, along with the associated medians. Based on Figure 9 and Table 25, it appears that health risks for the route can be predicted to within ±10% of the Table 10 baseline value for a sample size of 100 radiosonde profiles. Table 26 and Figure 10 confirm the choice of a sample size of 100 by showing a ±4% correspondence to Route 223 baseline health risk.

As additional confirmation of the sample sizes examined above, environmental consequences were estimated for 1,000 different sets of 20 to 400 radiosonde profiles. For the six meteorological stations listed in Table 2, contaminated area can be estimated to within ±3% of baseline values for a sample size of 100 and to within ±2% for a sample size of 200.

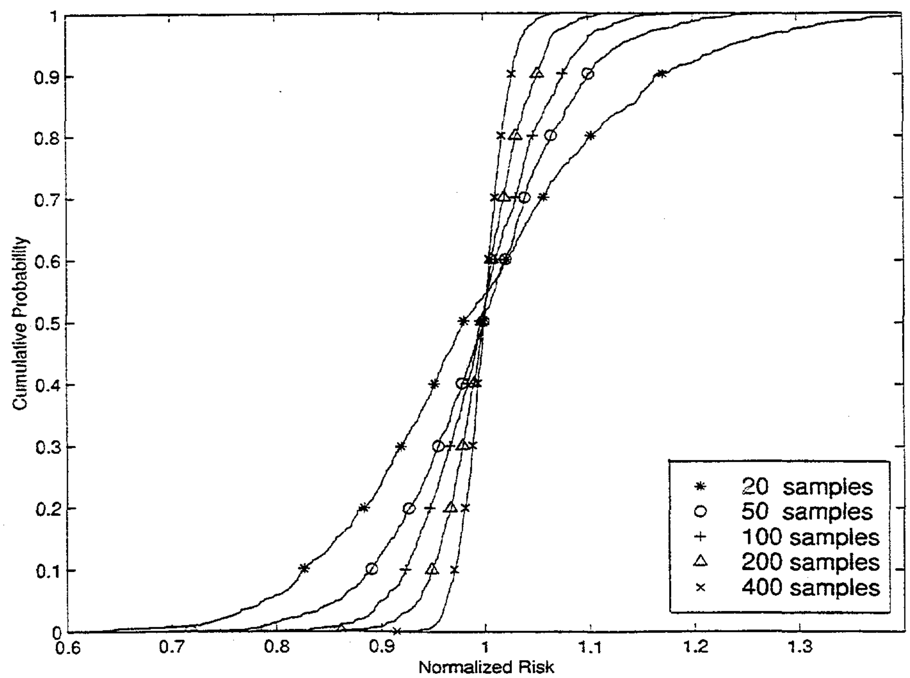

Figure 9. Cumulative Probability Curves for Route 4 Health Risk

Table 25. Median, 5th, and 95th Percentile for Route 4 Health Risk

Sample Size	5th Percentile	95th Percentile	Median
20	0.79	1.24	0.98
50	0.86	1.13	0.99
100	0.90	1.10	1.0
200	0.93	1.06	1.0
400	0.96	1.03	1.0

Table 26. Median, 5th, and 95th Percentile for Route 223 Health Risk

Sample Size	5th Percentile	95th Percentile	Median
20	0.91	1.10	0.99
50	0.95	1.06	1.0
100	0.96	1.04	1.0
200	0.97	1.03	1.0
400	0.99	1.02	1.0

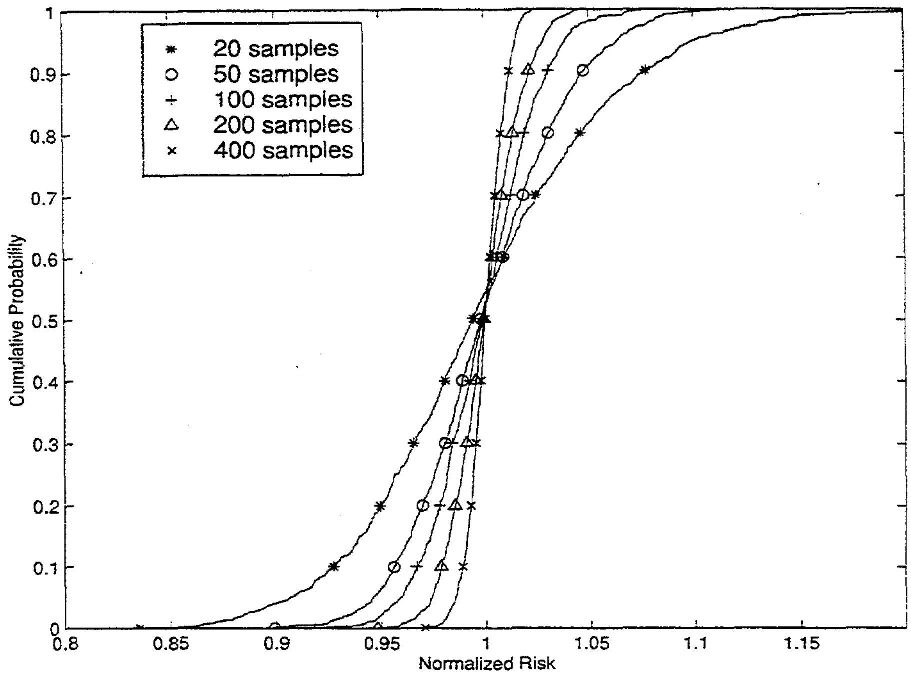

Figure 10. Cumulative Probability Curves for Route 223 Health Risk

The arguments for the selection of an acceptable sample size presented above are based on mean values of health consequence, environmental consequence, and health risk. While these mean values are considered representative, ADROIT does not rely solely upon mean consequence values in its calculation of risk. The actual *distribution* of consequences is key to the ADROIT methodology. Figure 11 is an example of how Route 4 health risk distributions generated from 10 different sets of 100 randomly selected radiosonde profiles compare to the baseline distribution generated from all of the radiosonde profiles for Amarillo and Albuquerque. These 10 examples are typical of the distributions generated for the 1,000 sampling iterations discussed above. In general, the sampled distributions compare well with the baseline distribution, showing slightly higher health risk at the lower cumulative probabilities and slightly lower health risk at the higher cumulative probabilities. These trends are as expected given that any sampling scheme is unlikely to adequately capture the extreme values of the distribution being sampled. Figure 11 is viewed as additional verification that the stability-class approach to weather characterization currently used in ADROIT can be replaced with an approach that uses sampled NCDC meteorological data to generate representative dispersion contours.

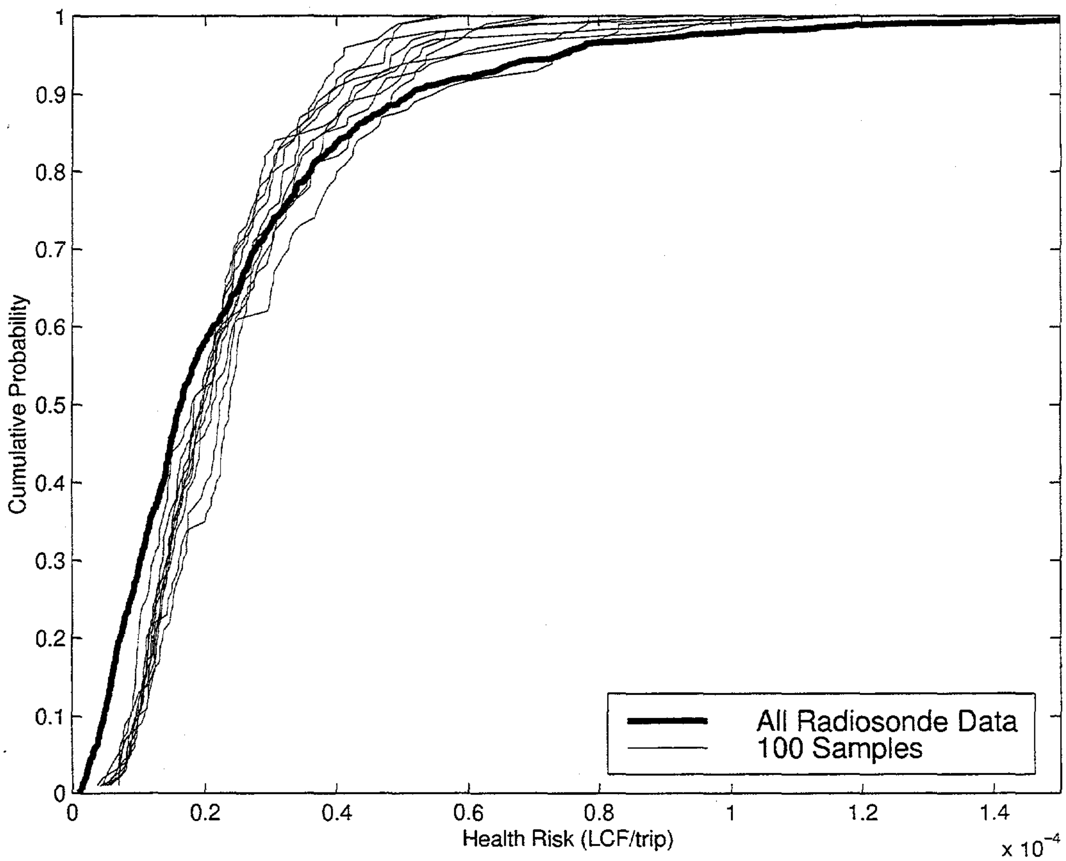

Figure 11. Example of Health Risk Distributions for Route 4

5.0 Summary

The stability-class approach to meteorological characterization used by ADROIT in previous analyses (e.g., [1]) has been compared to an alternative approach that directly uses NCDC radiosonde data in the underlying dispersion calculations. The comparison shows that, under certain circumstances, ADROIT's use of the stability-class approach could yield significant underestimates of health and environmental consequences (up to an order-of-magnitude). Such underestimates could adversely affect bottom-line risk values, biasing the results in a non-conservative direction. Based on these findings, the recommendation is made to replace the stability-class approach with a more detailed method of meteorological characterization. Evaluations of the affect of temporal and spatial resolution in meteorological data on consequence and risk predictions indicate that the NCDC database contains sufficient spatial and temporal detail for ADROIT applications.

Recognizing computer run-time and storage limitations, the use of all available NCDC radiosonde data in risk assessment calculations is not seen as a feasible option. However, it was found that for a single accident location, 200 randomly selected radiosonde profiles from the assigned meteorological station produces mean health consequences within 28% and mean environmental consequences within 3% of baseline values. By grouping the accident locations by operating environment, it was determined that the number of samples can be reduced to 100 and overall mean health risk values estimated to within 10% of the baseline values obtained using all of the radiosonde profiles (approximately 700 for a given meteorological station). One hundred samples produce environmental risks that are within 2% of baseline values. For calculations focused on estimating risk at multiple accident locations along a route, it is therefore recommended that the stability-class approach to meteorological characterization currently used in ADROIT be replaced with an approach that uses a sampled set of 100 radiosonde profiles from each weather station as input to the ERAD dispersion calculations required for a given cargo and route.

6.0 References

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Appendix A: Non Meteorological Input Used in ERAD

Input Description	Value
Roughness Length	0.01 m
Release Mechanism	Detonation
Mass of Explosives	107 kg
Heat of Detonation	4.81×10^6 J/kg
Height of Detonation	0 m AGL
Particle Distribution: *Lognormal*	minimum diameter = 0.1 μm maximum diameter = 200 μm median diameter = 42.7 μm geometric standard deviation = 5.0 μm
Mass Aerosolized	10.7 kg
Specific Activity	0.095 Ci/g
Inhalation Dose Coefficient	2.4×10^8 rem/Ci
Breathing Rate	4.7×10^{-4} m^3/s
Deposition Velocity	0.001 m/s
Maximum Aerodynamic Diameter Contributing to Dose	10 μm
Dosage Threshold	0.001 μg-s/m^3
Deposition Threshold	0.001 μg/m^2
Number of Monte Carlo Particles	2500
Random Number Seed	968071168

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Appendix B: Operating Environments for Accident Locations Along Route 4 and Route 223

Table B-1. Operating Environments for Accident Locations Along Route 4

Point Number	Latitude (°)	Longitude (°)	Station	Operating Environment
1	35.192	-101.76	AMA	Limited/Urban
2	35.193	-101.80	AMA	Limited/Urban
3	35.191	-101.88	AMA	Limited/Urban
4	35.187	-101.93	AMA	Limited/Urban
5	35.208	-102.16	AMA	Limited/Rural
6	35.269	-102.72	AMA	Limited/Rural
7	35.231	-102.85	AMA	Limited/Rural
8	35.193	-101.75	AMA	Other/Rural
9	35.221	-101.74	AMA	Other/Urban
10	35.068	-106.49	ABQ	Limited/Urban
11	35.076	-106.51	ABQ	Limited/Urban
12	35.133	-103.22	ABQ	Limited/Rural
13	35.124	-103.86	ABQ	Limited/Rural
14	35.053	-104.33	ABQ	Limited/Rural
15	35.011	-104.47	ABQ	Limited/Rural
16	34.979	-105.04	ABQ	Limited/Rural
17	34.992	-105.32	ABQ	Limited/Rural
18	35.005	-105.89	ABQ	Limited/Rural
19	35.095	-106.37	ABQ	Limited/Rural
20	35.070	-106.53	ABQ	Other/Urban

Table B-2. Operating Environments for Accident Locations Along Route 223

Point	Latitude (°)	Longitude (°)	Station	Operating Environment
1	46.694	-112.01	GTF	Limited/Urban
2	46.659	-112.01	GTF	Limited/Urban
3	46.592	-112.00	GTF	Limited/Urban
4	45.996	-112.47	GTF	Limited/Urban
5	45.991	-112.53	GTF	Limited/Urban
6	45.993	-112.55	GTF	Limited/Urban
7	46.007	-112.61	GTF	Limited/Urban
8	45.972	-112.66	GTF	Limited/Urban
9	45.963	-112.66	GTF	Limited/Urban
10	45.920	-112.67	GTF	Limited/Urban
11	45.857	-112.67	GTF	Limited/Urban
12	45.809	-112.70	GTF	Limited/Urban
13	45.796	-112.71	GTF	Limited/Urban
14	45.739	-112.72	GTF	Limited/Urban
15	45.715	-112.70	GTF	Limited/Urban
16	45.665	-112.68	GTF	Limited/Urban
17	43.222	-112.34	BOI	Limited/Urban
18	43.187	-112.37	BOI	Limited/Urban
19	41.299	-112.03	SLC	Limited/Urban
20	41.260	-112.02	SLC	Limited/Urban
21	41.220	-112.01	SLC	Limited/Urban
22	41.199	-112.00	SLC	Limited/Urban
23	41.137	-112.02	SLC	Limited/Urban
24	41.109	-112.01	SLC	Limited/Urban
25	41.066	-111.97	SLC	Limited/Urban
26	41.021	-111.94	SLC	Limited/Urban
27	40.995	-111.91	SLC	Limited/Urban
28	40.980	-111.90	SLC	Limited/Urban
29	40.948	-111.89	SLC	Limited/Urban
30	40.875	-111.90	SLC	Limited/Urban
31	40.852	-111.91	SLC	Limited/Urban
32	40.798	-111.92	SLC	Limited/Urban
33	40.753	-111.91	SLC	Limited/Urban
34	40.702	-111.90	SLC	Limited/Urban
35	40.686	-111.90	SLC	Limited/Urban
36	40.649	-111.90	SLC	Limited/Urban
37	40.575	-111.90	SLC	Limited/Urban
38	40.529	-111.89	SLC	Limited/Urban
39	40.485	-111.90	SLC	Limited/Urban
40	40.409	-111.86	SLC	Limited/Urban
41	40.398	-111.84	SLC	Limited/Urban
42	40.306	-111.72	SLC	Limited/Urban
43	40.248	-111.69	SLC	Limited/Urban
44	40.235	-111.68	SLC	Limited/Urban
45	40.179	-111.65	SLC	Limited/Urban
46	40.031	-111.76	SLC	Limited/Urban

Table B-2. Operating Environments for Accident Locations Along Route 223 (concluded)

Point	Latitude (°)	Longitude (°)	Station	Operating Environment
47	37.688	-113.08	SLC	Limited/Urban
48	37.656	-113.08	SLC	Limited/Urban
49	37.085	-113.58	SLC	Limited/Urban
50	37.040	-113.60	SLC	Limited/Urban
51	47.441	-111.48	GTF	Limited/Rural
52	47.119	-111.93	GTF	Limited/Rural
53	46.751	-112.01	GTF	Limited/Rural
54	46.320	-112.07	GTF	Limited/Rural
55	46.271	-112.10	GTF	Limited/Rural
56	45.454	-112.71	GTF	Limited/Rural
57	45.255	-112.65	GTF	Limited/Rural
58	44.944	-112.84	GTF	Limited/Rural
59	44.702	-112.68	GTF	Limited/Rural
60	44.336	-112.17	BOI	Limited/Rural
61	44.163	-112.24	BOI	Limited/Rural
62	43.896	-112.21	BOI	Limited/Rural
63	43.632	-112.08	BOI	Limited/Rural
64	42.802	-112.32	BOI	Limited/Rural
65	42.799	-112.26	BOI	Limited/Rural
66	42.328	-112.22	BOI	Limited/Rural
67	42.027	-112.21	BOI	Limited/Rural
68	41.730	-112.20	SLC	Limited/Rural
69	40.346	-111.76	SLC	Limited/Rural
70	39.982	-111.77	SLC	Limited/Rural
71	39.676	-111.85	SLC	Limited/Rural
72	39.216	-112.16	SLC	Limited/Rural
73	39.190	-112.19	SLC	Limited/Rural
74	38.667	-112.59	SLC	Limited/Rural
75	38.322	-112.65	SLC	Limited/Rural
76	37.980	-112.74	SLC	Limited/Rural
77	37.884	-112.80	SLC	Limited/Rural
78	37.624	-113.13	SLC	Limited/Rural
79	37.129	-113.52	SLC	Limited/Rural
80	36.753	-114.31	DRA	Limited/Rural
81	36.511	-114.70	DRA	Limited/Rural
82	36.295	-114.99	DRA	Limited/Rural
83	47.494	-111.23	GTF	Other/Urban
84	47.494	-111.29	GTF	Other/Urban
85	47.494	-111.31	GTF	Other/Urban
86	47.469	-111.36	GTF	Other/Urban
87	43.504	-112.05	BOI	Other/Urban
88	42.946	-112.44	BOI	Other/Urban
89	42.902	-112.44	BOI	Other/Urban
90	42.855	-112.42	BOI	Other/Urban
91	42.833	-112.41	BOI	Other/Urban
92	36.241	-115.07	DRA	Other/Urban

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Appendix C: Hourly Mean Health Consequences, Environmental Consequences , and Dose Areas Calculated Using MM4 Meteorological Input for Route 4

Table C-1. Mean Hourly Health Consequences for Route 4

Hour (GMT)	Accident Location									
	1	2	3	4	5	6	7	8	9	10
0000	17.39	24.17	35.11	24.38	6.28	5.84	6.34	14.77	14.52	17.78
0100	17.17	23.75	35.01	25.94	7.49	6.66	7.31	14.94	14.37	19.09
0200	18.39	24.51	33.71	24.04	6.81	6.69	7.24	16.12	16.37	20.78
0300	17.93	24.30	33.38	24.68	7.46	5.71	5.99	15.69	16.18	19.72
0400	16.62	23.22	33.18	25.68	8.58	6.84	6.47	14.71	14.09	21.35
0500	15.18	22.72	35.45	29.87	9.70	7.06	7.00	13.64	12.20	22.23
0600	14.97	22.85	35.56	31.68	9.04	6.62	6.89	13.02	12.61	24.15
0700	12.66	21.25	34.91	32.50	9.02	6.34	6.41	10.62	10.61	26.18
0800	11.68	20.02	34.11	34.30	9.45	6.58	5.93	9.77	9.19	27.41
0900	11.64	19.61	34.87	35.70	10.37	6.79	6.56	9.87	8.59	27.27
1000	10.87	18.96	32.95	33.79	9.53	6.45	5.65	8.90	7.63	29.47
1100	9.78	18.12	32.45	35.43	9.92	6.76	5.52	7.87	6.62	29.87
1200	9.74	18.65	33.27	36.19	9.81	5.97	5.44	7.74	6.72	28.86
1300	9.57	18.85	33.38	36.79	9.46	6.50	5.43	7.53	6.14	29.19
1400	9.55	18.62	32.70	36.63	11.25	7.16	6.12	7.55	6.42	32.26
1500	11.44	21.11	36.11	41.09	14.01	7.49	6.82	9.21	8.42	55.48
1600	17.33	28.14	43.34	44.64	13.26	7.17	7.19	14.25	12.19	49.47
1700	17.97	26.74	40.19	41.76	10.64	8.52	8.47	15.35	11.97	48.13
1800	17.35	26.98	40.20	38.24	8.45	7.93	8.18	14.45	11.93	43.04
1900	16.90	27.76	43.27	39.69	8.18	8.26	8.44	13.46	11.29	27.96
2000	16.34	26.45	40.24	33.81	6.28	6.06	5.69	12.83	11.61	22.64
2100	17.07	26.10	37.98	30.09	4.83	5.17	4.78	13.78	12.08	20.26
2200	15.99	24.07	35.78	28.11	4.23	4.59	4.64	13.22	11.86	18.98
2300	17.06	24.86	35.68	25.70	4.55	5.92	5.34	14.10	13.65	18.08
Average	14.61	22.99	35.95	32.95	8.69	6.63	6.41	12.22	11.14	28.32

Table C-1. Mean Hourly Health Consequences for Route 4 (concluded)

Hour (GMT)	Accident Location									
	11	12	13	14	15	16	17	18	19	20
0000	34.62	5.89	3.54	3.02	2.55	2.37	0.67	1.20	8.54	33.92
0100	36.22	5.37	4.57	3.49	3.19	3.32	1.39	1.77	10.25	36.46
0200	38.32	5.59	3.90	3.27	3.93	3.68	1.63	2.78	11.26	38.99
0300	35.13	5.81	4.67	4.05	3.78	3.13	2.62	3.35	11.34	36.22
0400	35.62	6.00	4.99	3.59	4.51	4.07	2.36	3.57	13.05	36.33
0500	35.85	5.62	5.24	4.02	4.40	3.90	3.17	5.10	17.17	37.01
0600	38.31	6.26	4.72	3.43	4.57	4.26	3.12	5.40	18.95	39.63
0700	39.50	5.45	4.22	2.93	3.81	4.06	3.59	5.24	20.81	40.87
0800	40.78	5.65	4.61	3.22	3.65	3.13	4.34	6.23	22.00	42.77
0900	41.38	4.85	5.20	2.91	3.31	3.46	4.20	5.13	21.49	43.64
1000	42.34	6.15	4.41	2.98	3.66	3.25	2.83	4.64	22.15	45.52
1100	41.11	5.71	4.06	2.58	3.45	3.43	3.91	7.45	22.86	44.24
1200	40.33	5.34	3.79	3.32	3.32	2.59	3.94	6.65	18.81	43.68
1300	41.01	4.66	3.80	2.80	3.69	2.44	4.50	7.58	18.64	44.59
1400	44.21	5.24	3.86	3.22	3.74	3.33	4.75	8.36	19.20	48.70
1500	70.41	5.28	5.13	3.13	4.83	4.29	5.96	8.76	32.36	77.43
1600	70.51	5.37	5.69	4.40	4.96	6.05	5.75	10.09	27.10	77.81
1700	74.89	6.63	6.19	4.38	5.36	6.69	5.29	9.27	22.09	80.90
1800	67.02	7.13	5.44	4.03	5.08	5.40	3.61	5.09	21.49	70.30
1900	50.25	5.55	3.78	3.19	4.05	3.91	1.84	2.88	12.93	53.59
2000	42.39	4.63	3.17	2.90	3.85	3.45	1.45	2.17	9.71	44.96
2100	38.40	4.85	3.34	2.41	2.05	1.95	1.53	1.92	8.42	40.55
2200	37.00	5.86	3.33	2.51	2.15	1.62	0.77	1.65	8.25	38.79
2300	36.19	5.35	3.15	2.07	1.87	1.68	1.13	1.40	6.88	37.38
Average	44.66	5.59	4.37	3.24	3.74	3.56	3.10	4.90	16.91	47.26

Table C-2. Mean Hourly Environmental Consequences for Route 4

Hour (GMT)	Contaminated Area MM4 point (24,23) (km^2)	Contaminated Area MM4 point (25,23) (km^2)	Contaminated Area MM4 point (26,23) (km^2)	Contaminated Area MM4 point (27,23) (km^2)	Contaminated Area MM4 point (28,23) (km^2)	Contaminated Area MM4 point (29,23) (km^2)
0000	377.9	365.6	399.0	418.6	429.8	419.5
0100	392.7	388.4	418.2	425.4	429.8	418.1
0200	406.3	405.0	424.0	423.1	420.5	414.5
0300	410.1	409.7	420.9	419.4	414.7	406.9
0400	416.7	405.1	418.9	413.4	409.8	406.1
0500	417.0	408.3	414.3	411.9	410.5	403.8
0600	411.3	401.4	411.6	409.1	410.9	396.9
0700	408.9	401.8	408.0	407.0	409.7	395.0
0800	406.0	402.2	404.9	407.6	409.8	393.1
0900	403.0	398.0	405.2	405.9	409.1	391.8
1000	405.0	395.6	405.2	403.1	409.2	387.1
1100	405.0	395.9	407.2	402.6	407.4	385.5
1200	399.2	396.8	403.3	404.8	403.9	386.8
1300	394.3	394.8	402.2	403.1	406.3	382.3
1400	397.5	393.4	403.9	397.3	402.9	379.5
1500	404.6	405.1	410.7	403.5	409.5	389.4
1600	414.6	418.9	424.3	412.6	419.4	398.6
1700	415.9	417.5	431.8	419.5	423.7	402.3
1800	414.1	415.7	422.8	413.6	425.9	399.8
1900	396.6	407.1	414.8	408.2	420.3	396.1
2000	389.3	391.2	405.8	396.7	410.5	391.1
2100	377.9	380.4	387.4	389.8	410.0	384.1
2200	372.2	372.7	380.6	388.0	403.1	394.1
2300	372.4	367.7	384.9	397.7	415.1	405.0
Average	400.4	397.4	408.7	407.6	413.4	397.0

Table C-3. Mean Hourly Dose Areas for Route 4

Hour (GMT)	Dose Area (24,23) (km^2)	Dose Area (25,23) (km^2)	Dose Area (26,23) (km^2)	Dose Area (27,23) (km^2)	Dose Area (28,23) (km^2)	Dose Area (29,23) (km^2)
0000	1404.1	1403.0	2463.7	3204.2	3923.6	3043.5
0100	1900.2	1903.4	3315.4	3690.5	4244.9	3425.1
0200	2236.1	2284.7	3616.1	3752.1	4308.8	3442.9
0300	2629.7	2626.1	3789.6	3729.4	4109.8	3320.3
0400	2814.9	2969.4	3852.5	3703.8	4066.5	3312.9
0500	2969.4	3219.6	3968.8	3750.9	4107.1	3287.9
0600	2918.7	3341.9	3951.4	3629.1	4132.8	3087.4
0700	3086.4	3424.2	3980.7	3563.4	4119.5	3081.2
0800	3009.1	3545.4	3954.3	3586.6	4145.1	3085.3
0900	2943.1	3393.6	3858.6	3572.6	4061.4	2965.8
1000	3135.4	3405.5	3841.3	3361.6	3898.7	2728.7
1100	3253.3	3562.3	3862.9	3346.3	3735.1	2511.1
1200	3351.4	3628.8	3749.0	3216.2	3438.3	2551.1
1300	3453.6	3687.6	3931.2	3319.1	3544.1	2400.5
1400	3775.1	3951.0	4242.4	3445.0	3785.4	2417.7
1500	4397.4	4500.4	4636.8	3760.9	4186.2	2681.1
1600	4637.5	5246.6	5450.0	4118.2	4560.4	2825.0
1700	3771.0	4517.4	5273.3	4046.4	4481.4	3032.7
1800	2978.1	3238.1	4080.5	3559.7	4314.4	2585.4
1900	2250.9	2502.8	3127.0	2977.7	3818.2	2270.2
2000	1946.8	2138.5	2622.1	2389.5	3360.2	2031.3
2100	1597.8	1702.2	2036.4	2237.9	3091.0	1796.7
2200	1393.7	1535.2	1898.9	2197.3	3071.6	1899.6
2300	1324.5	1441.2	1943.4	2408.3	3447.9	2448.6
Average	2799.1	3048.7	3643.6	3356.9	3914.7	2759.6

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Appendix D: Health Consequence Distributions

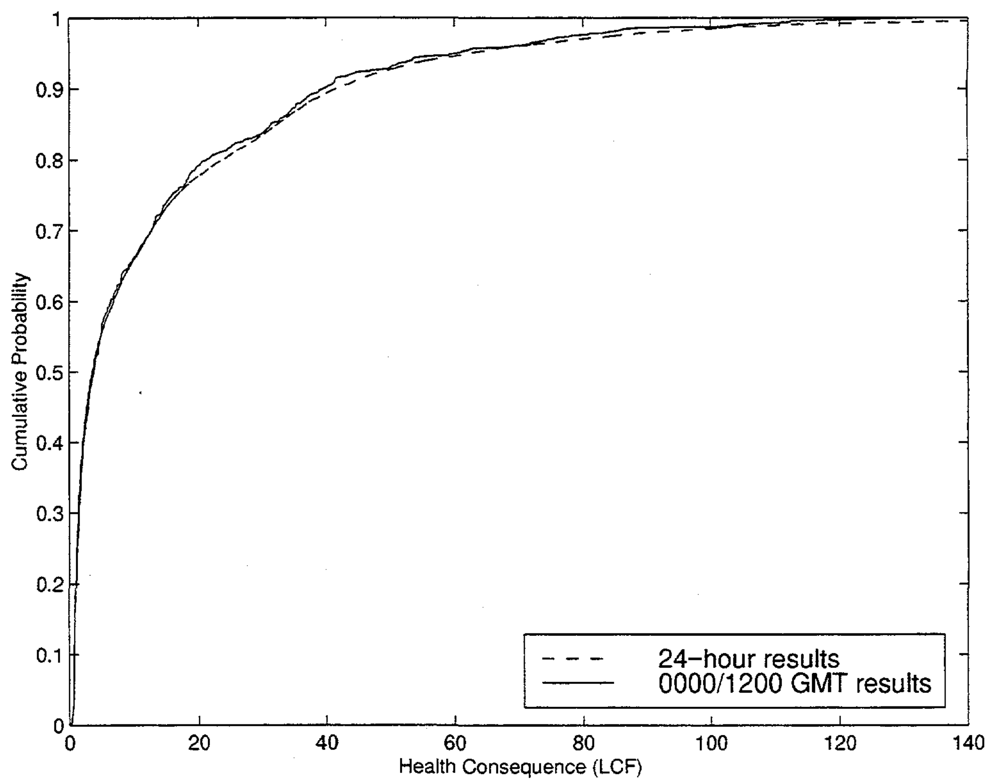

Figure D-1. Health Consequence Distributions for Accident Location 1

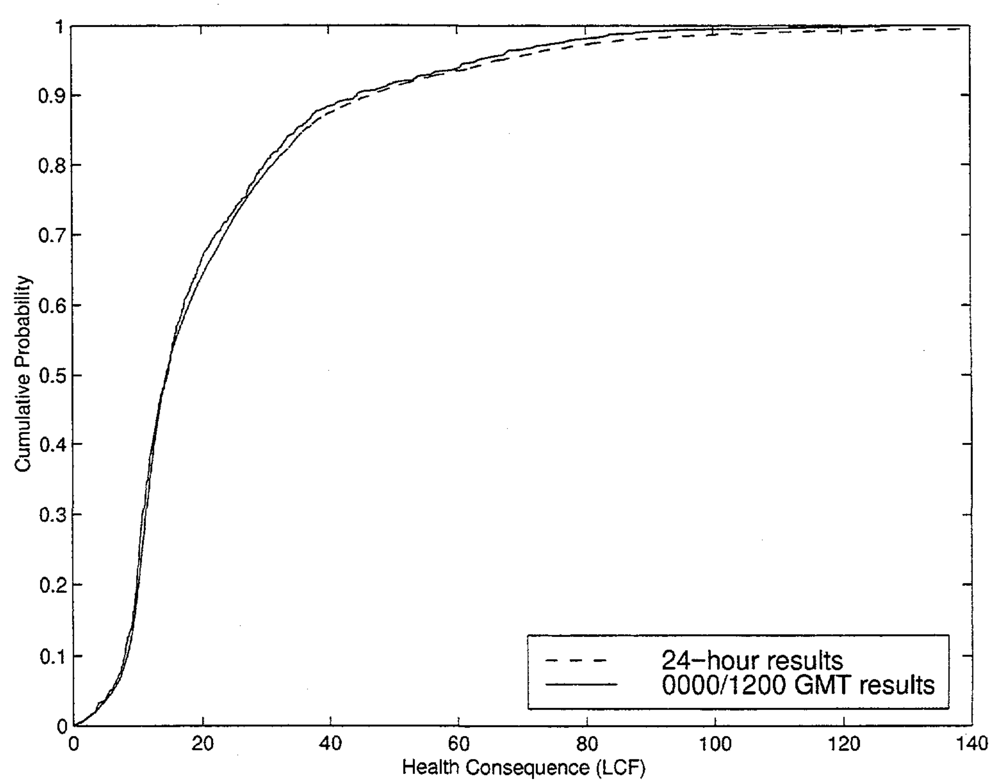

Figure D-2. Health Consequence Distributions for Accident Location 2

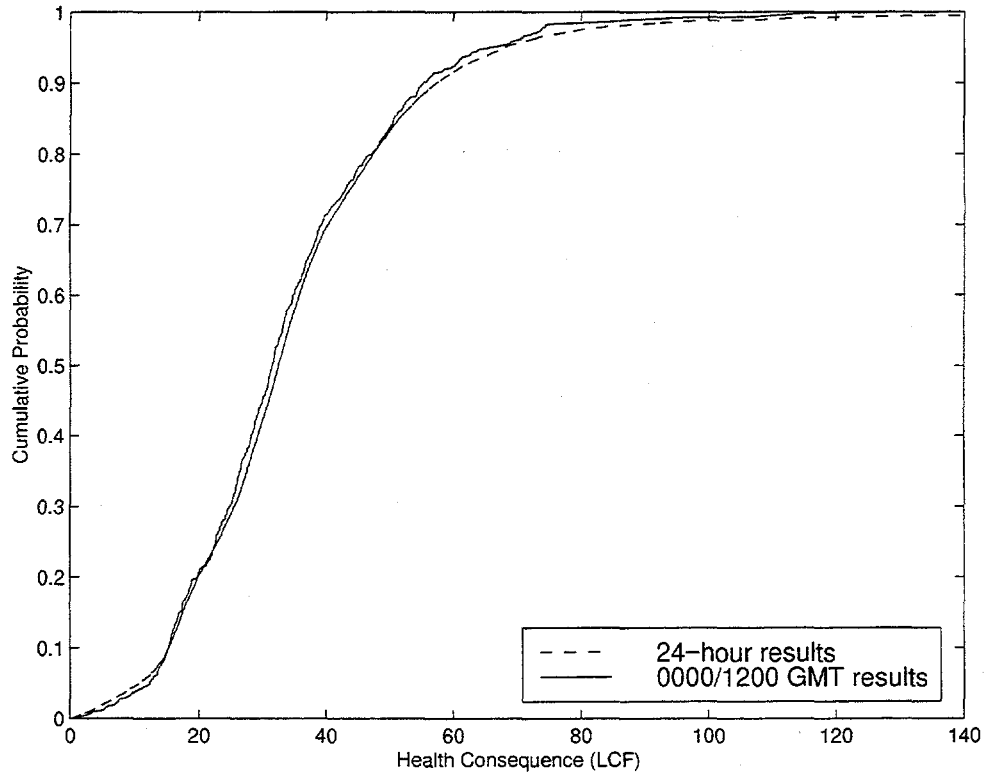

Figure D-3. Health Consequence Distributions for Accident Location 3

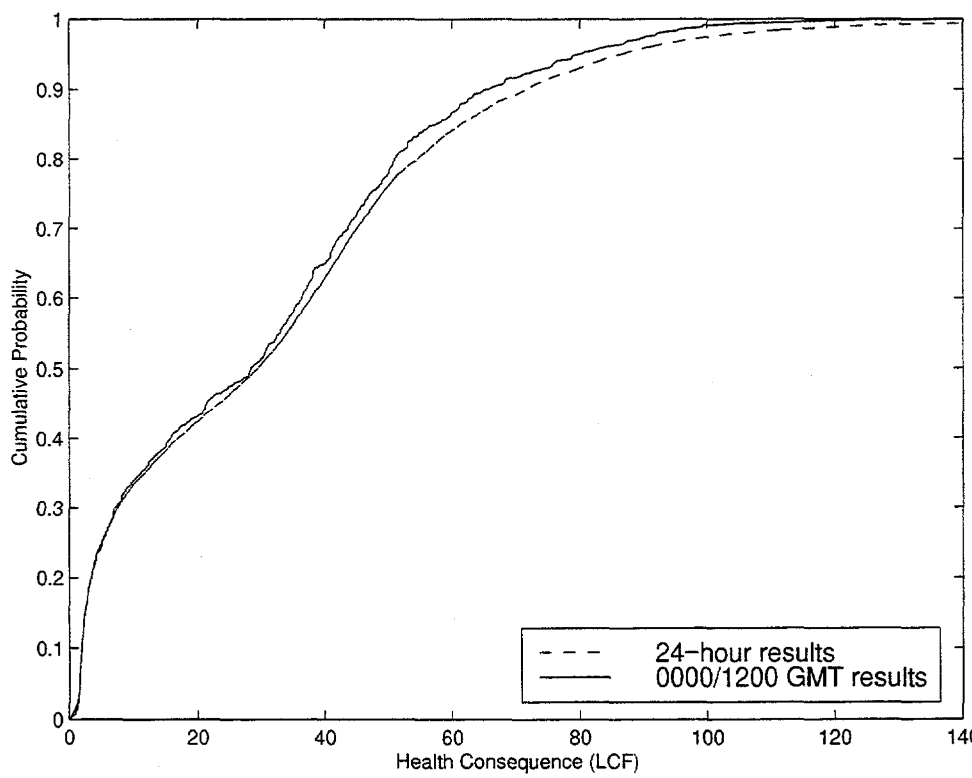

Figure D-4. Health Consequence Distributions for Accident Location 4

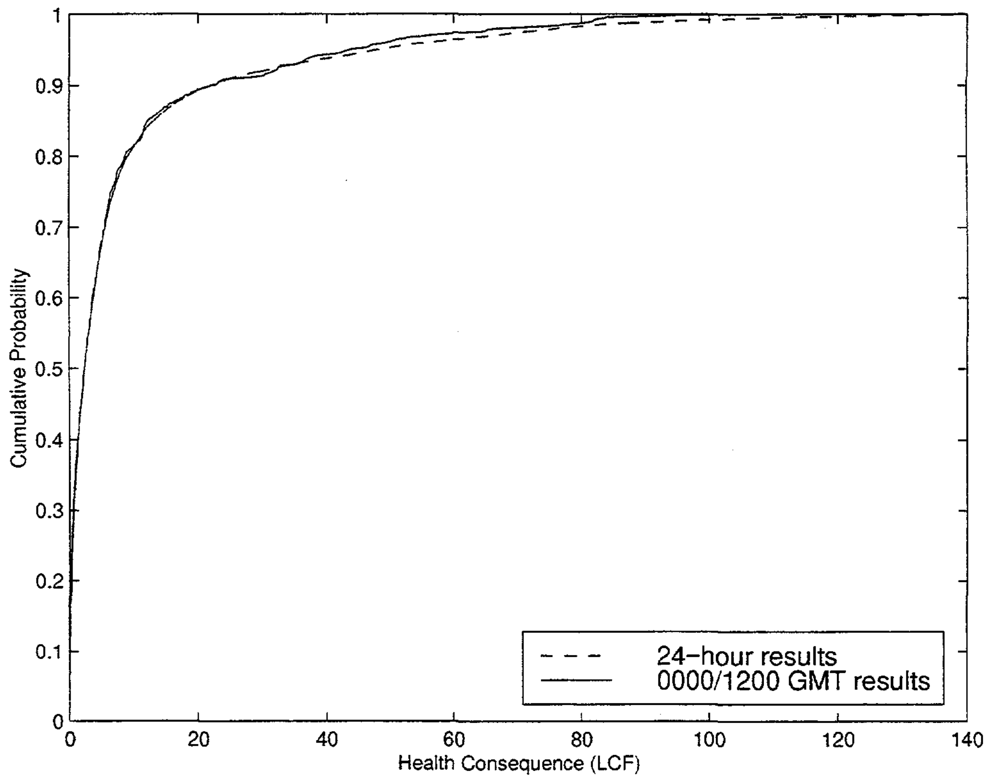

Figure D-5. Health Consequence Distributions for Accident Location 5

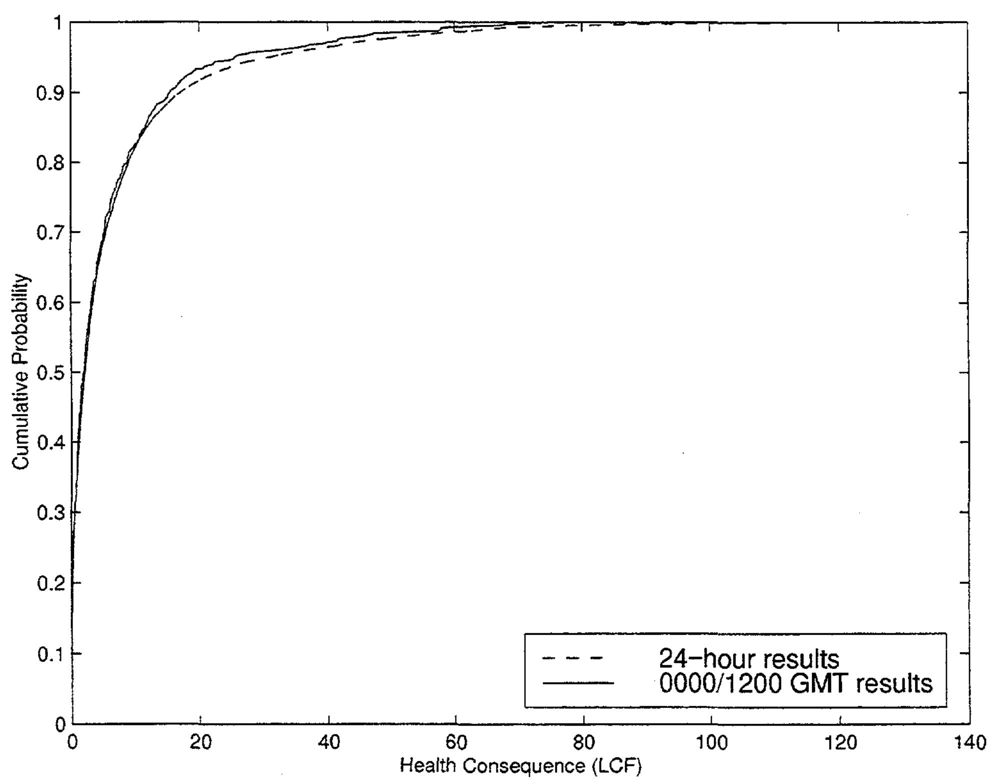

Figure D-6. Health Consequence Distributions for Accident Location 6

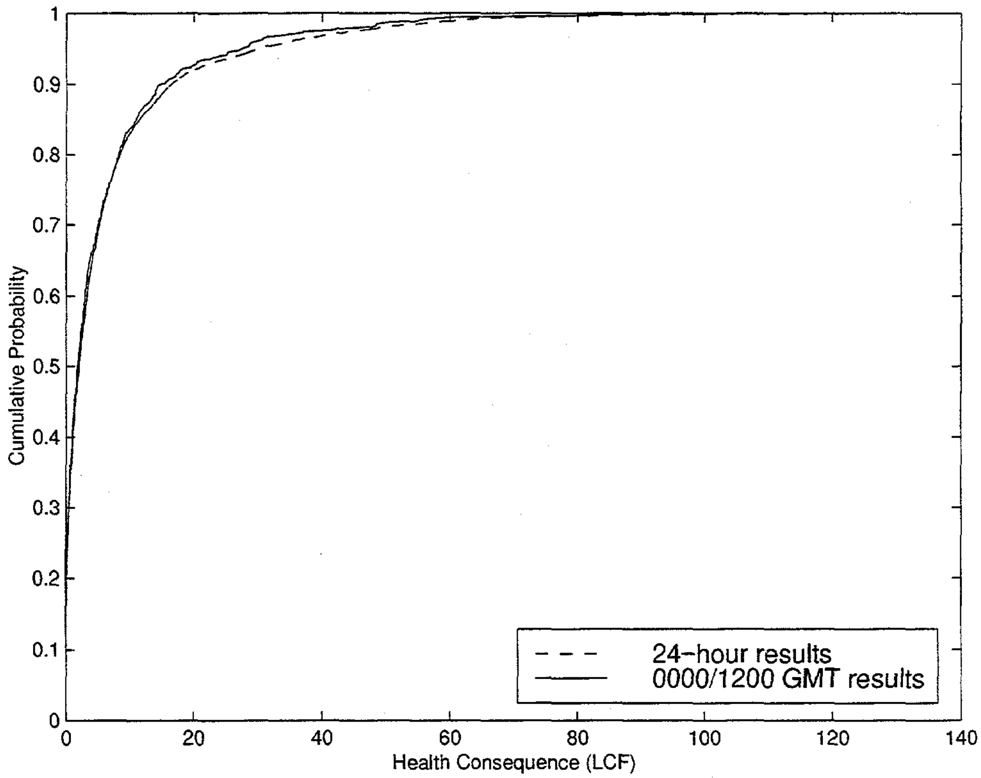

Figure D-7. Health Consequence Distributions for Accident Location 7

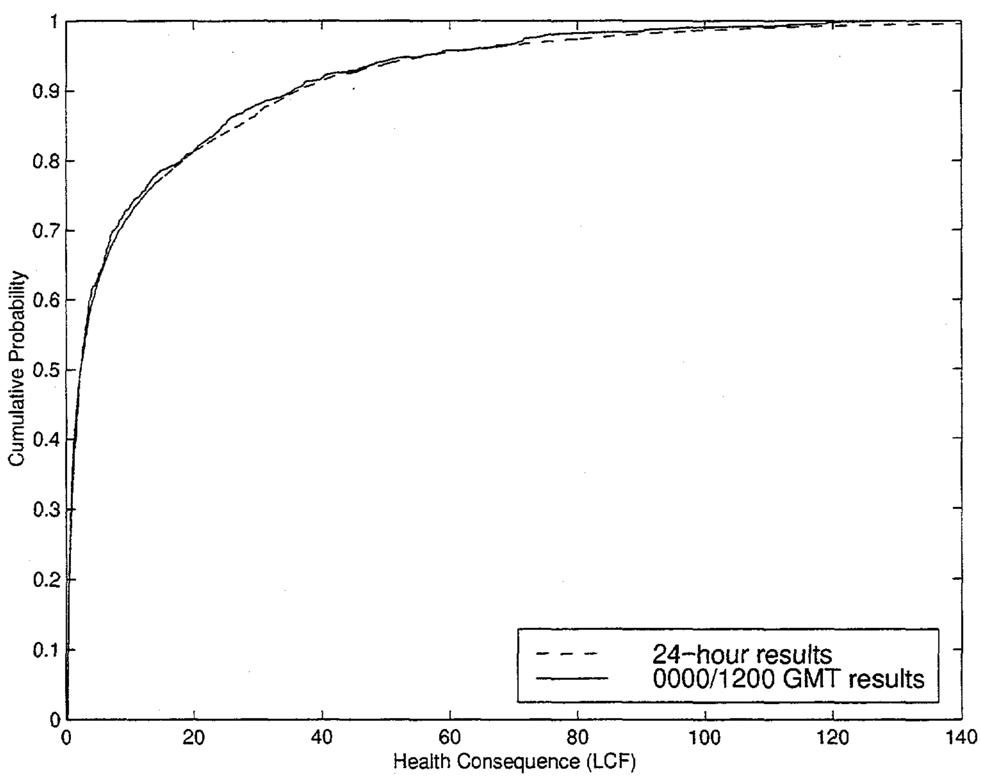

Figure D-8. Health Consequence Distributions for Accident Location 8

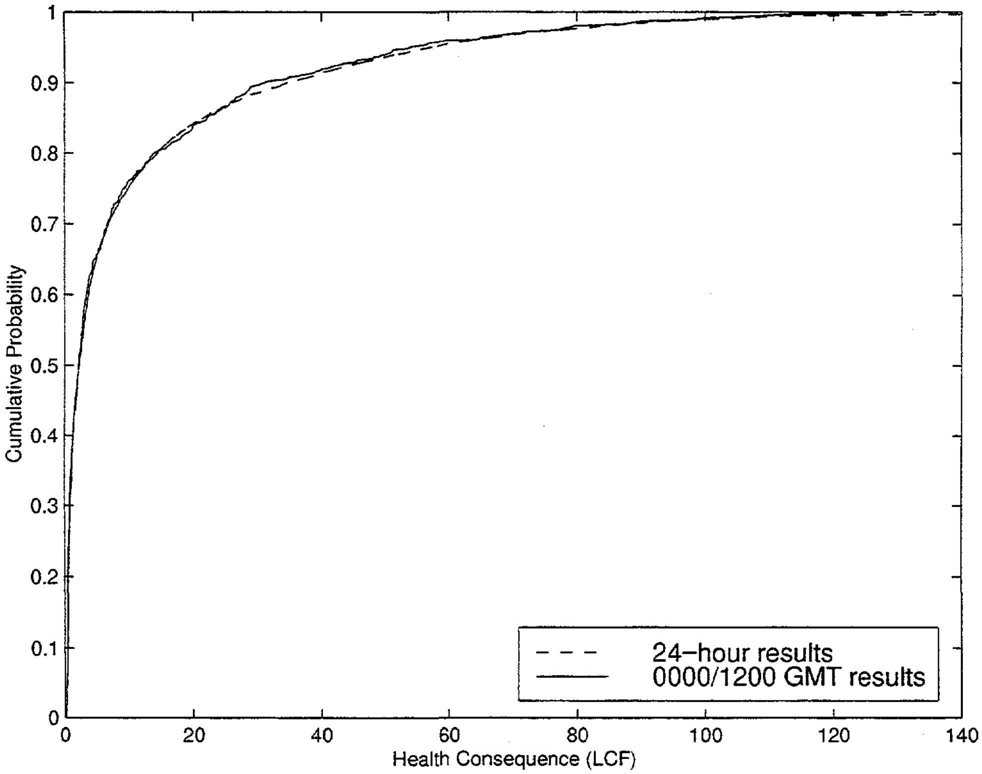

Figure D-9. Health Consequence Distributions for Accident Location 9

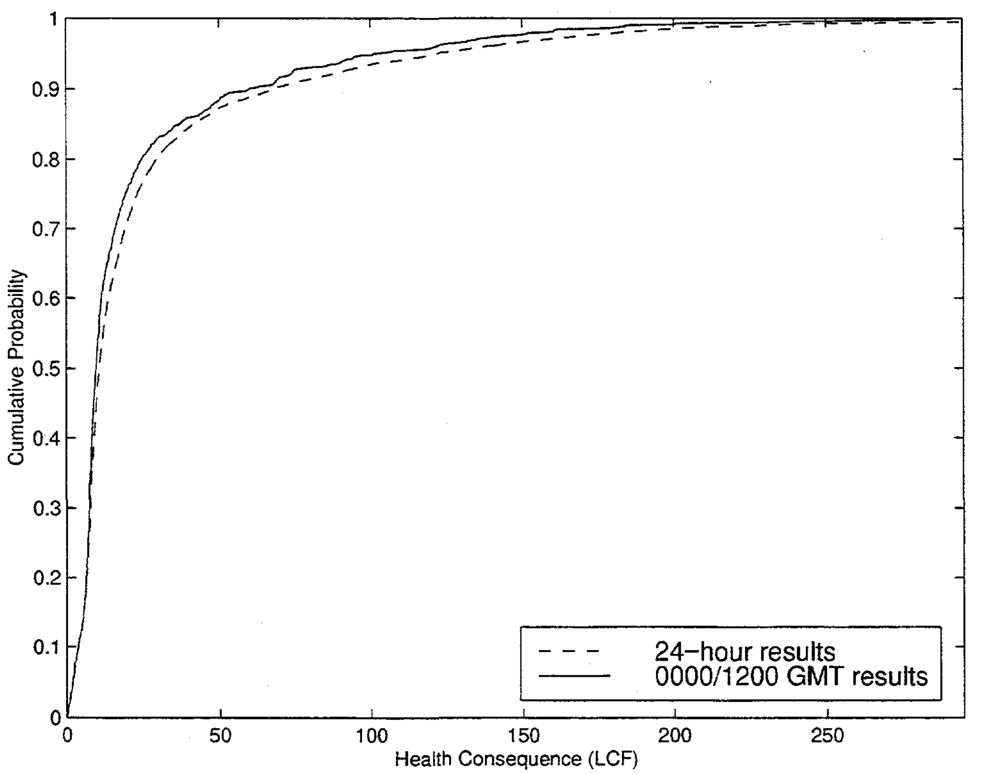

Figure D-10. Health Consequence Distributions for Accident Location 10

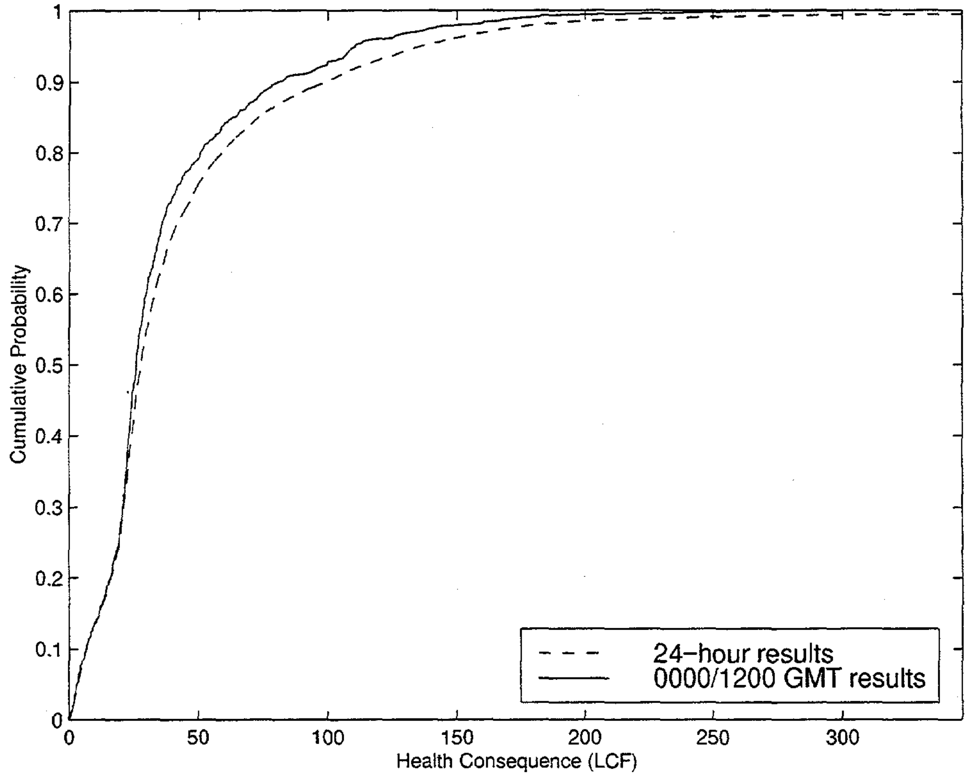

Figure D-11. Health Consequence Distributions for Accident Location 11

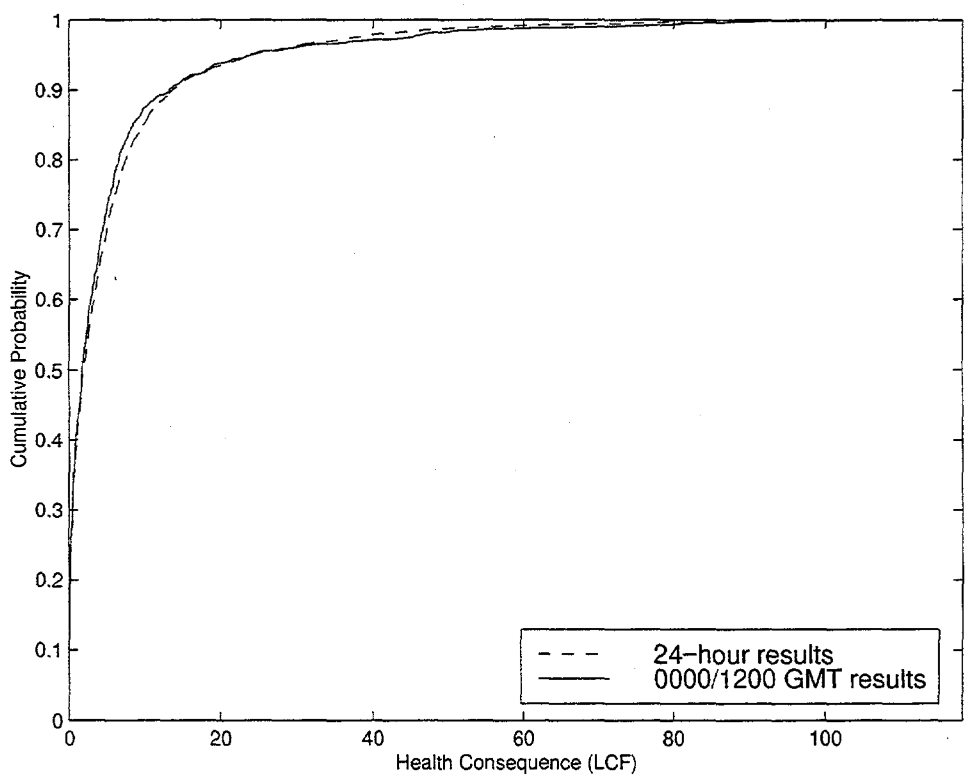

Figure D-12. Health Consequence Distributions for Accident Location 12

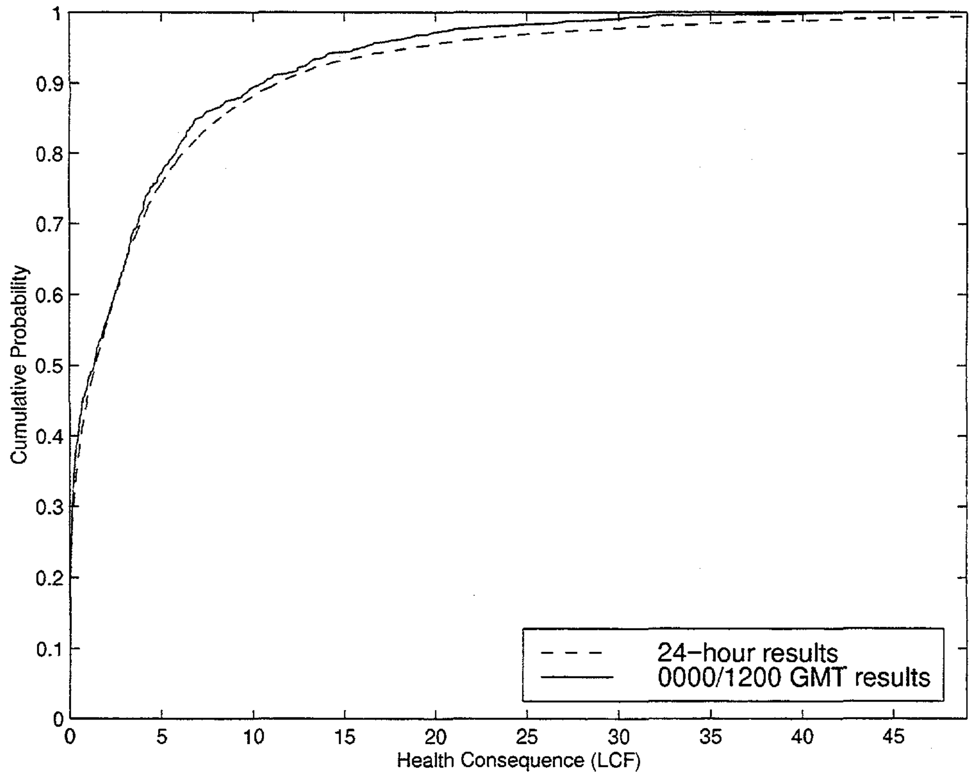

Figure D-13. Health Consequence Distributions for Accident Location 13

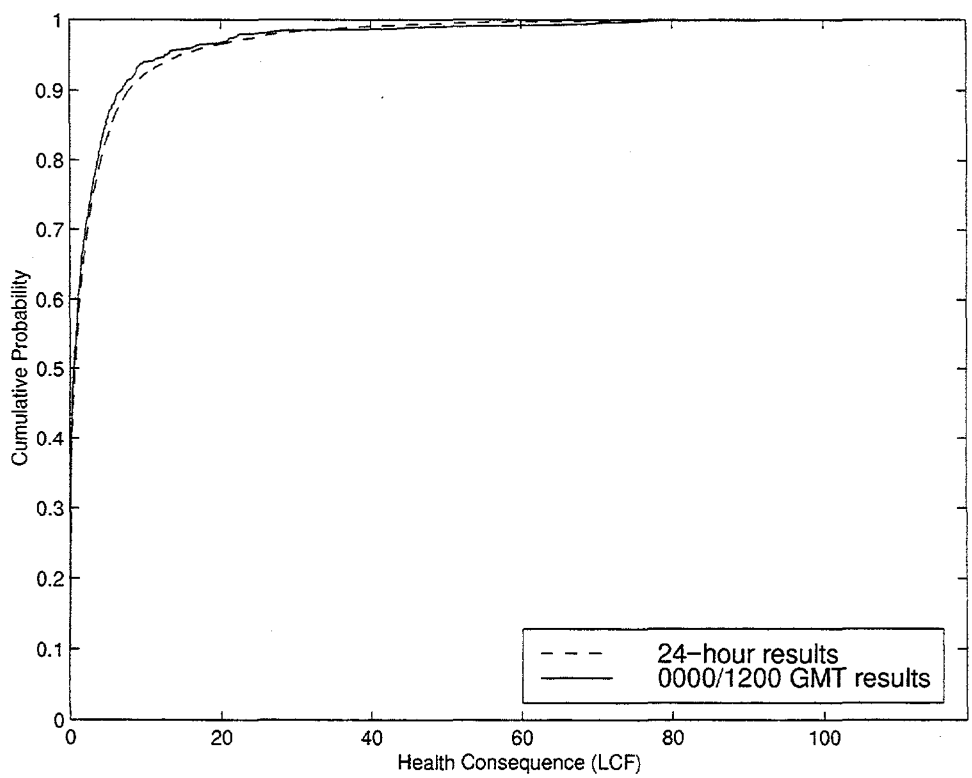

Figure D-14. Health Consequence Distributions for Accident Location 14

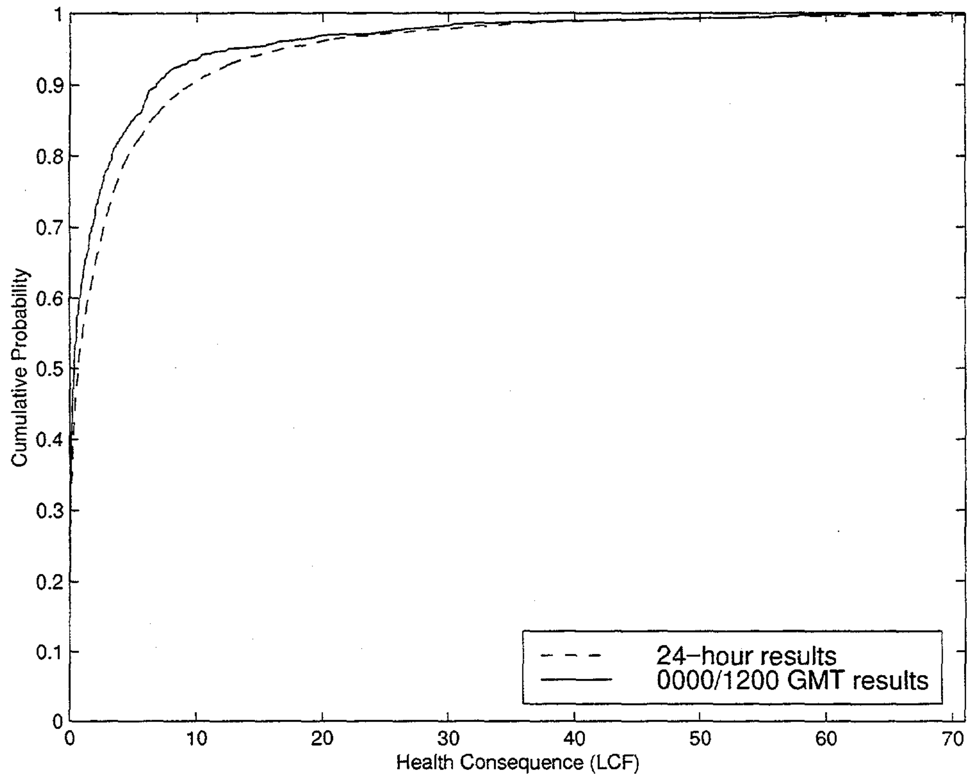

Figure D-15. Health Consequence Distributions for Accident Location 15

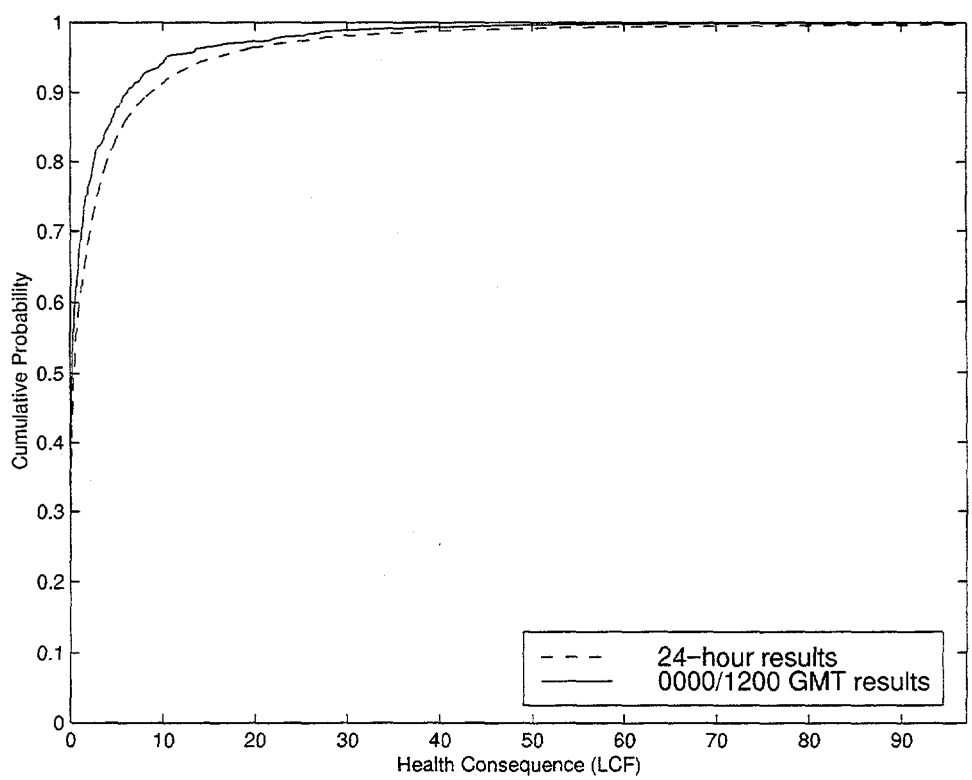

Figure D-16. Health Consequence Distributions for Accident Location 16

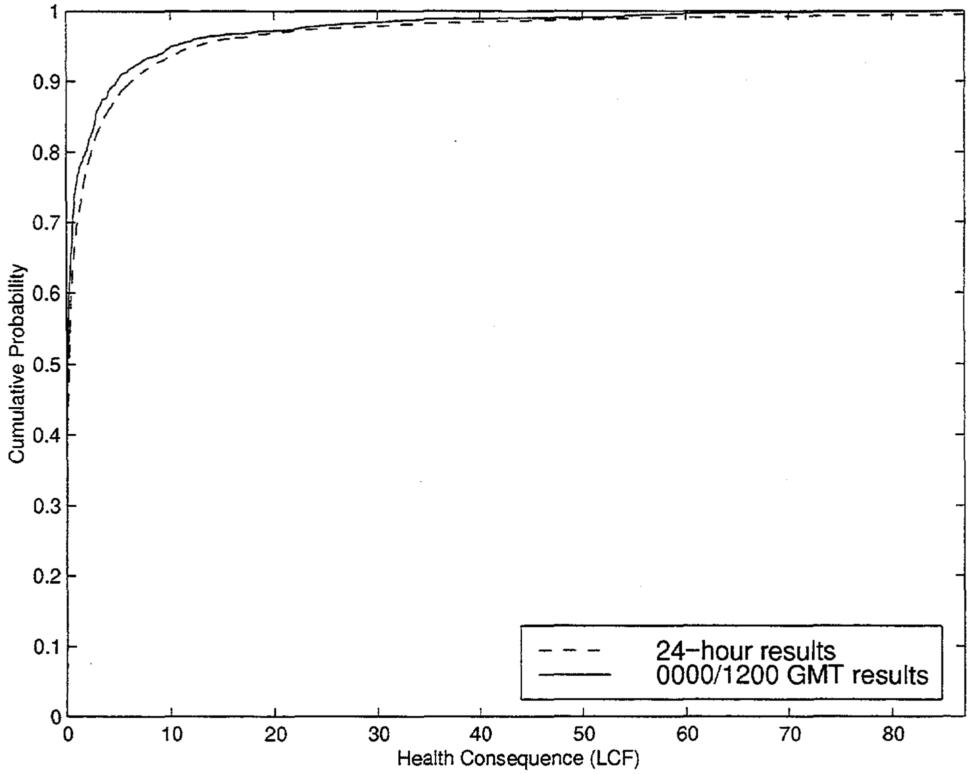

Figure D-17. Health Consequence Distributions for Accident Location 17

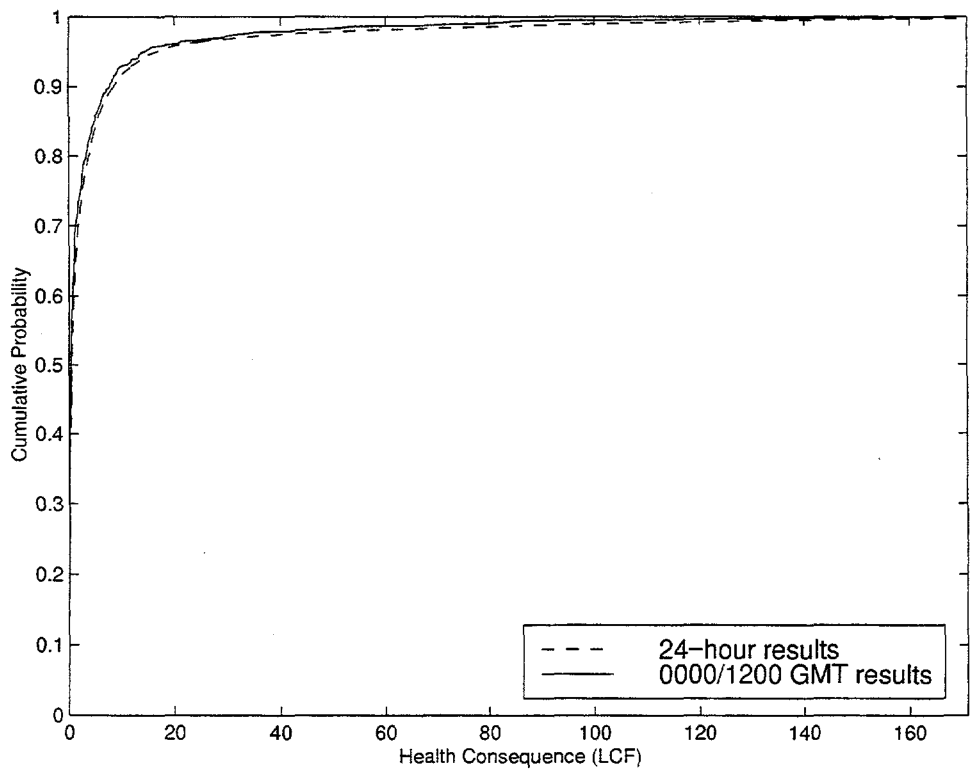

Figure D-18. Health Consequence Distributions for Accident Location 18

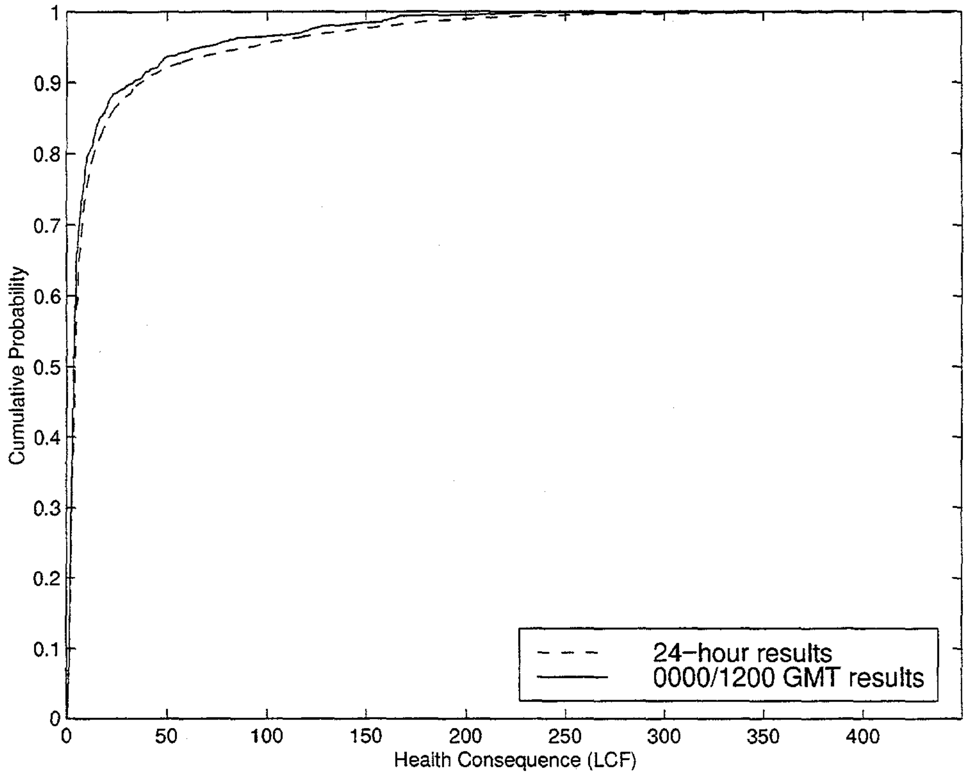

Figure D-19. Health Consequence Distributions for Accident Location 19

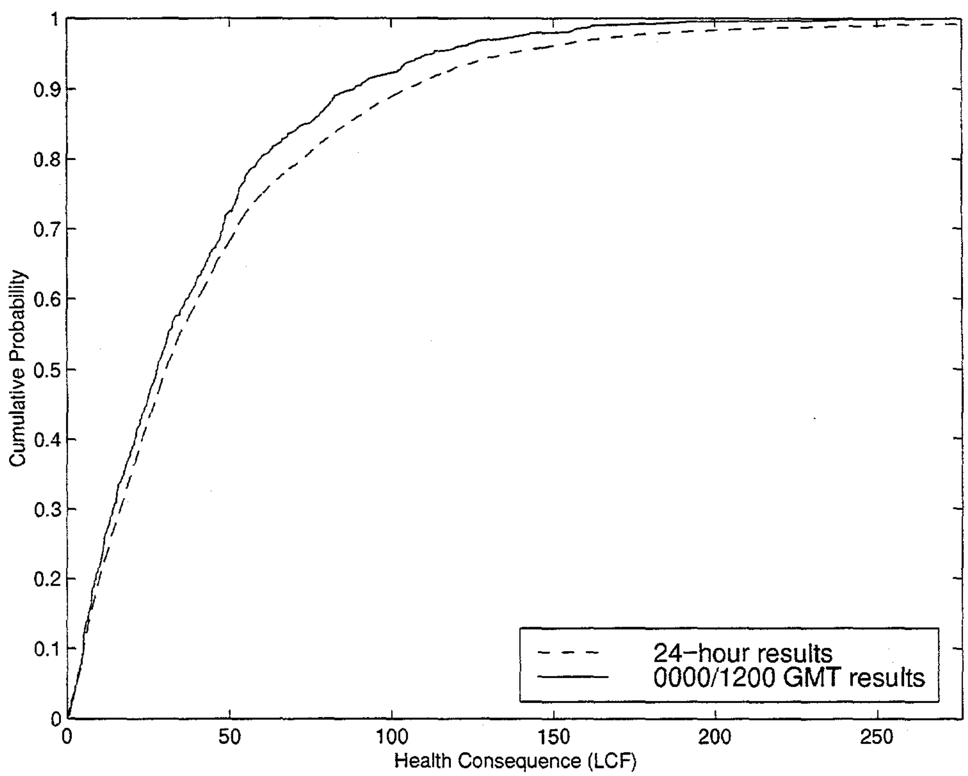

Figure D-20. Health Consequence Distributions for Accident Location 20

Distribution

2	Cindy Longenbaugh Department of Energy Albuquerque Operations Office Transportation Safeguards Division P.O. Box 5400 Albuquerque, NM 87185	
1	MS0767	D. B. Clauss, 6314
1	MS0767	J. M. Clauss, 6314
1	MS0767	B. W. Marshall, Jr., 6314
1	MS0763	C. D. Massey, 6331
15	MS0767	E. E. Ryder, 6314
1	MS9018	Central Technical Files, 8904-2
2	MS0899	Technical Library, 4916
2	MS0619	Review & Approval Desk, 12690 for DOE/OSTI