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A METHODOLOGY FOR ESTIMATING INCREMENTAL BENZENE EXPOSURES AND RISKS ASSOCIATED WITH GLYCOL DEHYDRATORS

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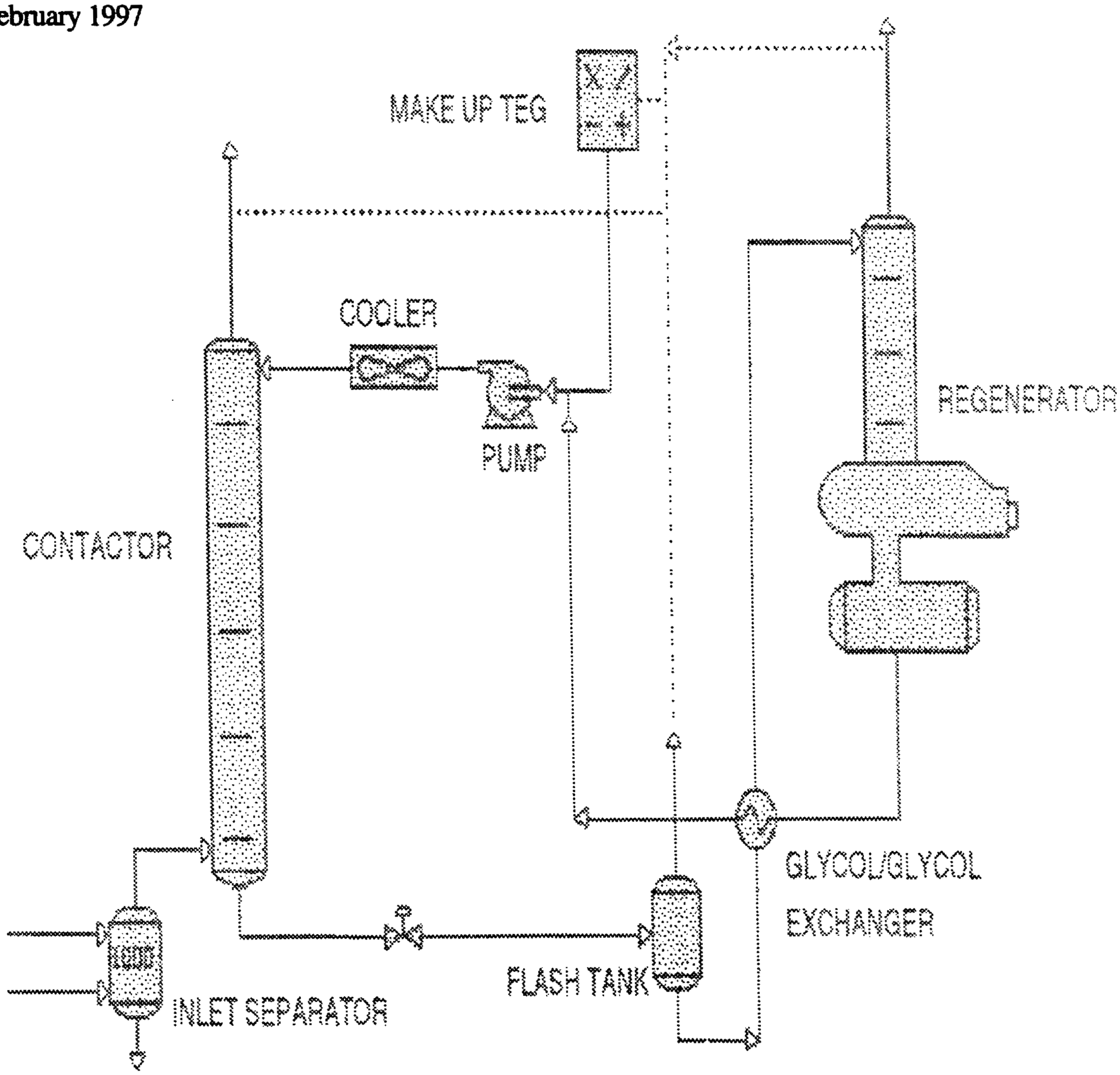

A Methodology for Estimating Incremental Benzene Exposures and Risks Associated With Glycol Dehydrators

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4644

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EXECUTIVE SUMMARY

The U.S. Environmental Protection Agency (EPA) is currently evaluating potential applicability criteria for glycol dehydrator air emission controls. To assist this evaluation, the American Petroleum Institute (API) commissioned TRJ Environmental, Inc. (TRJ) to develop a methodology to estimate benzene exposures and associated risks under representative emission conditions.

The EPA assisted in this research effort by performing a series of dispersion model runs using emission parameters suggested by API and meteorological data representing 348 weather stations in the United States. TRJ performed a series of statistical analyses on the results of these runs which indicated that the distribution of ambient (outdoor) benzene concentrations produced by an operating glycol dehydrator unit could be estimated as a function of benzene emission rate, vent velocity, vent diameter, land use (urban or rural), and source-to-receptor distance. Equations based on the statistical analyses were incorporated into a spreadsheet model capable of plotting "outdoor concentration vs. distance" for specified emission scenarios and concentration percentiles.

In addition to the spreadsheet model, a Monte Carlo routine for estimating lifetime cancer risk as a function of the estimated benzene concentration distribution was also developed. The entire process (spreadsheet program and Monte Carlo routine) was incorporated into a PC-based model called SimRisk. SimRisk generates a lifetime risk distribution that accounts for four factors that affect benzene exposure (residential occupancy period, time spent indoors and outdoors at the home location, indoor/outdoor ratio for benzene concentration, and breathing rate). The lifetime risk distribution is specific to benzene emission rate, vent velocity, vent diameter, land use (urban or rural), and source-to-receptor distance.

A simplified version of SimRisk was developed that can be used to estimate the 50th and 95th percentile values of lifetime risk solely as a function of benzene emission rate, source-to-receptor distance, and land use. This simplified risk model could be incorporated into control applicability criteria for glycol dehydrator vent emissions. To determine the applicability of controls to a specific unit, the analyst would use a simple graph or lookup table obtained from the model to determine the minimum source-to-residence distance associated with a specified lifetime cancer risk. If the actual distance from the glycol dehydrator unit to the nearest residence exceeds this minimum distance, the analyst could assume that the glycol dehydrator unit requires no further emission controls. If, however, the actual distance from the glycol dehydrator unit to the nearest residence is equal to or less than this minimum distance, then the source may be subject to additional controls.

This model is applicable only to glycol dehydrators operating under a specific set of conditions and should not be used outside of the following ranges:

30 meters ≤ distance ≤ meters 2000 meters

2 inches ≤ vent diameter ≤ 4 inches

1 ton/year ≤ emission rate ≤ 7 tons/year

3.2 feet/sec ≤ vent velocity ≤ 20.3 feet/sec.

Section 1
INTRODUCTION

The U.S. Environmental Protection Agency (EPA) is currently evaluating potential applicability criteria for glycol dehydrator air emission controls. To assist this evaluation, the American Petroleum Institute (API) commissioned TRJ Environmental to develop a methodology to estimate benzene exposures and associated risks under representative emission conditions.

This report is divided into seven sections. Section 2 describes preliminary risk assessment analyses performed by EPA prior to the startup of this project. The analyses included dispersion model runs using 348 meteorological stations and the application of Monte Carlo modeling techniques to the dispersion model results. Section 2 also summarizes a series of exploratory analyses in which the SCREEN3 dispersion model was applied to eight emission scenarios identified as representative of typical operating conditions. The model produced an estimate of the maximum benzene concentration at each of 10 distances considered in the earlier EPA dispersion model runs.

Section 3 presents the results of a special analysis in which Version 2 of the Industrial Source Complex dispersion model (ISC2) was applied to 45 meteorological stations selected by API as representative of areas where glycol dehydrators were likely to be located. After completion of the special analysis, API and EPA jointly developed a set of 24 emission scenarios to be used in subsequent dispersion modeling runs. Section 4 describes the 24 emission scenarios and presents the results of applying the ISC2 model to 348 meteorological stations under each scenario. Researchers statistically analyzed these results and developed a spreadsheet model for estimating outdoor benzene concentrations as a function of source-to-receptor distance and emission scenario. Section 4 describes the model and provides sample outputs.

Section 5 describes development of a PC-based model incorporating the spreadsheet and a Monte Carlo routine combining the outdoor benzene concentrations with randomly generated exposure factors to determine lifetime risk distributions. Section 6 presents a simplified method for estimating the 50th and 95th percentiles of these lifetime risk distributions. Section 7 discusses the limitations of the proposed modeling approach and provides recommendations for further research. Section 7 also describes a method by which model estimates can be used to determine whether or not a specific glycol dehydrator should be subject to controls for reducing benzene emissions.

Section 2
SCREENING ANALYSIS

The work in this report extends research conducted in 1995 by the Risk and Exposure Assessment Group (REAG) of EPA (Appendix A). Briefly, REAG acquired meteorological data for the 348 U.S. sites listed in Appendix B from the National Climatic Center in Asheville, North Carolina. The sites included all U.S. meteorological stations for which data were available at the time of the REAG analysis. REAG applied the ISC2-LT (long-term) dispersion model to each of the 348 sites and produced estimates of ambient (outdoor) benzene concentration at each of 160 points on a receptor grid surrounding a hypothetical glycol dehydrator unit. The receptor grid was laid out in a polar pattern with ten concentric rings at distances of 10, 20, 30, 50, 100, 200, 300, 500, 1000, and 2000 meters. These rings were intercepted by 16 equally spaced radial arms extending from the emission source to produce the 160 receptor points. The emission scenarios were defined according to the assumptions listed in Table A-1.

REAG applied Monte Carlo modeling techniques to the dispersion model estimates to determine lifetime cancer risk probabilities for people residing at various distances from the hypothetical glycol dehydrator unit. The modeling approach explicitly accounted for variability in breathing rate, time spent away from home, residential occupancy period, and indoor/outdoor ratio. REAG provided API with an informal summary of the input assumptions for the Monte Carlo analysis and examples of the model's output (personal communication, Mike Dusetzina, REAG, March 7, 1996). API reviewed these materials and directed TRJ to perform a series of screening analyses to determine the possible effects of varying the modeling assumptions concerning benzene emission rates, vent flow rates, and land use characteristics.

EPA's SCREEN3 dispersion model was applied to eight emission scenarios identified by API as representative of typical operating conditions. The model produced an estimate of the maximum benzene concentration at each of 10 distances considered in the earlier EPA dispersion model runs. Table 2-1 lists the assumptions common to all runs. Table 2-2 presents the conditions specific to each run and lists the estimated concentrations at six selected distances.

Table 2-1. American Petroleum Institute specifications for SCREEN3.

Model specification	Value
Source type	Point
Stack height	10 feet
Stack diameter	2 inches
Stack gas exit temperature	225 degrees F.
Air temperature	293 degrees K. (default)
Receptor height	2 meters
Building downwash calculation?	No
Terrain	Flat
Fumigation calculation?	No
Modeled meteorological conditions	All stabilities and wind speeds

The results in Table 2-2 are grouped in pairs by benzene, toluene, ethylbenzene, and xylene (BTEX) concentration in natural gas and land use. Within each pair, the runs differ with respect to benzene emission rate and total gas exit velocity from the vent. When the values associated with a benzene emission rate of 7 tons/year are divided by the paired values associated with the 1 ton/year runs, the resulting ratios increase with distance. For example, the ratio under the assumption of BTEX concentration = 550 ppmv in the natural gas and land use = urban is 4.90 for the 10 m distance and 6.94 for the 2 km distance. These results suggest that the dispersion model estimates for maximum benzene concentration are not proportional to emission rate when distances are relatively small.

The results listed in Table 2-2 also show that dispersion model estimates for rural locations tend to be higher over longer distances than corresponding estimates for urban locations. Consider, for example, the results associated with BTEX concentration = 550 ppmv in natural gas and benzene emission rate = 7 tons/year. Under these conditions, the maximum concentrations at 100 m and 500 m are 493 and 40.84 $\mu g/m^3$, respectively, for urban locations and 1204 and 289.5 $\mu g/m^3$, respectively, for rural locations. This example demonstrates a projected 12-fold concentration decrease between 100 m and 500 m for urban locations with only a 4-fold decrease between 100 m and 500 m for rural locations. This difference in the "concentration vs. distance" patterns for urban and rural sites can be explained by the higher turbulence caused by the urban "heat island" effect. This turbulence tends to disperse airborne pollutants closer to the emission point, causing a more rapid decrease in concentration with distance.

In summary, results of the screening analyses suggest that (1) dispersion model estimates of maximum outdoor benzene concentration are not proportional to emission rate when distances are relatively small and (2) the dispersion model concentration estimates for rural locations tend to be higher over longer distances than corresponding estimates for urban locations.

Table 2-2. Benzene concentration estimates ($\mu g/m^3$) from dispersion model runs which applied SCREEN3 to generic glycol reboiler vents.[a]

BTEX concentration[b], ppmv	Land use	Benzene emission rate, tons/yr	Exit velocity[c], ft/sec	Distance, m					
				10	100	200	500	1000	2000
550	Urban	1	1.59	1573	88.45	28.76	5.98	1.95	0.70
		7	10.83	7715	493	186.5	40.84	13.45	4.86
	Rural	1	1.59	1957	204.5	140.3	49.72	18.06	6.49
		7	10.83	5644	1204	547.0	289.5	117.1	43.71
250	Urban	1	2.93	1490	84.14	28.33	5.96	1.95	0.70
		7	20.27	5209	435.4	179.4	40.49	13.41	4.85
	Rural	1	2.93	1589	183.3	122.6	47.78	17.79	6.45
		7	20.27	3124	1129	423.7	262.1	112.7	43.00

[a]Stack parameters common to all runs can be found in Table 2-1.
[b]BTEX concentration (ppmv) of inlet natural gas to glycol dehydrator with an operating pressure of 855 psig, operating temperature of 100 degrees F, and glycol circulation rate of 3 gallons TEG per pound of water removed.
[c]Exit velocity is based on total volumetric flow rate of vent gas calculated using the GRI-Glycalc model.

Section 3

AN EPA TEST RUN OF ISC2 USING 45 SELECTED METEOROLOGICAL STATIONS

As discussed in Section 2, REAG applied the ISC2 dispersion model to data from 348 meteorological stations in an initial analysis of risks associated with benzene emitted by glycol dehydrators. These sites were selected to represent all areas of the United States. A second application of ISC2 was performed using a subset of 45 meteorological stations (Table 3-1) selected to represent areas where glycol dehydrators operating in oil and gas production fields were likely to be located. These stations are located in 17 states known to have operating glycol dehydrator units.

REAG assisted API by performing a test run of ISC2 based on the conditions listed in Table 3-2. The run assumed that the exit velocity was 1.59 ft/sec, the benzene emission rate was 1 ton/year, and the land use was rural. The remaining conditions were identical to those used in the SCREEN3 runs described in Section 2.

Table 3-3 provides descriptive statistics for the benzene concentration estimates according to distance from source. The statistics for each distance are based on 720 individual benzene concentration estimates, one for each combination of meteorological station (45 possibilities) and compass direction (16 possibilities). As expected, the value for each statistic decreases as distance increases. The distributions are positively skewed with relatively long upper tails. Plots on semi-log paper suggest that the empirical distribution of benzene concentrations at each distance can be well fit by a lognormal distribution. This finding is consistent with the results of subsequent analyses described in Section 4.

Table 3-1. Meteorological stations representing 45 geographical areas where glycol dehydrators are likely to be located.

State	Location	Site ID*
AK	Barter Island Airport	27401
AK	Barrow/W Post-W Rodgers	27502
AL	Mobile/WSO Airport	13894
CA	Fresno Air Terminal	93193
CA	Long Beach/WSO Airport	23129
CA	Los Angeles International Airport	23174
CA	Santa Barbara Airport	23190
CA	Redding/Aaf	24257
IL	Springfield/Capital Airport	93822
IN	Evansville Regional Airport	93817
KS	Wichita/Mid-Continent Airport	03928
KS	Concordia/Blosser Mun. Airport	13984
KY	Paducah/WSO Airport	03816
KY	Jackson/Julian Carroll Airport	03889
LA	Lake Charles/Municipal	03937
LA	New Orleans Int'l Airport	12916
LA	Shreveport/Regional Airport	13957
LA	Baton Rouge/Ryan Airport	13970
MS	Meriden/Key Field	13865
MO	Kansas City/Int'l Airport	03947
MO	Kansas City Airport	13988
MT	Cut Bank Airport	24137
ND	Williston/Sloulin Int'l Airport	94014
NM	Roswell	23009
OH	Toledo/Express Airport	94830
OK	Oklahoma City/Will Rodgers	13967
OK	Tulsa/International Airport	13968
PA	Pittsburgh/Macon Airport	94823
TX	Stephenville	03969
TX	Victoria/WSO Airport	12912
TX	Port Arthur/Jefferson City	12917
TX	Brownsville/International Airport	12919
TX	San Antonio	12921
TX	Corpus Christie/Int'l Airport	12924

(continued)

Table 3-1 (Continued)

State	Location	Site ID*
TX	Houston Intercontinental	12960
TX	Abilene/Municipal Airport	13962
TX	Wichita Falls/Municipal Airport	13966
TX	Midland/Regional Airport	23023
TX	San Angelo/WSO Airport	23034
TX	Lubbock/Regional Airport	23042
WV	Huntington/Tri-State Airport	03860
WV	Beckley/Raleigh Co. Memorial	03872
WV	Charleston/Kenawba Airport	13866
WY	Lander/Hunt Field	24021
WY	Rock Springs Airport	24027

*Site ID refers to the meteorological station STAR Site number (see complete listing of sites in Appendix B).

Table 3-2. Specifications for the Test Run of ISC2 applied to 45 meteorological stations.

Parameter	Specification
Number of meteorological stations	45 (selected by API)
Exit velocity	1.59 feet/sec
Benzene emission rate	1 ton/year
Land use	Rural
Source type	Point
Stack height	10 feet
Stack diameter	2 inches
Stack gas exit temperature	225 degrees F.
Air temperature	293 degrees K. (default)
Receptor height	2 meters
Building downwash calculation?	No
Terrain	Flat
Fumigation calculation?	No
Modeled meteorological conditions	All stabilities and wind speeds

Table 3-3. Descriptive statistics for estimated benzene concentrations (µg/m^3) at specified distances from 45 hypothetical emission sources.[a]

Ring	Distance, meters	n	Benzene concentration, µg/m^3 Arith. mean	Arith. S. D.	Minimum	25%	50%	75%	Maximum
1	10	720	19.68	11.97	1.75	11.75	16.73	24.33	92.44
2	20	720	11.27	6.76	1.03	6.76	9.62	13.97	52.39
3	30	720	7.43	4.35	0.82	4.51	6.40	9.16	33.64
4	50	720	4.12	2.44	0.44	2.49	3.55	5.09	18.91
5	100	720	1.66	1.01	0.17	0.98	1.41	2.07	7.92
6	200	720	0.60	0.38	0.05	0.35	0.51	0.75	2.99
7	300	720	0.32	0.21	0.03	0.18	0.27	0.41	1.63
8	500	720	0.140	0.091	0.011	0.078	0.112	0.179	0.724
9	1000	720	0.046	0.030	0.003	0.025	0.038	0.058	0.242
10	2000	720	0.015	0.010	0.001	0.008	0.013	0.019	0.080

[a]These data were obtained from an ISC2 dispersion model run performed by the Risk and Exposure Assessment Group, U.S. Environmental Protection Agency. Table 3-1 lists the 45 meteorological stations used in the runs. Emission conditions are described in Table 3-2. Each of the 45 sites produced 16 concentration values for each of the 10 rings listed in the table above (45 sites x 16 values/ring = 720 values/ring for all sites).

Following the completion of the test run, API conferred with EPA concerning the use of the 45 stations in an analysis to estimate lifetime cancer risks associated with benzene emitted by glycol dehydrators. EPA recommended using the complete set of 348 meteorological stations that were used in the initial EPA risk assessment (Appendix A). These stations were considered to provide a more complete range of potential exposure conditions. Section 4 describes model development using the 348 meteorological stations.

Section 4
INITIAL MODEL DEVELOPMENT

After completion of the test run described in Section 3, API and EPA jointly developed a set of 24 emission scenarios to be used in subsequent dispersion modeling runs. These scenarios are listed in Table 4-1. Each scenario specifies benzene emission rate (1 or 7 tons/year), vent velocity (3.21, 10.9, or 20.3 feet/sec), vent diameter (2 or 4 inches), and a land use (urban or rural). Conditions common to all scenarios are listed below:

release height = 12 feet

release temperature = 225 degrees F

For each scenario, EPA ran the ISC2 dispersion model for each of the 348 meteorological stations. The far-left column in Table 4-1 lists the names of the 24 data files produced by these runs. Each data file contained 55,680 values of annual average outdoor benzene concentration: one for each combination of meteorological station (348 possibilities), distance from source (10 possibilities), and compass direction (16 possibilities).

Each of the EPA data files was reformatted into a new file suitable for statistical analyses. Tables C-1 through C-12 in Appendix C provide descriptive statistics calculated from these files. Each table provides results for one combination of vent velocity, vent diameter, and land use. The results within each table are further stratified by distance and emission rate. The statistics in each table row are based on 5,568 outdoor benzene concentrations (348 stations times 16 compass points). Each set of 5,568 values was referred to as a "scenario-distance data set" (SDDS).

Table 4-1. Dispersion model output files received from the Risk and Exposure Assessment Group (Jan. 26 and Feb. 1, 1996).[a]

REAG file name	Benzene emission rate, tons/year	Vent diameter, inches	Vent velocity, ft/sec	Land use
723.21r	7	2	3.21	rural
723.21u	7	2	3.21	urban
7210.9r	7	2	10.9	rural
7210.9u	7	2	10.9	urban
7220.3r	7	2	20.3	rural
7220.3u	7	2	20.3	urban
743.21r	7	4	3.21	rural
743.21u	7	4	3.21	urban
7410.9r	7	4	10.9	rural
7410.9u	7	4	10.9	urban
7420.3r	7	4	20.3	rural
7420.3u	7	4	20.3	urban
123.21r	1	2	3.21	rural
123.21u	1	2	3.21	urban
1210.9r	1	2	10.9	rural
1210.9u	1	2	10.9	urban
1220.3r	1	2	20.3	rural
1220.3u	1	2	20.3	urban
143.21r	1	4	3.21	rural
143.21u	1	4	3.21	urban
1410.9r	1	4	10.9	rural
1410.9u	1	4	10.9	urban
1420.3r	1	4	20.3	rural
1420.3u	1	4	20.3	urban

[a]All runs used 348 meteorological stations. Stack height = 12 feet. Release temperature = 225 degrees F.

Analyses of the SDDS revealed that the lognormal distribution usually provided a good fit to the data. A lognormal distribution can be completely specified by its geometric mean (GM) and geometric standard deviation (GSD). If data are well fit by a lognormal distribution, the GM will closely match the median (i.e., the 50th percentile value). Each pair of GM and median values listed in Appendix C match within 2 percent.

The GM and GSD values listed for a particular SDDS can be used to estimate any percentile in the distribution of outdoor benzene concentrations associated with the SDDS. To estimate the benzene concentration corresponding to the P percentile [$C_{out}(P)$], calculate the quantity

$$C_{out}(P) = (GM)(GSD)^{z} \tag{1}$$

where the area under the unit normal curve from zero to z is equal to P expressed as a fraction. Values of z for selected percentiles are listed below:

percentile	z value
5	-1.645
10	-1.282
25	-0.6745
50	0
75	0.6745
90	1.282
95	1.645
99	2.326

For example, the GM and GSD of the first SDDS listed in Table C-1 of Appendix C are 10.1 $\mu g/m^3$ and 1.768, respectively. The 95th percentile can be estimated by the expression

$$C_{out}(95\%) = (10.1)(1.768)^{1.645} = 25.8\ \mu g/m^3. \tag{2}$$

The actual 95th percentile is 26.0 $\mu g/m^3$, a difference of less than 1 percent.

A series of exploratory stepwise linear regression (SLR) analyses was performed to determine whether the geometric means and geometric standard deviations listed in

Appendix C could be estimated directly from the parameters defining the scenario (emission rate, vent velocity, vent diameter, and land use). The SLR analyses indicated that the geometric means could be estimated well at all distances between 10 and 2000 meters, whereas the geometric standard deviations could be estimated well for distances between 30 and 2000 meters.

The geometric means in Appendix C were found to be proportional to emission rate when other parameters were held constant. Researchers subsequently performed a series of followup SLR analyses on the quantity

$$\text{LNRATIO} = \ln[(\text{geometric mean benzene conc.})/(\text{benzene emission rate})] \qquad (3)$$

and found that LNRATIO could be estimated well at all distances between 10 and 2000 meters. Regression results based on separate analyses of the urban and rural data are included in Table 4-2.

The geometric standard deviation (a dimensionless quantity) was found to be independent of benzene emission rate. Regression results for geometric standard deviation based on separate analyses of the urban and rural data are included in Table 4-3. Note that these regression analyses omitted dispersion modeling results for distances of 10 and 20 meters. TRJ did not find a regression equation that could provide a good fit to dispersion model estimates for all distances when these two distances were included. Consequently, the regression analyses were applied to data for distances of 30 to 2000 meters. TRJ found that the following equations could be used to estimate the geometric standard deviations for 10 and 20 meters as a function of the geometric standard deviation estimated for 30 meters:

Urban:

$$\text{GSD(10 meters)} = (1.020)[\text{GSD(30 meters)}] \qquad (4)$$

$$\text{GSD(20 meters)} = (1.014)[\text{GSD(30 meters)}] \qquad (5)$$

Rural:

$$\text{GSD(10 meters)} = (1.008)[\text{GSD(30 meters)}] \qquad (6)$$

$$\text{GSD(20 meters)} = (1.004)[\text{GSD(30 meters)}] \qquad (7)$$

Table 4-2. Results of stepwise linear regression analyses performed on the LNRATIO parameter of a lognormal distribution fitting benzene concentrations estimated by applying the ISC2 dispersion model to 348 meteorological stations.[a,b]

Land use	Predictor variable	Regression coefficient[c]	Cumulative R^2 value[d]
urban	constant	9.79478	0.0000
	ln(distance)	-2.08838	0.9805
	1/(distance)	-30.6184	0.9993
	distance	2.693E-4	0.9996
	velocity	-0.00447	0.9997
	$1/(\text{distance})^2$	51.4401	0.9998
	diameter/distance	-0.48561	0.9998
rural	constant	8.19990	0.0000
	ln(distance)	-1.63484	0.9765
	1/(distance)	-26.4672	0.9989
	velocity/distance	-0.11091	0.9993
	$1/(\text{distance})^2$	65.2323	0.9996
	ln(diameter)	-0.08316	0.9997
	velocity	-0.00294	0.9998

[a]LNRATIO = ln[(geometric mean benzene conc.)/(benzene emission rate, tons/year)]
[b]Units: geometric benzene concentration ($\mu g/m^3$), benzene emission rate (tons/year), distance (meters), velocity (feet/sec), diameter (inches).
[c]The p value for each regression coefficient is less than 0.0001.
[d]Coefficient of determination indicating fraction of total variance in LNRATIO explained by predictor variables.

The regression results in Tables 4-2 and 4-3 are stated as equations for estimating LNRATIO and GSD in Table 4-4. These equations provide a means for determining the percentiles of the benzene distribution expected to occur under a specific emission scenario such that (1) the common set of conditions apply and (2) the distance, vent diameter, emission rate, and vent velocity fall within the following ranges:

30 meters $\leq$ distance $\leq$ 2000 meters

2 inches $\leq$ vent diameter $\leq$ 4 inches

1 ton/year $\leq$ emission rate $\leq$ 7 tons/year

3.21 feet/sec $\leq$ vent velocity $\leq$ 20.3 feet/sec.

Equations 4 through 7 can be used to produce estimates of GSD for 10 and 20 meters. Table 4-5 presents the entire estimation procedure as a series of six steps.

Table 4-3. Regression equations for estimating the geometric standard deviation (GSD) of a lognormal distribution fitting benzene concentrations estimated by applying the ISC2 dispersion model to 348 meteorological stations (distance $\geq$ 30 meters).[a]

Land use	Predictor variable	Regression coefficient[b]	Cumulative R^2 value[c]
urban	constant	1.57788	0.0000
	ln(distance)	0.03743	0.8919
	1/[(distance)(velocity]	-6.83247	0.9695
	ln(velocity)	0.01573	0.9840
	ln(diameter)	0.01292	0.9885
	distance/velocity	3.169E-5	0.9901
rural	constant	1.52967	0.0000
	ln(distance)	0.05567	0.9613
	$1/(\text{distance})^2$	-47.8347	0.9740
	distance	-1.933E-5	0.9814
	diameter	-0.00355	0.9856
	1/[(distance)(velocity)]	-1.41478	0.9874

[a]Units: geometric standard deviation (dimensionless), distance (meters), velocity (feet/sec), diameter (inches).
[b]The p value for each regression coefficient is less than 0.0005.
[c]Coefficient of determination indicating fraction of total variance in GSD explained by predictor variables.

Table 4-4. Equations for estimating LNRATIO and GSD based on the regression results presented in Tables 4-2 and 4-3.

<u>Urban land use</u>:

$$\mathrm{LNRATIO} = 9.79478 - (2.08838)[\ln(D)] - (30.6184)(1/D) + (2.693E\text{-}4)(D) - (0.00447)(V) + (51.4401)(1/D^2) - (0.48561)(d/D)$$

$$\mathrm{GSD} = 1.57788 + (0.03743)[\ln(D)] - (6.83247)[1/(D)(V)] + (0.01573)[\ln(V)] + (0.01292)[\ln(d)] + (3.169E\text{-}5)(D/V)$$

<u>Rural land use</u>:

$$\mathrm{LNRATIO} = 8.1999 - (1.63484)[\ln(D)] - (26.4672)(1/D) - (0.11091)(V/D) + (65.2323)(1/D^2) - (0.08316)[\ln(d)] - (0.00294)(V)$$

$$\mathrm{GSD} = 1.52967 + (0.05567)[\ln(D)] - (47.8347)(1/D^2) - (1.933E\text{-}5)(D) - (0.00355)(d) - (1.41478)[1/(D)(V)$$

The variables are defined as follows:

LNRATIO = ln[(geometric mean benzene conc.)/(benzene emission rate)]

GSD = geometric standard deviation (dimensionless)

D = distance from source (meters)

V = vent velocity (ft/sec)

d = diameter of vent (inches).

Units for LNRATIO: geometric mean benzene concentration ($\mu g/m^3$), benzene emission rate (tons/year).

Table 4-5. Procedure for estimating random values of outdoor benzene concentrations according to user-specified emission conditions.

Step	Explanation
1	Specify land use, distance from source, benzene emission rate, vent velocity, and vent diameter.
2	Use appropriate regression equation from Table 4-4 to estimate LNRATIO for land use, distance, vent velocity, and vent diameter specified in Step 1. LNRATIO is defined by the expression LNRATIO = ln[(geom. mean benzene conc.)/(benzene emiss. rate)].
3	Estimate geometric mean by the equation: geometric mean = $(e^{LNRATIO})$(benzene emission rate) where the benzene emission rate is the value specified in Step 1.
4	If distance is between 30 and 2000 meters, use the appropriate equation from Table 4-4 to estimate geometric standard deviation for land use, vent velocity, and vent diameter specified in Step 1. If distance = 10 or 20 meters, calculate geometric standard deviation for 30 meters using Table 4-4 equation and then apply one of the following conversion equations: Urban land use GSD(10 meters) = (1.020)[GSD(30 meters)] GSD(20 meters) = (1.014)[GSD(30 meters)]. Rural land use GSD(10 meters) = (1.008)[GSD(30 meters)] GSD(20 meters) = (1.004)[GSD(30 meters)].
5	Randomly select z value from unit normal distribution (i.e., mean = 0, standard deviation = 1).
6	Calculate benzene concentration for random z value using equation: $C_{out} = (GM)(GSD)^z$. where GM is the geometric mean determined in Step 3, GSD is the geometric standard deviation determined in Step 4, and z is the value of the normal variate determined in Step 5.

The procedure presented in Table 4-5 was incorporated into a spreadsheet model that (1) calculates the distribution of outdoor benzene concentrations at 24 distances from 10 m to 2000 m and (2) plots the results for user-specified percentiles. Figure 4-1 presents sample graphs of outdoor benzene concentration (95th percentile) versus distance produced by the program. The specified conditions were benzene emission rate = 1 ton/year, vent velocity = 2.93 ft/sec, and vent diameter = 2 inches. Separate graphs are provided for urban and rural land use. Figure 4-2 shows the same data plotted on a log-log scale.

The reader should note that this model is based on the implicit assumption that the dispersion modeling results for the specified set of 348 meteorological stations provide an unbiased representation of the distribution of benzene concentration in the vicinity of a randomly selected glycol dehydrator unit. The reader should also note that the benzene concentration estimated by the model represents the incremental contribution of the glycol dehydrator to the total benzene concentration in the outdoor air. Section 5 provides a methodology for using outputs of the model to estimate incremental benzene exposures from glycol dehydrators and associated incremental cancer risks.

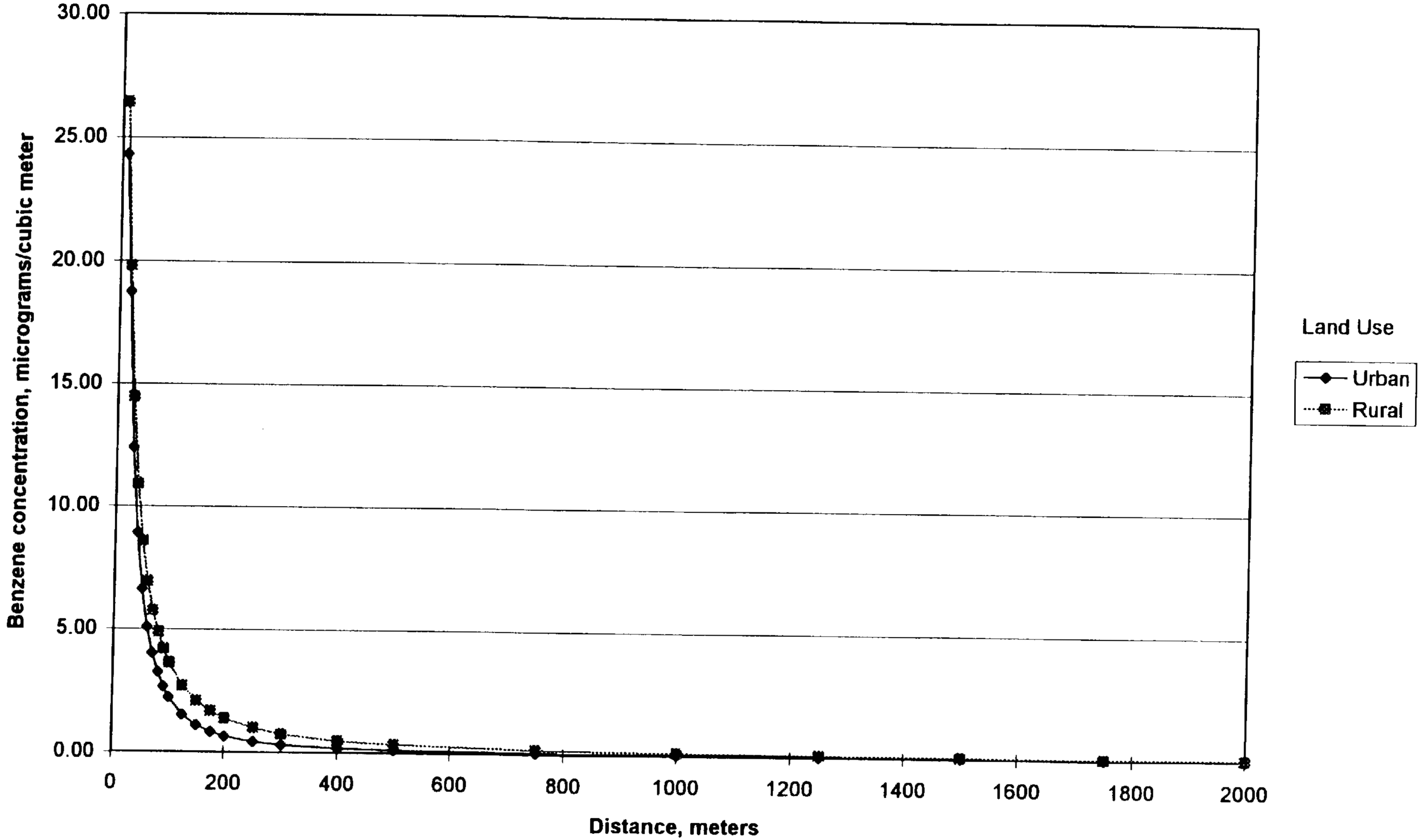

Figure 4-1. Estimated relationships between 95th percentile of outdoor benzene concentration (µg/m³) and distance (meters) from glycol dehydrator for specified emission conditions (benzene emission rate = 1 ton/year, vent velocity = 2.93 ft/sec, vent diameter = 2 inches).

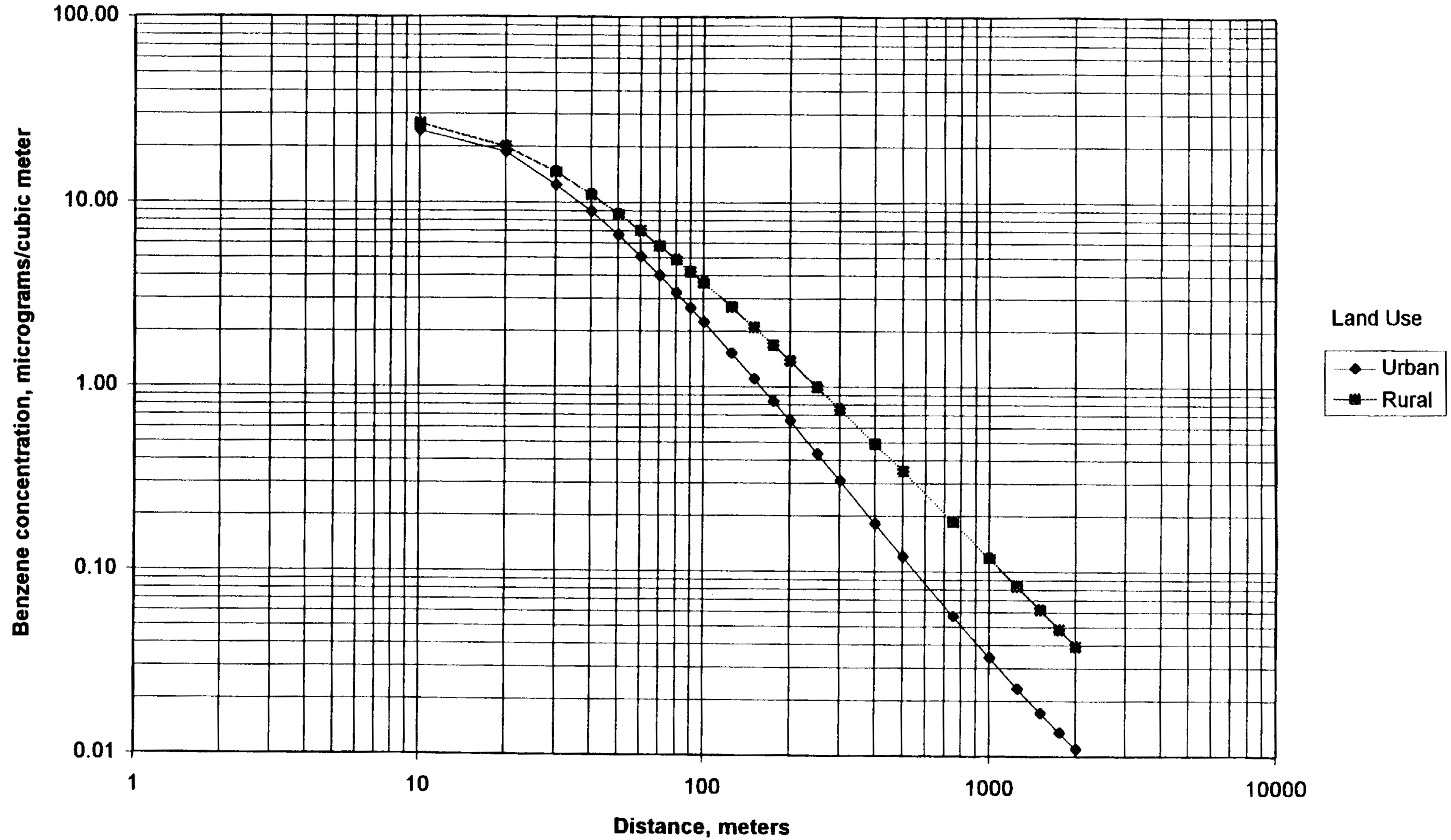

Figure 4-2. Log-log plots showing estimated relationships between 95th percentile of outdoor benzene concentration ($\mu g/m^3$) and distance (meters) from glycol dehydrator for specified emission conditions (benzene emission rate = 1 ton/year, vent velocity = 2.93 ft/sec, vent diameter = 2 inches).

Section 5
ESTIMATING INCREMENTAL BENZENE EXPOSURES AND ASSOCIATED CANCER RISKS

SIMRISK

The model described in Section 4 provides the parameters of a lognormal distribution for a specified distance and set of emission conditions. As previously noted, this distribution represents the incremental contribution of the glycol dehydrator unit to the total benzene concentration in the outdoor air.

TRJ developed a Monte Carlo procedure that can be applied to the lognormal distribution to estimate the lifetime risk of cancer associated with exposure to benzene emitted by the glycol dehydrator unit. The entire process has been incorporated into a PC-based model called SimRisk. SimRisk consists of two basic modules:

Outdoor concentration:	provides distributions of outdoor benzene concentrations at specified distances for a particular emission scenario (i.e., benzene emission rate, vent velocity, vent diameter, and land use).
Lifetime risk:	provides distributions of lifetime cancer risks at specified distances based on the distribution of outdoor benzene concentrations and exposure factors.

The outdoor concentration module determines the parameters of a lognormal distribution for each of 24 distances between 10 m and 2000 m. The parameters are estimated using regression equations (Table 4-4) fit to dispersion modeling results for selected emission scenarios applied to 348 meteorological stations.

The lifetime risk module operates on the lognormal distributions provided by the outdoor concentration module. The module randomly generates an outdoor benzene concentration and an exposure pattern for each of n simulated persons, where n is a number (typically 1000+) selected by the model user. Each exposure pattern is defined by five exposure factors:

1. Residential occupancy period;
2. Number of hours per day spent at the residential location;
3. Number of hours per day spent outdoors at the residential location;
4. Indoor/outdoor ratio for residence; and
5. Ventilation ratio.

The model randomly selects a value for each factor from a distribution specified by the user. The following subsection provides recommendations for these distributions.

DEFAULT DISTRIBUTIONS FOR EXPOSURE FACTORS

Residential occupancy period (Y_{ROP}) is defined as the number of years between the date that a person moves into a new residence and the date that a person moves out of the residence or dies. SimRisk assigns a value of Y_{ROP} to each simulated person. The Y_{ROP} value determines the total number of years that the person has the potential for exposure to benzene emitted by the glycol dehydrator. Under default assumptions, the Y_{ROP} value is randomly selected from a distribution considered to be representative of the general U.S. population (Table 5-1). This distribution was generated by applying Monte Carlo techniques to recent data on mobility and mortality for the general U.S. population. The procedure is described in a report by Johnson and Capel (1992).

SimRisk also assigns a value to each simulated person for the number of hours per day spent at the residential location (H_{res}). The model assumes that all exposure to benzene emitted by glycol dehydrators occurs at a person's residential location. Under default assumptions, the H_{res} value is randomly selected from a triangular distribution with a lower limit of 8 hours, a peak probability at 16.37 hours, and an upper limit of 24 hours. The lower and upper limits are based on the assumption that a person will spend at least 8 hours at home each day and no more than 24 hours. The peak probability value (16.37 hours) was obtained from a recent national survey of time/activity patterns (Robinson, 1996). The value is the sum of the average time durations for 16 home-based activities identified by Robinson.

Table 5-1. Default assumptions for the exposure factors used in SimRisk runs.

*Parameter	Distribution	Value	Cumulative percentage
H_{res}	triangular	minimum = 8 h peak = 16.37 h maximum = 24 h	0 52.3 100
H_{out}	point estimate	1 h	
$R_{I/O}$	triangular	minimum = 0.72 maximum = 1.00	0 100
R_{vent}	lognormal	GM = 0.9384 GSD = 1.4391	50 not applicable
Y_{ROP}	histogram	0 years 2 years 4 years 9 years 16 years 26 years 33 years 41 years 47 years 51 years 55 years 59 years 87 years	0 10 25 50 75 90 95 98 99 99.5 99.8 99.9 100

*H_{res} = number of hours per day spent at the residential location.
H_{out} = number of hour per day spent outdoors at the residential location.
$R_{I/O}$ = ratio of indoor to outdoor benzene concentration for homes free of indoor benzene sources.
R_{vent} = ratio of daily average ventilation rate (m3/day) of a particular person to average daily ventilation rate of all people.
Y_{ROP} = number of years between the date that a person moves into a new residence and the date that a person moves out of the residence.

The time spent at home (H_{res}) is divided into indoor and outdoor periods by assigning each person a value for number of hours per day spent outdoors at the residential location (H_{out}). Data provided by Robinson (1996) suggest that the average person spends only 43 minutes per day outdoors in the vicinity of his or her residence. SimRisk uses a conservative point estimate of 1 hour per day as the default value of H_{out}.

Indoor/outdoor benzene ratio is defined as the long-term average ratio of indoor benzene concentration to outdoor benzene concentration for homes that are free of indoor benzene sources. Data for estimating this quantity are relatively scarce; past studies have usually measured indoor/outdoor ratios in residences with known or suspected indoor benzene sources. In such cases, the calculated indoor/outdoor ratio usually exceeds 1.00.

In preliminary EPA risk assessments, REAG represented the distribution of indoor/outdoor ratio by a triangular distribution with a lower limit of 0.38, an upper limit of 1.00, and a most probable value of 0.90. The lower limit (0.38) is based on statistical analyses of data collected by EPA in the Baltimore TEAM study (Johnson *et al.*, 1993). This value is questionable, as it requires that a highly effective benzene removal mechanism be present within the residence. No such removal mechanism has been positively identified to date. The upper limit (1.00) is the maximum possible value for the indoor/outdoor ratio and corresponds to the complete absence of removal mechanisms. REAG has characterized the estimate of the most probable value (0.90) as an informed guess.

Ms. Jill Mozier of IT Air Quality Services recently completed a survey of the scientific literature relating to indoor/outdoor ratios for benzene (Johnson *et al.*, 1996). The survey identified only seven studies in which researchers measured indoor/outdoor ratios in homes considered to be free of benzene sources, two of which were conducted in Japan. Based on the limited data available from these studies, Ms. Mozier suggests that the indoor/outdoor ratio should fall between 0.72 and 1.00 with the most probable value being 1.00 (personal communication, March 6, 1996). These estimates are the basis of the default indoor/outdoor ($R_{I/O}$) distribution presented in Table 5-1. The distribution is a triangular distribution with a lower limit of 0.72, an upper limit of 1.00, and a most probable value of 1.00.

According to the Integrated Risk Information System (IRIS), the inhalation unit risk estimate (URE) for benzene is 8.3×10^{-6} $(\mu g/m^3)^{-1}$. Although the value is based on occupational health studies of adult workers, EPA applies it to other population groups based on the assumption that cancer risk is independent of body size under average ventilation conditions. According to Robert McCaughy of EPA (personal communication, March 8, 1996), it is reasonable to adjust the URE to account for variations in people's activities. To perform this adjustment, SimRisk multiplies the URE by ventilation ratio (R_{vent}). This parameter is defined as the ratio of the daily ventilation rate (m^3/day) of a particular person to the average daily ventilation rate of all people, after all ventilation rates have been adjusted for body size. By definition, the ratio is greater than 1 for active people and less than 1 for inactive people.

There have been few studies which have measured the ventilation rates of ordinary people for extended periods of time as they pursue typical daily activities. Four such studies have been conducted by a team directed by Dr. Jack Hackney. Each study used experimental subjects representing one of the following groups: elementary school students, high school students, outdoor workers, and construction workers. The pulse rate of each subject was monitored over a 16 to 24 hour period as the subject completed an activity diary. The minute-average pulse rates were converted to corresponding estimates of minute-average ventilation rate using a calibration curve specific to each subject. The calibration curve was developed by measuring pulse rate and ventilation rate simultaneously as the subject completed a graduated series of exercise tests. The ventilation rates were subsequently converted to equivalent ventilation rate (EVR) by dividing each ventilation rate value by the estimated body surface area of the subject.

In earlier work, Ted Johnson analyzed the EVR data from the four Hackney studies to identify factors that could be used to predict EVR values in Monte Carlo simulations (Johnson and McCoy, 1995). As part of the current study, Ted Johnson compiled daily average EVR values for the 74 subjects who participated in the four Hackney studies. These daily average EVR values were converted to "normalized" EVR values by dividing each individual value by the group mean (11.396 liters min^{-1} m^{-2}). The resulting empirical distribution had an arithmetic mean of 1.0000 and an arithmetic standard deviation of 0.3577. The empirical distribution was found to be well fit by a lognormal distribution with a geometric mean of 0.9384 and a geometric standard deviation of 1.4391. This lognormal distribution is proposed as the default distribution for R_{vent}. The proposal is based on the assumption that the conversion of ventilation rate to normalized EVR removed all variability attributable to differences in body size. The remaining variability in the distribution of normalized EVR is assumed to represent person-to-person differences in activity levels.

CALCULATION OF LIFETIME RISK

As previously discussed, SimRisk constructs an exposure pattern for each simulated person. The exposure pattern can be used to estimate the total mass of benzene respired over the person's lifetime using the following equation:

$$M_{lifetime} = (365 \text{ days/yr})(C_{out})[(H_{res} - H_{out})(R_{I/O}) + H_{out}](V_{avg})(R_{vent})(Y_{ROP})/(24 \text{ hrs}). \quad (8)$$

The variables are defined as follows:

$M_{lifetime}$ = total mass of benzene respired over the person's lifetime (μg)
C_{out} = outdoor benzene conc. at residential location (μg/m^3)
H_{res} = time per day spent at residential location (hours)
H_{out} = time per day spent outdoors at residential location (hours)
$R_{I/O}$ = indoor/outdoor benzene ratio
V_{avg} = average daily ventilation rate (m^3/day)
R_{vent} = ratio of individual ventilation rate to average ventilation rate
Y_{ROP} = residential occupancy period (years)

Note that the variables C_{out} and $M_{lifetime}$ apply only to benzene emitted by the glycol dehydrator unit.

The $M_{lifetime}$ value can be converted to a corresponding cancer risk probability by the equation:

$$I_{lifetime} = (M_{lifetime})(URE)/(N_{lifetime}) \quad (9)$$

in which

$I_{lifetime}$ = lifetime risk of cancer

URE = unit risk estimate = 8.3 x 10^{-6} ($\mu g/m^3)^{-1}$

$N_{lifetime}$ = unit lifetime mass estimate (μg)

The unit lifetime mass estimate ($N_{lifetime}$) is defined here as "the respired benzene mass that produces a risk probability of 8.3 x 10^{-6} in the average person." EPA estimates that the continual exposure of an average person to a benzene concentration of 1 $\mu g/m^3$ for 70 years will produce a risk probability of 8.3 x 10^{-6}. Consequently, the value of $N_{lifetime}$ can be calculated by the expression

$$N_{lifetime} = (70 \text{ years})(365 \text{ days/year})(V_{avg})(1\ \mu g/m^3) \quad (10)$$

in which

V_{avg} = average daily ventilation rate (m^3/day).

Making the appropriate substitutions, Equation 9 can be expressed as

$$I_{lifetime} = (C_{out})[(H_{res} - H_{out})(R_{I/O}) + H_{out}](R_{vent})(Y_{ROP})(8.3 \times 10^{-6})/[(24 \text{ hrs})(70 \text{ yrs})(1\ \mu g/m^3)]. \quad (11)$$

SimRisk uses this equation to estimate the cancer risk of each simulated person. The residence of the simulated person is assumed to be located at a specified distance (10 to 2000 meters) from the glycol dehydrator unit. The value of C_{out} is determined by randomly selecting a value from the lognormal distribution determined by the procedure described in Section 4. Table 4-4 outlines the selection procedure. Note that the parameters of the lognormal distribution are functions of the specified distance, land use, and benzene emission conditions (benzene emission rate, vent velocity, and vent diameter).

SimRisk determines the value for each of the remaining variables in Equation 11 by either (1) randomly sampling a distribution specified for the variable or (2) using a specified point estimate. Table 5-1 provides defaults for these distributions and point estimates.

A value of $I_{lifetime}$ is determined for each of n simulated persons residing at a given distance. SimRisk performs the calculations for 24 distances between 10 and 2000 meters. The following example shows how SimRisk calculated the cancer risk for one simulated person in one run of the program:

<u>Example SimRisk Calculation</u>

1. The user specified the following emission conditions:

   benzene emission rate = 1 ton/year

   vent velocity = 2.93 feet/sec

   vent diameter = 2 inches

   land use = urban

   distance to emission source = 300 m.

2. Following Steps 1 through 4 in Table 4-4, the outdoor concentration module calculated the following parameter values for the lognormal distribution of C_{out} at distance = 300 meters (urban land use).

   Geometric mean = 0.116 $\mu g/m^3$

   Geometric standard deviation = 1.813 (dimensionless).

3. Following Steps 5 and 6 in Table 4-4, the SimRisk program randomly selected the value z = -0.970 to yield the value C_{out} = 0.065 $\mu g/m^3$.

4. The SimRisk program randomly selected the following values from the distributions listed in Table 5-1.

   H_{res} = 13.54 hours

   H_{out} = 1 hour

   $R_{I/O}$ = 0.936

   R_{vent} = 0.874

   Y_{ROP} = 37.45 years

5. SimRisk used Equation 11 to calculate the following estimate of lifetime risk for one simulated person at distance = 300 m:

   $I_{lifetime} = 1.34 \times 10^{-7}$.

SimRisk performs Steps 3 through 5 for each of n iterations to produce a simulated population of n persons residing at distance = 300 m. The risks assigned to these n persons provide a risk distribution for the specified distance (Figure 5-1). The entire process is repeated for each of 24 distances between 10 m and 2000 m. SimRisk plots these results as distribution percentiles versus distance.

The graph in Figures 5-1 presents the results of a complete SimRisk run for the same emission scenario (i.e., benzene emission rate = 1 ton/year, vent velocity = 2.93 ft/sec, vent diameter = 2 inches, and land use = urban). The SimRisk run produced 1000 lifetime risk estimates for each of the 24 distances. Figure 5-2 plots the 50th percentile of the risk estimates at each distance. (Note that the distance scale is not linear for distances greater than 100 m.)

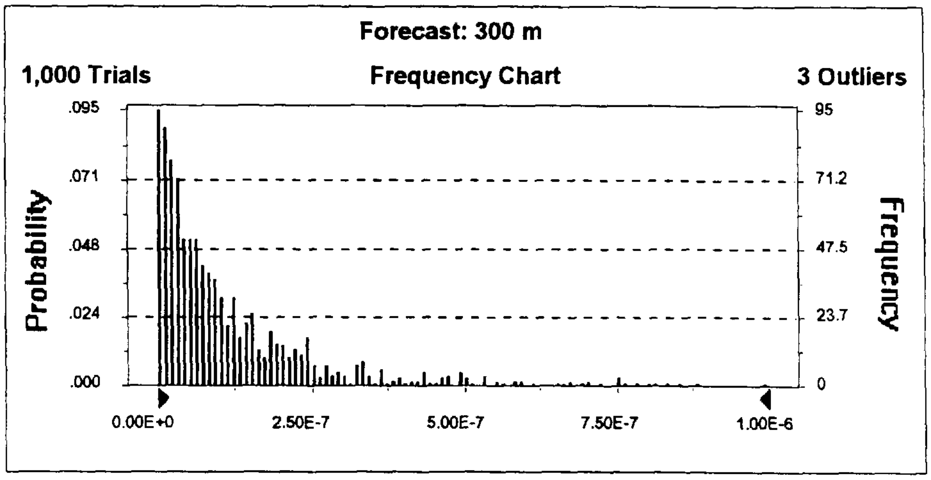

Figure 5-1. Estimated frequency of lifetime risk when distance to glycol dehydrator equals 300 meters (benzene emission rate = 1 ton/year, vent velocity = 2.93 ft/sec, vent diameter = 2 inches, and land use = urban).

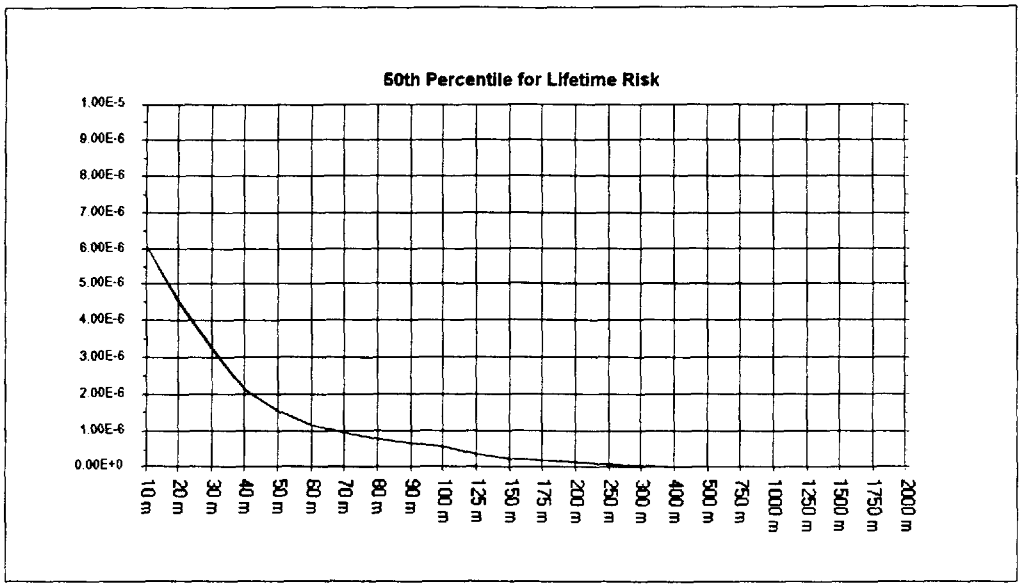

Figure 5-2. Estimate of the 50th percentile of lifetime risk versus distance from glycol dehydrator (benzene emission rate = 1 ton/year, vent velocity = 2.93 ft/sec, vent diameter = 2 inches, and land use = urban).

Section 6

A SIMPLIFIED METHOD FOR ESTIMATING 50TH AND 95TH PERCENTILE VALUES OF LIFETIME RISK

The risk distributions produced by multiple runs of SimRisk were analyzed with the goal of developing a method for predicting the output of the model given only the input conditions. Such methods are designated "repro models" as they reproduce the results of a complex model without requiring that the complex model be run by the user. With respect to the SimRisk model, researchers desired a repro model that would estimate the 50th and 95th percentiles of the lifetime risk distribution at each distance without having to perform the Monte Carlo simulation.

A review of SimRisk outputs indicated that the 50th and 95th percentile values for lifetime risk at each distance were highly correlated with GM, the geometric mean value of the outdoor benzene concentration determined for the distance. In addition, the relationships were relatively constant for distances from 10 m to 2000 m. The following equations were developed to represent these relationships:

50th percentile lifetime risk ($I_{lifetime\text{-}50}$)

$$\text{Urban: } I_{lifetime\text{-}50} = (5.733 \times 10^{-7})(GM) \tag{12}$$

$$\text{Rural: } I_{lifetime\text{-}50} = (5.724 \times 10^{-7})(GM) \tag{13}$$

95th percentile lifetime risk ($I_{lifetime\text{-}95}$)

$$\text{Urban: } I_{lifetime\text{-}95} = (3.505 \times 10^{-6})(GM) \tag{14}$$

$$\text{Rural: } I_{lifetime\text{-}95} = (3.533 \times 10^{-6})(GM) \tag{15}$$

In the full SimRisk model, GM is estimated by the equation

$$GM = (e^{LNRATIO})(BER) \tag{16}$$

where BER is the benzene emission rate of the glycol dehydrator and LNRATIO is estimated by the regression equations listed in Table 4-4. TRJ found the following alternative set of regression equations could be used to estimate LNRATIO:

$$\text{Urban: } LNRATIO = 7.84825 - (1.76785)[\ln(D)] \tag{17}$$
$$\text{Rural: } LNRATIO = 6.84611 - (1.45381)[\ln(D)] \tag{18}$$

Note that distance (D) is the only independent variable in each equation. Researchers found that vent velocity and vent diameter could be omitted from the regression equations with a negligible reduction in R^2 value. (The R^2 values for equations 17 and 18 each exceeded 0.995.) However, it should also be noted that the regression analyses omitted distances of 10 m and 20 m, as the relationship between LNRATIO and ln(D) was found to be non-linear when these values were included. Consequently, Equations 17 and 18 are not recommended for use with distances less than 30 m.

Using the relationship in Equation 16, one can derive the following equations from Equations 17 and 18, respectively:

$$\text{Urban: } GM = (2561)(BER)(D^{-1.76785}) \tag{19}$$
$$\text{Rural: } GM = (940.2)(BER)(D^{-1.45381}) \tag{20}$$

With appropriate substitutions, Equations 12 through 15 can be expressed as follows:

50th percentile lifetime risk ($I_{lifetime\text{-}50}$)

$$\text{Urban: } I_{lifetime\text{-}50} = (1.468 \times 10^{-3})(BER)(D^{-1.76785}) \tag{21}$$
$$\text{Rural: } I_{lifetime\text{-}50} = (5.382 \times 10^{-4})(BER)(D^{-1.45381}) \tag{22}$$

95th percentile lifetime risk ($I_{lifetime\text{-}95}$)

$$\text{Urban: } I_{lifetime\text{-}95} = (8.977 \times 10^{-3})(BER)(D^{-1.76785}) \tag{23}$$
$$\text{Rural: } I_{lifetime\text{-}95} = (3.322 \times 10^{-3})(BER)(D^{-1.45381}) \tag{24}$$

These equations provide a means for estimating the 50th and 95th percentile values of lifetime risk as a simple function of land use, emission rate, and distance. The graph in Figure 6-1 plots Equation 21 (50th percentile, urban land use) when BER = 1, 3, 5, and 7 tons/year. Figures 6-2, 6-3, and 6-4 plot similar graphs for Equations 22, 23, and 24, respectively.

Solving Equations 21 through 24 for distance (D) yields the following equations:

Distance associated with 50th percentile lifetime risk (D_{50})

Urban: $D_{50} = \{(I_{lifetime\text{-}50})/[(1.468 \times 10^{-3})(BER)]\}^{-0.56566}$ (25)

Rural: $D_{50} = \{(I_{lifetime\text{-}50})/[(5.382 \times 10^{-4})(BER)]\}^{-0.68785}$ (26)

Distance associated with 95th percentile lifetime risk (D_{95})

Urban: $D_{95} = \{(I_{lifetime\text{-}95})/[(8.977 \times 10^{-3})(BER)]\}^{-0.56566}$ (27)

Rural: $D_{95} = \{(I_{lifetime\text{-}95})/[(3.322 \times 10^{-3})(BER)]\}^{-0.68785}$ (28)

The graph in Figure 6-5 plots Equation 25 when $I_{lifetime\text{-}95} = 10^{-4}$, 10^{-5}, and 10^{-6}. Equations 26, 27, and 28 are plotted in Figures 6-6, 6-7, and 6-8, respectively.

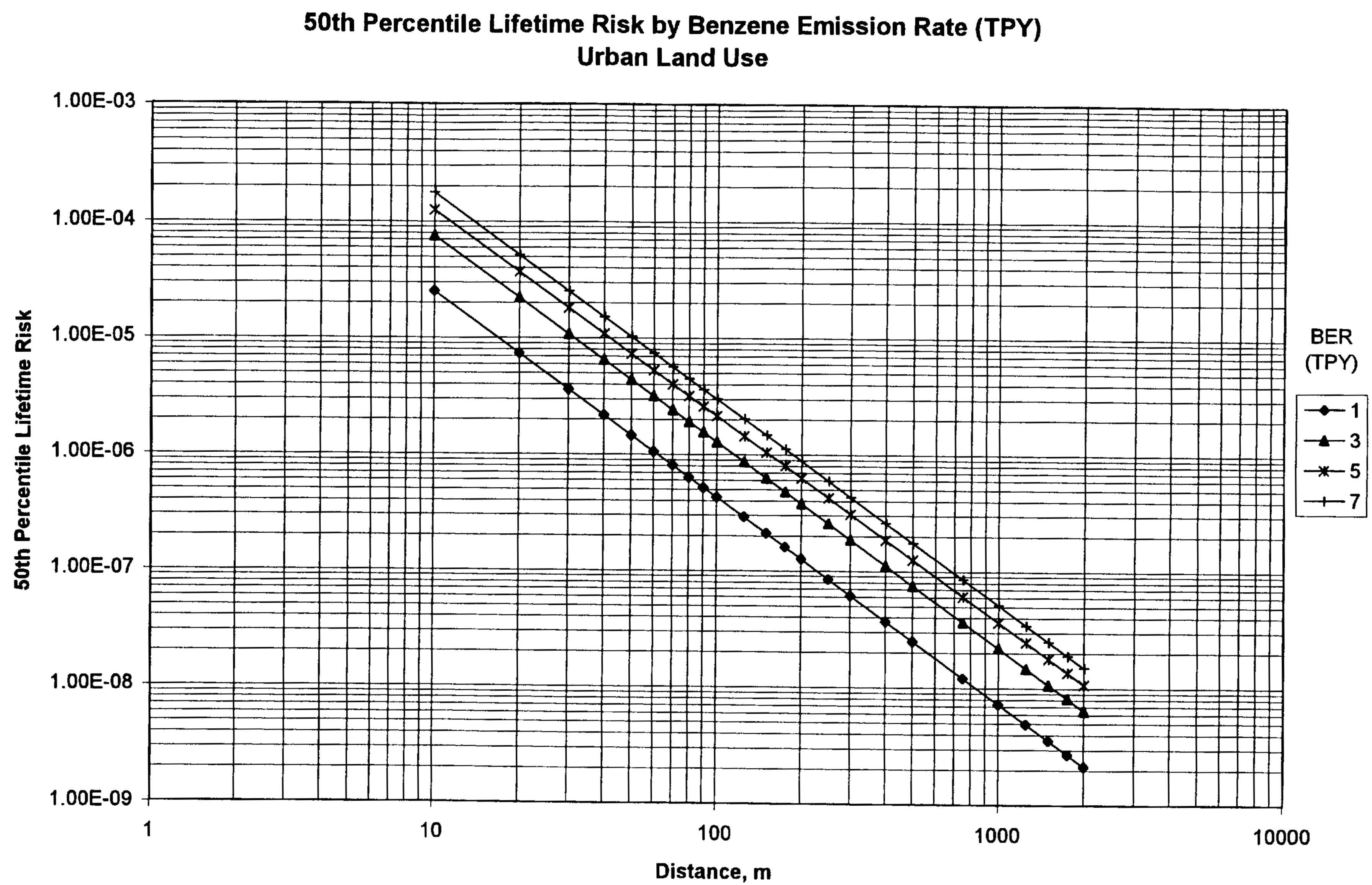

Figure 6-1. Estimate of the 50th percentile of lifetime risk versus distance (meters) for indicated benzene emission rate (tons/year) and urban land use (2 inches $\leq$ vent diameter $\leq$ 4 inches, 3.21 ft/sec $\leq$ vent velocity $\leq$ 20.3 ft/sec).

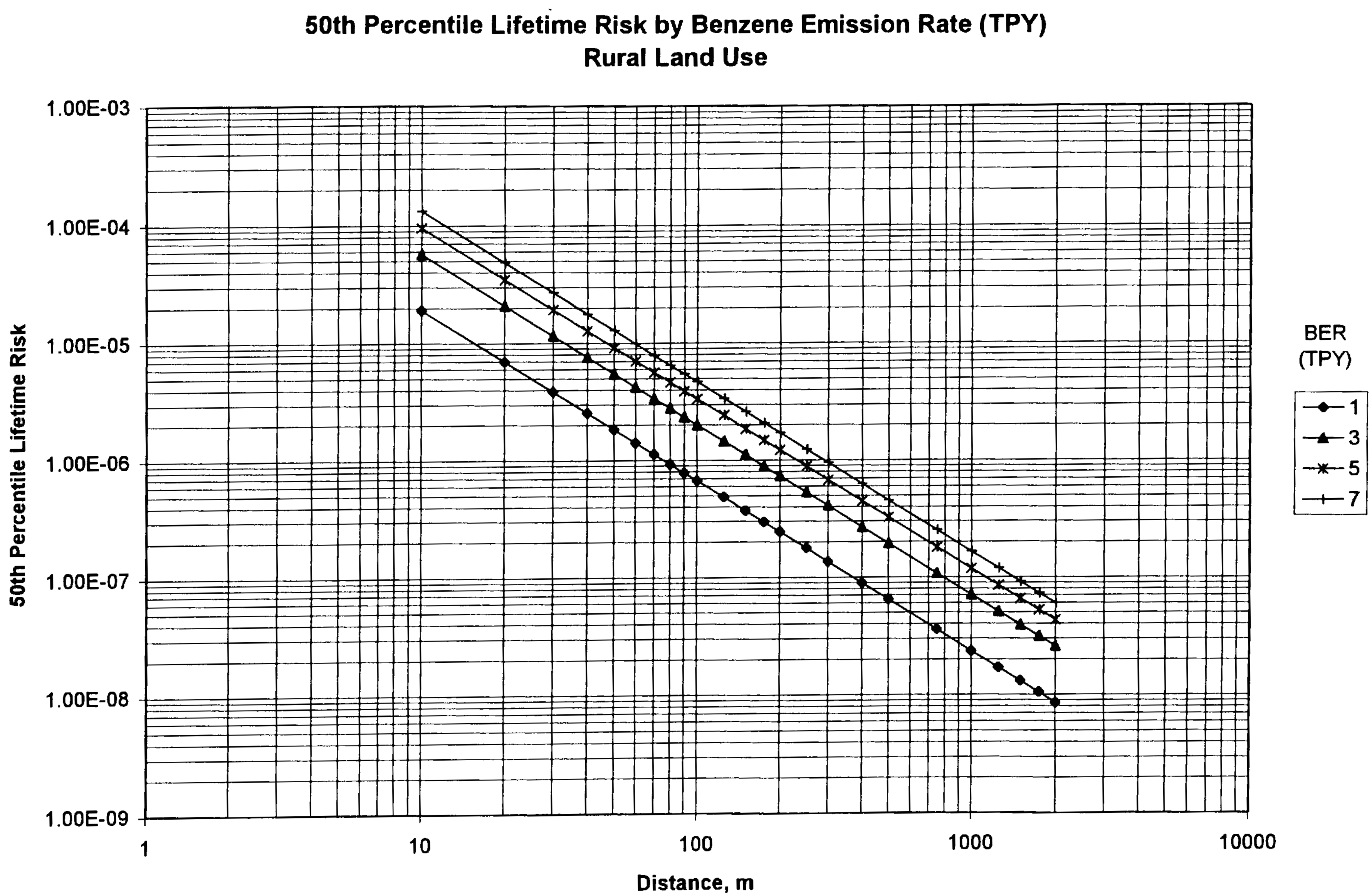

Figure 6-2. Estimate of the 50th percentile of lifetime risk versus distance (meters) for indicated benzene emission rate (tons/year) and rural land use (2 inches ≤ vent diameter ≤ 4 inches, 3.21 ft/sec ≤ vent velocity ≤ 20.3 ft/sec).

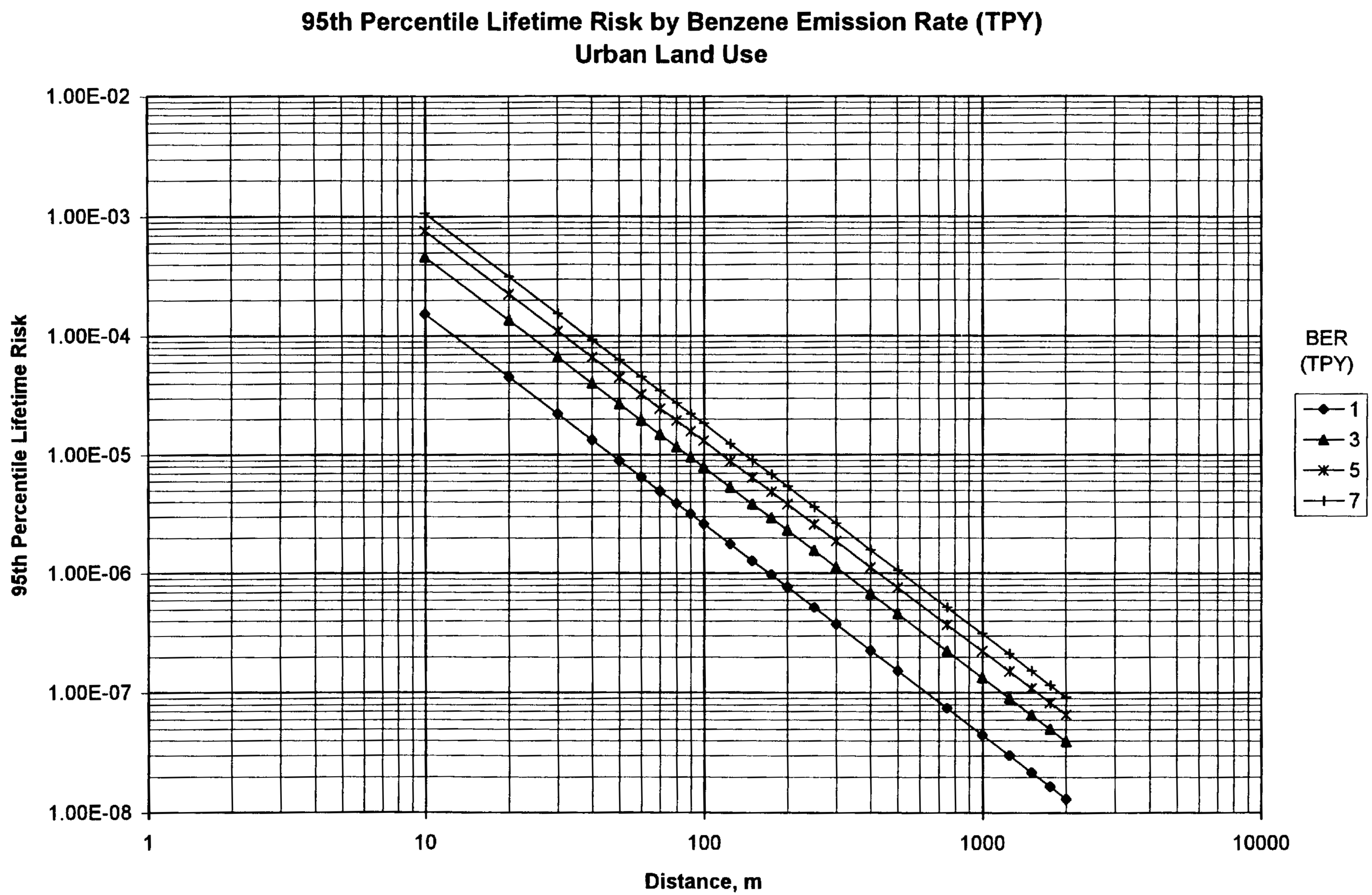

Figure 6-3. Estimate of the 95th percentile of lifetime risk versus distance (meters) for indicated benzene emission rate (tons/year) and urban land use (2 inches ≤ vent diameter ≤ 4 inches, 3.21 ft/sec ≤ vent velocity ≤ 20.3 ft/sec).

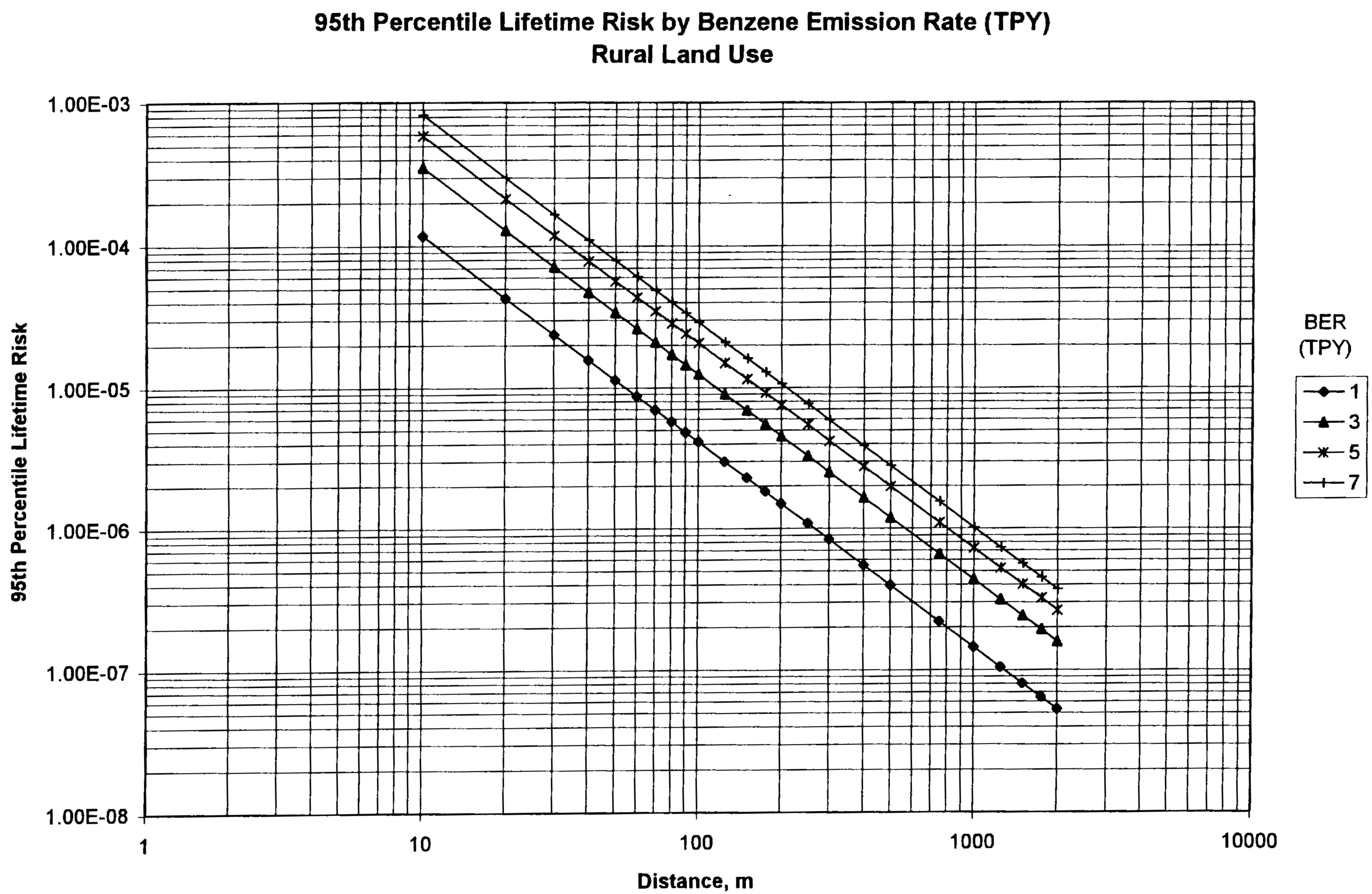

Figure 6-4. Estimate of the 95th percentile of lifetime risk versus distance (meters) for indicated benzene emission rate (tons/year) and rural land use (2 inches ≤ vent diameter ≤ 4 inches, 3.21 ft/sec ≤ vent velocity ≤ 20.3 ft/sec).

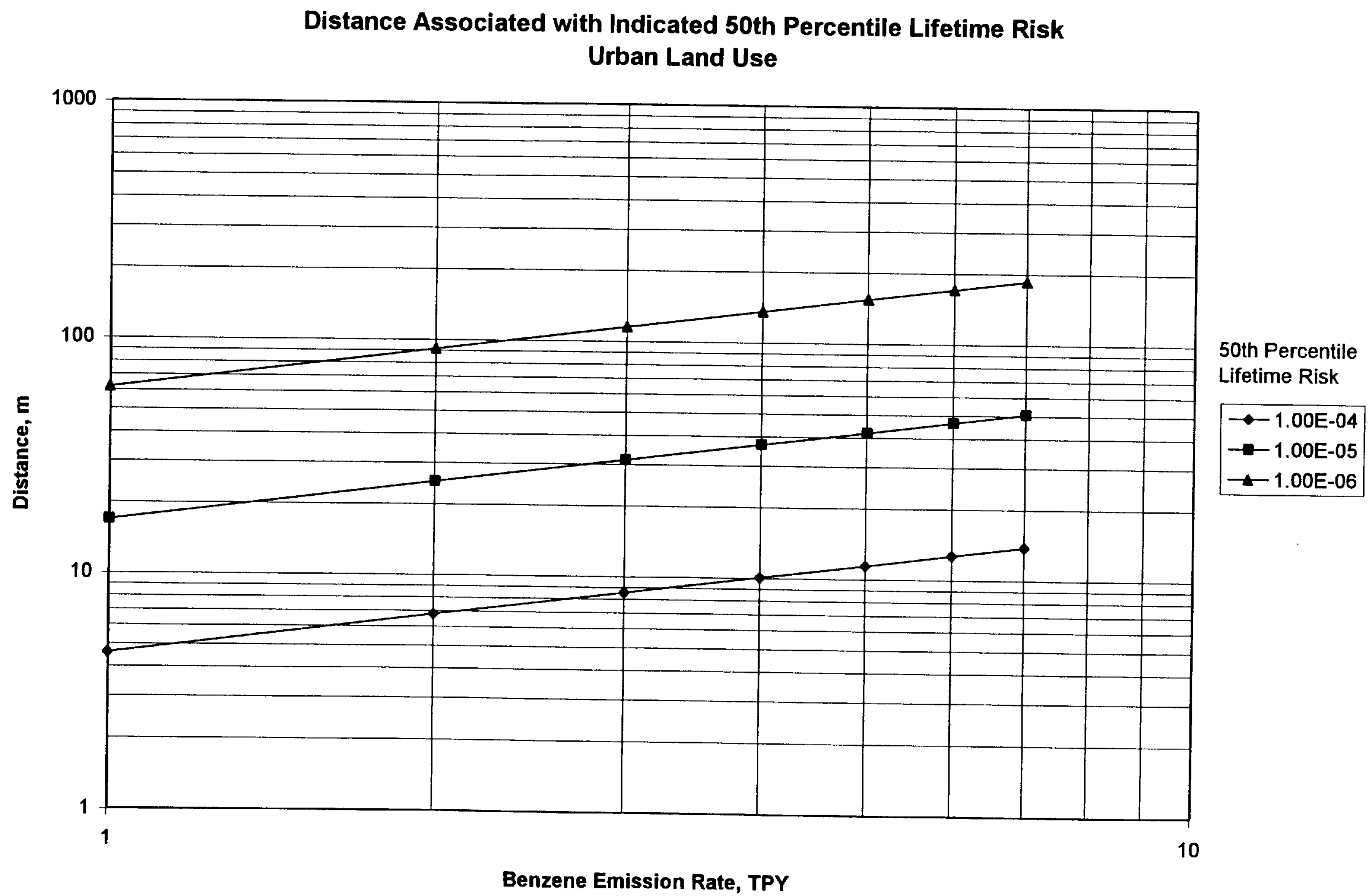

Figure 6-5. Estimate of the distance (meters) associated with the indicated 50th percentile lifetime risk versus benzene emission rate (tons/year) for urban land use (2 inches $\leq$ vent diameter $\leq$ 4 inches, 3.21 ft/sec $\leq$ vent velocity $\leq$ 20.3 ft/sec).

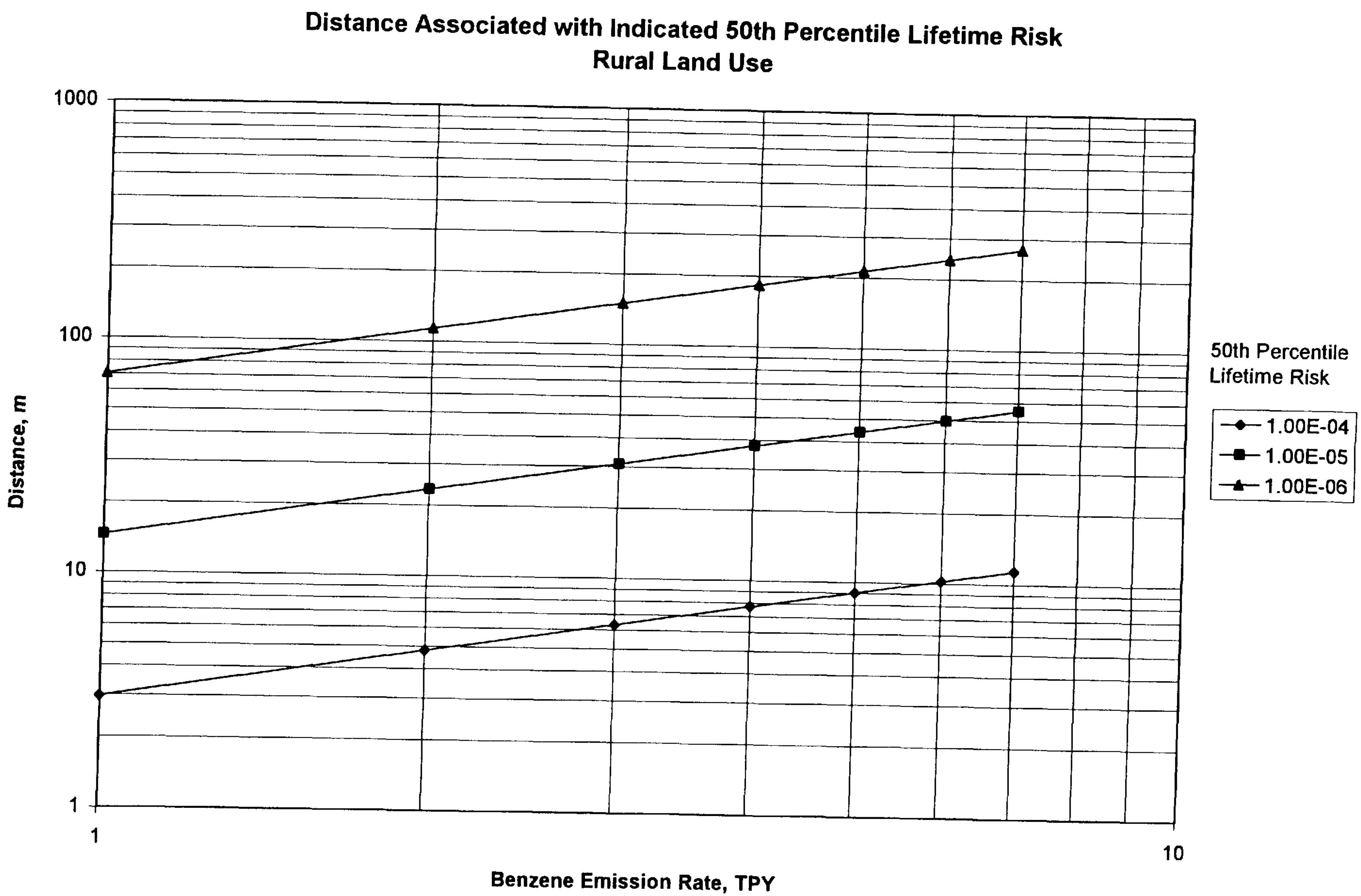

Figure 6-6. Estimate of the distance (meters) associated with the indicated 50th percentile lifetime risk versus benzene emission rate (tons/year) for rural land use (2 inches $\leq$ vent diameter $\leq$ 4 inches, 3.21 ft/sec $\leq$ vent velocity $\leq$ 20.3 ft/sec).

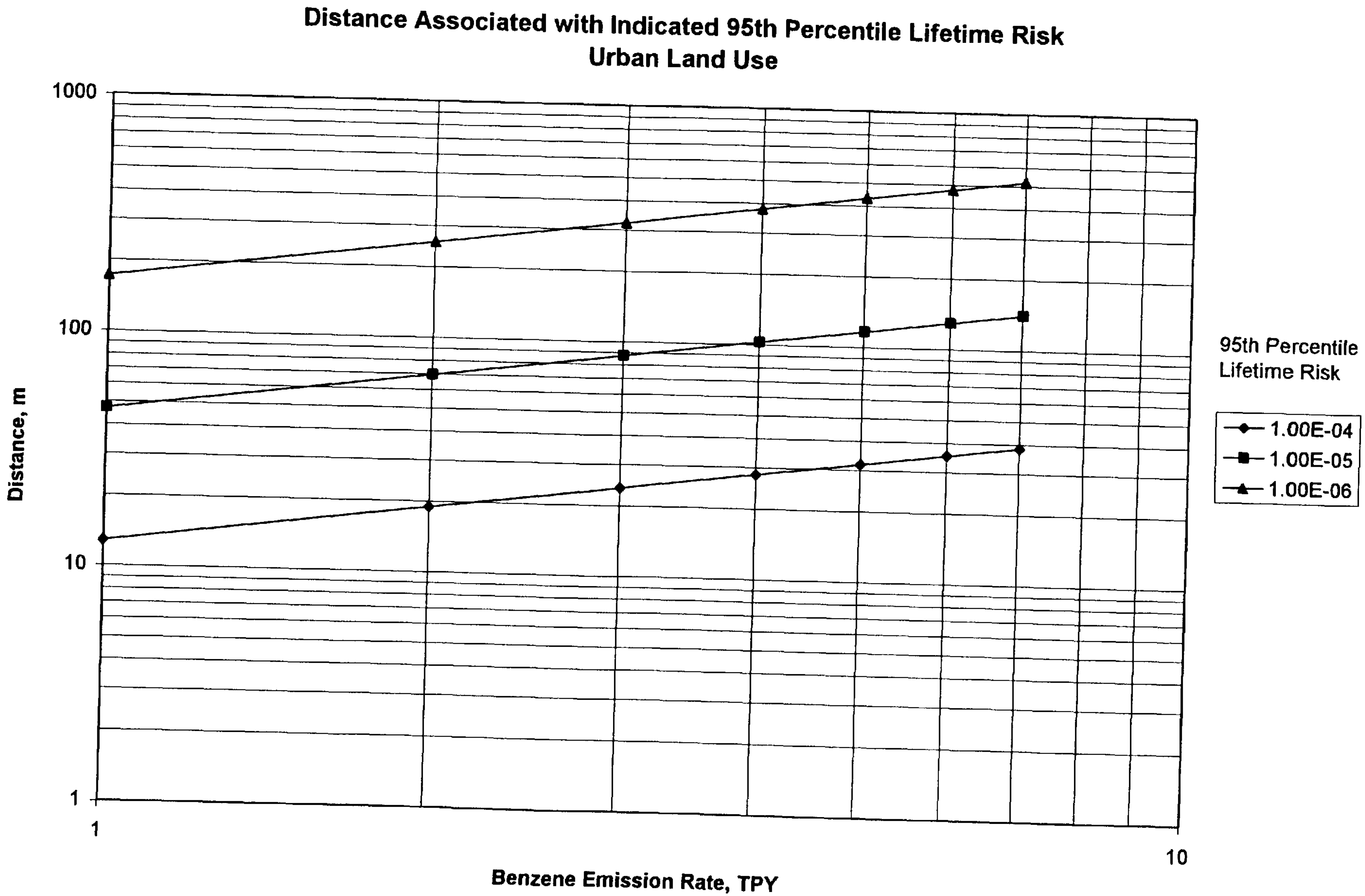

Figure 6-7. Estimate of the distance (meters) associated with the indicated 95th percentile lifetime risk versus benzene emission rate (tons/year) for urban land use (2 inches $\leq$ vent diameter $\leq$ 4 inches, 3.21 ft/sec $\leq$ vent velocity $\leq$ 20.3 ft/sec).

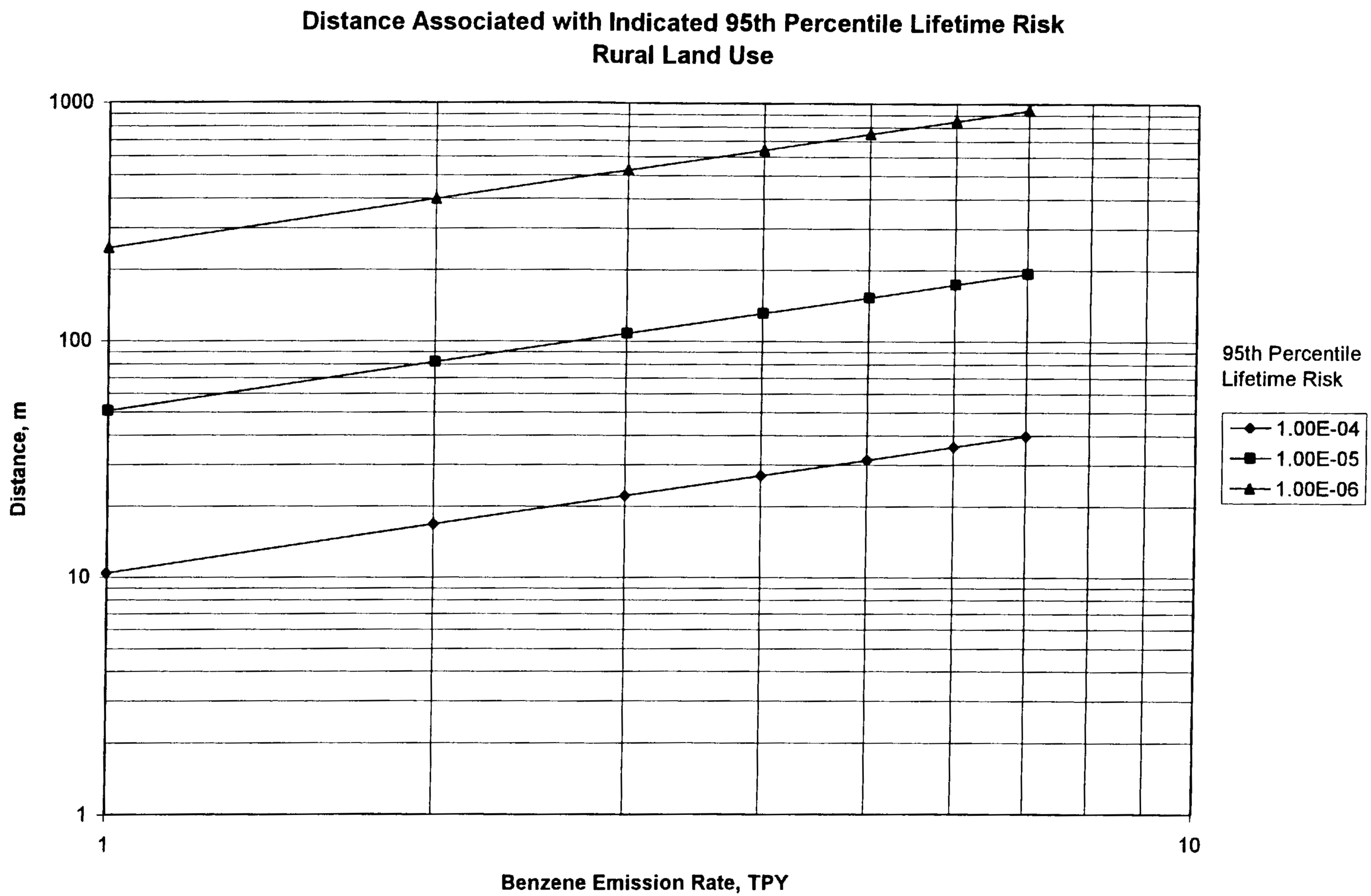

Figure 6-8. Estimate of the distance (meters) associated with the indicated 95th percentile lifetime risk versus benzene emission rate (tons/year) for rural land use (2 inches $\leq$ vent diameter $\leq$ 4 inches, 3.21 ft/sec $\leq$ vent velocity $\leq$ 20.3 ft/sec).

Section 7
DISCUSSION

Section 5 presented a model incorporating Monte Carlo procedures (SimRisk) for determining the distribution of excess lifetime cancer risks associated with benzene emissions from glycol dehydrators. The model provides risk estimates that are specific to source-to-receptor distance, benzene emission rate, vent velocity, vent diameter, and land use. The model is based on the results of statistical analyses performed on a database containing 1.3 million simulated outdoor benzene concentrations. This database was produced by dispersion model runs which applied 24 emission scenarios to 348 meteorological stations.

The SimRisk model is based on dispersion modeling data which represent the following ranges of distances and emission conditions:

$$10 \text{ m} \leq \text{distance} \leq 2000 \text{ m}$$
$$2 \text{ inches} \leq \text{vent diameter} \leq 4 \text{ inches}$$
$$1 \text{ ton/year} \leq \text{emission rate} \leq 7 \text{ tons/year}$$
$$3.21 \text{ feet/sec} \leq \text{vent velocity} \leq 20.3 \text{ feet/sec.}$$

The user should note that the model may not perform well outside of these ranges. In particular, the user is cautioned against using SimRisk (Section 5) for distances less than 10 m. The simplified method described in Section 6 should not be used for distances less than 30 m.

The simplified method for estimating risk described in Section 6 could be used to develop applicability criteria for glycol dehydrator emission controls. The analyst would use Equation 25 or 26, depending on land use, to determine the source-to-receptor distance associated with a specified risk. This distance would be designated the "minimum-permitted separation distance" (MPSD). The MPSD would be compared to the actual distance separating the unit from the nearest residence, designated the "nearest-residence separation distance" (NRSD). If the NRSD exceeds the MPSD, the glycol dehydrator unit is assumed to require no further controls. If the NRSD is equal to or less than the MPSD, the unit may be subject to additional controls.

The following example illustrates the application of this method. A glycol dehydrator unit has an estimated benzene emission rate of 7 tons/year. The actual distance from the glycol dehydrator unit to the nearest dwelling in an urban area is known to be approximately 75 meters; i.e., NRSD = 75 meters. If regulators have determined that a risk level of 1×10^{-5} (50th percentile) is an acceptable control applicability criterion, then Equation 25 can be used to determine a value for MPSD as shown below:

$$MPSD = D_{50} = \{(I_{lifetime\text{-}50})/[(1.468 \times 10^{-3})(BER)]\}^{-0.56566}$$

$$MPSD = \{(1 \times 10^{-5})/[(1.468 \times 10^{-3})(7)]\}^{-0.56566}$$

$$MPSD = 50.5 \text{ meters.}$$

Because the NRSD value (75 meters) exceeds the MPSD value (50.5 meters), no controls are necessary.

Section 8

REFERENCES

Johnson, Ted and J. Capel. 1992. *A Monte Carlo Approach to Simulating Residential Occupancy Periods and Its Application to the General U.S. Population*, EPA-450/3-92-011, U.S. Environmental Protection Agency, Research Triangle Park, N.C.

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Johnson, Ted, J. Warnasch, M. McCoy, J. Capel,, and M. Riley. 1996. *Developmental Research for the Hazardous Air Pollutant Exposure Model (HAPEM) as Applied to Mobile Source Pollutants*, IT Corporation, Durham, North Carolina.

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Technical Reference Manual for GRI-ClyCALC™: A Program for Estimating Emissions from Glycol Dehydration of Natural Gas, Version 2.0, Gas Research Institute, July 1994.

U.S. EPA. 1992. *User's Guide for the Industrial Source Complex (ISC2) Dispersion Models*, Volume I - User Instructions, EPA-450/4-92-008a, U.S. Environmental Protection Agency, March 1992.

Appendix A

INITIAL MONTE CARLO ANALYSES BY EPA'S RISK AND EXPOSURE ASSESSMENT GROUP

INITIAL MONTE CARLO ANALYSES BY EPA'S RISK AND EXPOSURE ASSESSMENT GROUP

The work described in this report extends research conducted in 1995 by the Risk and Exposure Assessment Group (REAG) of EPA. REAG acquired meteorological data for the 348 U.S. sites listed in Appendix B from the National Climatic Center in Asheville, North Carolina. The sites included all U.S. meteorological stations for which data were available at the time of the analysis. REAG applied the ISC2-LT dispersion model to each of the 348 sites for four selected benzene emission rates (1, 2, 5, and 9 tons per year). In these runs, the ISC2-LT model was configured to produce estimates of ambient (outdoor) benzene concentration at each of 160 points on a receptor grid surrounding a hypothetical glycol dehydrator unit. The receptor grid was laid out in a polar pattern with ten concentric rings at distances of 10, 20, 30, 50, 100, 200, 300, 500, 1000, and 2000 meters. These rings were intercepted by 16 equally-spaced radial arms extending from the emission source to produce the 160 receptor points. The emission scenarios were defined according to assumptions listed in Table A-1.

REAG created a file listing the maximum benzene concentration from the ISC2-LT run for each meteorological station. In addition, one meteorological station was selected at random to provide a file of benzene concentrations by distance and wind direction. A truncated normal distribution was fit to the benzene concentrations at each of the 10 distances. These truncated normal distributions were adjusted according to the maximum concentrations determined for each distance by applying ISC2-LT to the 348 sites. A separate set of 10 truncated normal distributions were obtained for each of the four emission rates. By applying a Monte Carlo modeling program to these truncated normal distributions, REAG generated a distribution of outdoor benzene concentrations at each distance for each emission rate.

Table A-1. Specifications for ISC2 dispersion model runs performed in 1995 by the Risk and Exposure Assessment Group (U.S. Environmental Protection Agency) using 348 meteorological stations.

Model specification	Value
Release height, feet	12
Release temp., degrees F	225
Stack gas exit flow rate, scf/hr	291
Vent diameter, inches	6[a]
Stack gas exit velocity, ft/sec	0.13[a]
Benzene emission rate, tons/year	1, 2, 5, and 9
Receptor height, meters	0

[a]REAG is not certain these values are representative.

The Monte Carlo modeling program was then used to determine the lifetime cancer risks associated with these outdoor benzene concentrations. The modeling approach explicitly accounted for variability in breathing rate, time spent away from home, residential occupancy period, and indoor/outdoor ratio. Each of these factors was represented by a distribution obtained from the Exposure Factors Handbook or from the scientific literature. The Monte Carlo analysis produced distributions of benzene exposure and associated lifetime risks for hypothetical persons located at each of the 10 distances. It should be noted that high lifetime risks were characterized through the use of upper percentile values (e.g., 95th percentile) rather than as the risk associated with a hypothetical "maximum exposed individual."

Appendix B

348 METEOROLOGICAL STATIONS USED IN DISPERSION MODEL RUNS

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                         LL          IIIIII    SSSSSSSS   ;;;;      11
                         LL            II    SS           ;;;;    1111
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STAR Site	14737	Allentown/Betlehem-Easton Arp	PA	Lat	40.6500	Long	75.4330	For Data Years		XXXXXX
STAR Site	14739	Boston/Logan Int'l Arpt	MA	Lat	42.3670	Long	71.0330	For Data Years		XXXXXX
STAR Site	14740	Hartford/Bradley Int'l Arpt	CT	Lat	41.9330	Long	72.6830	For Data Years		XXXXXX
STAR Site	14742	Burlington/Int'l Arpt	VT	Lat	44.4670	Long	73.1500	For Data Years		XXXXXX
STAR Site	14745	Concord/Municipal Arpt	NH	Lat	43.2000	Long	71.5000	For Data Years		XXXXXX
STAR Site	14751	Harrisburg/Capital City Arpt	PA	Lat	40.2170	Long	76.8500	For Data Years		XXXXXX
STAR Site	14764	Portland/Int'l Jetport	ME	Lat	43.6500	Long	70.3170	For Data Years		XXXXXX
STAR Site	14765	Providence/T F Green State Ar	RI	Lat	41.7330	Long	71.4330	For Data Years		XXXXXX
STAR Site	14768	Rochester/Rochester-Monroe Co	NY	Lat	43.1170	Long	77.6670	For Data Years		XXXXXX
STAR Site	14771	Syracuse/Hancock Int'l Arpt	NY	Lat	43.1170	Long	76.1170	For Data Years		XXXXXX
STAR Site	14777	Wilkes-Barre/Wb-Scranton WSO	PA	Lat	41.3330	Long	75.7330	For Data Years		XXXXXX
STAR Site	14778	Williamsport-Lycoming /County	PA	Lat	41.2500	Long	76.9170	For Data Years		XXXXXX
STAR Site	14820	Cleveland/Hopkins Int'l Arpt	OH	Lat	41.4170	Long	81.8670	For Data Years		XXXXXX
STAR Site	14821	Columbus/Port Columbus Int'l	OH	Lat	40.0000	Long	82.8830	For Data Years		XXXXXX
STAR Site	14822	Detroit/City Airport	MI	Lat	42.4170	Long	83.0170	For Data Years		XXXXXX
STAR Site	14826	Flint/Bishop Arpt	MI	Lat	42.9670	Long	83.7500	For Data Years		XXXXXX
STAR Site	14827	Fort Wayne/Baer Field	IN	Lat	41.0000	Long	85.2000	For Data Years		XXXXXX
STAR Site	14836	Lansing/Capital City Arpt	MI	Lat	42.7670	Long	84.6000	For Data Years		XXXXXX
STAR Site	14837	Madison/Dane Co Regional Arpt	WI	Lat	43.1330	Long	89.3330	For Data Years		XXXXXX
STAR Site	14839	Milwaukee/General Mitchell Fi	WI	Lat	42.9500	Long	87.9000	For Data Years		XXXXXX
STAR Site	14840	Muskegon/County Arpt	MI	Lat	43.1670	Long	86.2330	For Data Years		XXXXXX
STAR Site	14842	Peoria/Greater Peoria Arpt	IL	Lat	40.6670	Long	89.6830	For Data Years		XXXXXX
STAR Site	14847	Sault Ste Marie/NWSO	MI	Lat	46.4670	Long	84.3500	For Data Years		XXXXXX
STAR Site	14848	South Bend/Michiana Regional	IN	Lat	41.7000	Long	86.3170	For Data Years		XXXXXX
STAR Site	14850	Traverse City/Faa Airport	MI	Lat	44.7330	Long	85.5830	For Data Years		XXXXXX
STAR Site	14852	Youngstown/Municipal Arpt	OH	Lat	41.2500	Long	80.6670	For Data Years		XXXXXX
STAR Site	14860	Erie/Int'l Arpt	PA	Lat	42.0830	Long	80.1830	For Data Years		XXXXXX
STAR Site	14895	Akron/Akron-Canton Regional	OH	Lat	40.9170	Long	81.4330	For Data Years		XXXXXX
STAR Site	14898	Green Bay/Austin Straubel Fie	WI	Lat	44.4830	Long	88.1330	For Data Years		XXXXXX
STAR Site	14913	Duluth/Int'l Arpt	MN	Lat	46.8330	Long	92.1830	For Data Years		XXXXXX
STAR Site	14914	Fargo/Hector Field	ND	Lat	46.9000	Long	96.8000	For Data Years		XXXXXX

STAR Site 14918	International Falls/Int'l Arp	MN	Lat	48.5670	Long	93.3830	For Data Years	XXXXXX
STAR Site 14920	La Crosse/Municipal Arpt	WI	Lat	43.8670	Long	91.2500	For Data Years	XXXXXX
STAR Site 14922	Minneapolis-St Paul/Int'l Arp	MN	Lat	44.8830	Long	93.2170	For Data Years	XXXXXX
STAR Site 14923	Moline/Quad-City Arpt	IL	Lat	41.4500	Long	90.5000	For Data Years	XXXXXX
STAR Site 14925	Rochester/Municipal Arpt	MN	Lat	43.9170	Long	92.5000	For Data Years	XXXXXX
STAR Site 14929	Aberdeen/Regional Arpt	SD	Lat	45.4500	Long	98.4330	For Data Years	XXXXXX
STAR Site 14933	Des Moines/Int'l Arpt	IA	Lat	41.5330	Long	93.6500	For Data Years	XXXX
STAR Site 14935	Grand Island/Arpt	NE	Lat	40.9670	Long	98.3170	For Data Years	XXXXXX
STAR Site 14936	Huron/Regional Arpt	SD	Lat	44.3830	Long	98.2170	For Data Years	XXXXXX
STAR Site 14939	Lincoln/Municipal Arpt	NE	Lat	40.8500	Long	96.7500	For Data Years	XXXXXX
STAR Site 14940	Mason City/Faa Airport	IA	Lat	43.1500	Long	93.3330	For Data Years	XXXXXX
STAR Site 14941	Norfolk/Karl Stefan Mem Arpt	NE	Lat	41.9830	Long	97.4330	For Data Years	XXXXXX
STAR Site 14942	Omaha/Eppley Airfield	NE	Lat	41.3000	Long	95.9000	For Data Years	XXXXXX
STAR Site 14943	Sioux City/Municipal Arpt	IA	Lat	42.4000	Long	96.3830	For Data Years	XXXXXX
STAR Site 14944	Sioux Falls/Foss Field	SD	Lat	43.5670	Long	96.7330	For Data Years	XXXXXX
STAR Site 14991	Eau Claire/Faa Airport	WI	Lat	44.8670	Long	91.4830	For Data Years	XXXXXX
STAR Site 21504	Hilo/General Lyman Field	HI	Lat	19.7170	Long	155.0670	For Data Years	XXXXXX
STAR Site 22521	Honolulu/Int'l Arpt	HI	Lat	21.3330	Long	157.9170	For Data Years	XXXXXX
STAR Site 22536	Lihue/Arpt	HI	Lat	21.9830	Long	159.3500	For Data Years	XXXXXX
STAR Site 23009	Roswell/Industrial Air Park	NM	Lat	33.3000	Long	104.5330	For Data Years	XXXXXX
STAR Site 23023	Midland/Regional Air Terminal	TX	Lat	31.9500	Long	102.1830	For Data Years	XXXXX
STAR Site 23034	San Angelo/WSO Airport	TX	Lat	31.3670	Long	100.5000	For Data Years	XXXXXX
STAR Site 23042	Lubbock/Regional Arpt	TX	Lat	33.6500	Long	101.8170	For Data Years	XXXXXX
STAR Site 23044	El Paso/Int'l Arpt	TX	Lat	31.8000	Long	106.4000	For Data Years	XXXXXX
STAR Site 23047	Amarillo/Int'l Arpt	TX	Lat	35.2330	Long	101.7000	For Data Years	XXXXXX
STAR Site 23050	Albuquerque/Int'l Arpt	NM	Lat	35.0500	Long	106.6170	For Data Years	XXXXXX
STAR Site 23062	Denver/Stapleton Int'l Arpt	CO	Lat	39.7670	Long	104.8670	For Data Years	XXXXXX
STAR Site 23063	Eagle/Faa Airport	CO	Lat	39.6500	Long	106.9170	For Data Years	XXXXXX
STAR Site 23065	Goodland/Renner Field	KS	Lat	39.3670	Long	101.7000	For Data Years	X X
STAR Site 23066	Grand Junction/Walker Field	CO	Lat	39.1170	Long	108.5330	For Data Years	XXXXXX
STAR Site 23081	Gallup/Faa Airport	NM	Lat	35.5170	Long	108.7830	For Data Years	XXXXXX
STAR Site 23129	Long Beach/WSO Airport	CA	Lat	33.8170	Long	118.1500	For Data Years	XXXXXX
STAR Site 23153	Tonopah/Faa Airport	NV	Lat	38.0670	Long	117.0830	For Data Years	XX
STAR Site 23154	Ely/Yelland Field	NV	Lat	39.2830	Long	114.8500	For Data Years	X
STAR Site 23160	Tucson/Int'l Arpt	AZ	Lat	32.1330	Long	110.9330	For Data Years	XXXXXX
STAR Site 23161	Daggett/Faa Airport	CA	Lat	34.8670	Long	116.7830	For Data Years	XXXXXX
STAR Site 23169	Las Vegas/Mccarran Int'l Arpt	NV	Lat	36.0830	Long	115.1670	For Data Years	XX
STAR Site 23174	Los Angeles/Int'l Arpt	CA	Lat	33.9330	Long	118.3830	For Data Years	XXXXXX
STAR Site 23183	Phoenix/Sky Harbor Int'l Arpt	AZ	Lat	33.4330	Long	112.0170	For Data Years	XXXXXX
STAR Site 23184	Prescott/Municipal	AZ	Lat	34.6500	Long	112.4330	For Data Years	XXXXXX
STAR Site 23185	Reno/Cannon Int'l Arpt	NV	Lat	39.5000	Long	119.7830	For Data Years	XXXXXX
STAR Site 23188	San Diego/Lindbergh Field	CA	Lat	32.7330	Long	117.1670	For Data Years	XXXXXX
STAR Site 23190	Santa Barbara/Faa Airport	CA	Lat	34.4330	Long	119.8330	For Data Years	XXXXXX
STAR Site 23232	Sacramento/Executive Arpt	CA	Lat	38.5170	Long	121.5000	For Data Years	XXX
STAR Site 23234	San Francisco/Int'l Arpt	CA	Lat	37.6170	Long	122.3830	For Data Years	XXXXXX
STAR Site 24011	Bismarck/Municipal Arpt	ND	Lat	46.7670	Long	100.7500	For Data Years	XXXXXX
STAR Site 24013	Minot/Faa Airport	ND	Lat	48.2670	Long	101.2830	For Data Years	XXXXXX
STAR Site 24018	Cheyenne/Municipal Arpt	WY	Lat	41.1500	Long	104.8170	For Data Years	XXXXX
STAR Site 24021	Lander/Hunt Field	WY	Lat	42.8170	Long	108.7330	For Data Years	XXXXXX
STAR Site 24023	North Platte/Lee Bird Fld	NE	Lat	41.1330	Long	100.6830	For Data Years	XXXXXX
STAR Site 24025	Pierre/Faa Airport	SD	Lat	44.3830	Long	100.2830	For Data Years	XXXXXX
STAR Site 24027	Rock Springs/Faa Airport	WY	Lat	41.6000	Long	109.0670	For Data Years	XXXXXX
STAR Site 24028	Scottsbluff/County Airport	NE	Lat	41.8670	Long	103.6000	For Data Years	XXXXXX
STAR Site 24029	Sheridan/County Arpt	WY	Lat	44.7670	Long	106.9670	For Data Years	XXXXXX
STAR Site 24033	Billings/Logan Int'l Arpt	MT	Lat	45.8000	Long	108.5330	For Data Years	XXXXXX
STAR Site 24036	Lewistown/Faa Arpt	MT	Lat	47.0670	Long	109.4500	For Data Years	XXXXXX
STAR Site 24037	Miles City/Municipal Arpt	MT	Lat	46.4330	Long	105.8670	For Data Years	XX
STAR Site 24089	Casper/Natrona Co Int'l Arpt	WY	Lat	42.9170	Long	106.4670	For Data Years	XXXXX
STAR Site 24090	Rapid City/Regional Arpt	SD	Lat	44.0500	Long	103.0670	For Data Years	XXXXXX
STAR Site 24121	Elko/Municipal Arpt	NV	Lat	40.8330	Long	115.7830	For Data Years	XXX XX

STAR	Site	24127	Salt Lake City/Int'l Arpt	UT	Lat	40.7830	Long	111.9500	For	Data	Years	XXXXXX
STAR	Site	24128	Winnemucca/WSO Airport	NV	Lat	40.9000	Long	117.8000	For	Data	Years	XXXX
STAR	Site	24131	Boise/Air Terminal	ID	Lat	43.5670	Long	116.2170	For	Data	Years	XXXXXX
STAR	Site	24137	Cut Bank/Faa Airport	MT	Lat	48.6000	Long	112.3670	For	Data	Years	X
STAR	Site	24143	Great Falls/Int'l Arpt	MT	Lat	47.4830	Long	111.3670	For	Data	Years	XXXXXX
STAR	Site	24144	Helena/Arpt	MT	Lat	46.6000	Long	112.0000	For	Data	Years	XXXX X
STAR	Site	24146	Kalispell/Glacier Pk Int'l Ap	MT	Lat	48.3000	Long	114.2670	For	Data	Years	XXXXXX
STAR	Site	24153	Missoula/Johnson-Bell Fld	MT	Lat	46.9170	Long	114.0830	For	Data	Years	XXXXXX
STAR	Site	24155	Pendleton/Municipal Arpt	OR	Lat	45.6830	Long	118.8500	For	Data	Years	XXXXXX
STAR	Site	24156	Pocatello/Municipal Arpt	ID	Lat	42.9170	Long	112.6000	For	Data	Years	XXXXXX
STAR	Site	24157	Spokane/Int'l Arpt	WA	Lat	47.6330	Long	117.5330	For	Data	Years	XXXXXX
STAR	Site	24172	Lovelock/Faa Airport	NV	Lat	40.0670	Long	118.5500	For	Data	Years	X
STAR	Site	24216	Red Bluff/Municipal Arpt	CA	Lat	40.1500	Long	122.2500	For	Data	Years	XX
STAR	Site	24221	Eugene/Mahlon Sweet Arpt	OR	Lat	44.1170	Long	123.2170	For	Data	Years	XXXXXX
STAR	Site	24225	Medford/Jackson County Arpt	OR	Lat	42.3830	Long	122.8830	For	Data	Years	XXXXXX
STAR	Site	24227	Olympia/Arpt	WA	Lat	46.9670	Long	122.9000	For	Data	Years	XXXXXX
STAR	Site	24229	Portland/Int'l Arpt	OR	Lat	45.6000	Long	122.6000	For	Data	Years	XXXXXX
STAR	Site	24230	Redmond/Faa Airport	OR	Lat	44.2670	Long	121.1500	For	Data	Years	XXXXXX
STAR	Site	24232	Salem/Mcnary Field	OR	Lat	44.9170	Long	123.0000	For	Data	Years	XXXXXX
STAR	Site	24233	Seattle/Seattle-Tacoma Int'l	WA	Lat	47.4500	Long	122.3000	For	Data	Years	XXXXXX
STAR	Site	24243	Yakima/Air Terminal	WA	Lat	46.5670	Long	120.5330	For	Data	Years	XXXXX
STAR	Site	24257	Redding/Aaf	CA	Lat	40.5000	Long	122.3000	For	Data	Years	XXX
STAR	Site	24283	Arcata/Arpt	CA	Lat	40.9830	Long	124.1000	For	Data	Years	XXXXXX
STAR	Site	24284	North Bend/Faa Airport	OR	Lat	43.4170	Long	124.2500	For	Data	Years	XXXXXX
STAR	Site	25308	Annette/WSO Airport	AK	Lat	55.0330	Long	131.5670	For	Data	Years	X
STAR	Site	25309	Juneau/Int'l Arpt	AK	Lat	58.3670	Long	134.5830	For	Data	Years	XXX
STAR	Site	25339	Yakutat/State Arpt	AK	Lat	59.5170	Long	139.6670	For	Data	Years	XXXXXX
STAR	Site	25501	Kodiak/U S C G Base	AK	Lat	57.7500	Long	152.5000	For	Data	Years	XXXXXX
STAR	Site	25503	King Salmon/Arpt	AK	Lat	58.6830	Long	156.6500	For	Data	Years	XXXXXX
STAR	Site	25507	Homer/Arpt	AK	Lat	59.6330	Long	151.5000	For	Data	Years	XXXXXX
STAR	Site	25624	Cold Bay/Arpt	AK	Lat	55.2000	Long	162.7170	For	Data	Years	XXXXXX
STAR	Site	25713	St Paul Island/Arpt	AK	Lat	57.1500	Long	170.2170	For	Data	Years	X XXX
STAR	Site	26411	Fairbanks/Int'l Arpt	AK	Lat	64.8170	Long	147.8670	For	Data	Years	XXXXXX
STAR	Site	26442	Valdez/WSO	AK	Lat	61.1330	Long	146.3500	For	Data	Years	XXXXXX
STAR	Site	26451	Anchorage/Wsmo Airport	AK	Lat	61.1670	Long	150.0170	For	Data	Years	XXXXXX
STAR	Site	26510	Mc Grath/Arpt	AK	Lat	62.9670	Long	155.6170	For	Data	Years	XXXXX
STAR	Site	26528	Talkeetna/State Arpt	AK	Lat	62.3000	Long	150.1000	For	Data	Years	XX X
STAR	Site	26533	Bettles/Bettles Field	AK	Lat	66.9170	Long	151.5170	For	Data	Years	XXXXXX
STAR	Site	26615	Bethel/WSO Airport	AK	Lat	60.7830	Long	161.8000	For	Data	Years	XXXXXX
STAR	Site	26616	Kotzebue/Ralph Wein Memorial	AK	Lat	66.8670	Long	162.6330	For	Data	Years	XXXXXX
STAR	Site	26617	Nome/Municipal Arpt	AK	Lat	64.5000	Long	165.4330	For	Data	Years	XXXXXX
STAR	Site	27401	Barter Island/WSO Airport	AK	Lat	70.1330	Long	143.6330	For	Data	Years	XXXXX
STAR	Site	27502	Barrow/W Post-W Rogers Arpt	AK	Lat	71.3000	Long	156.7830	For	Data	Years	XXXXXX
STAR	Site	93037	Colorado Springs/Municipal Ar	CO	Lat	38.8170	Long	104.7170	For	Data	Years	XXXXXX
STAR	Site	93129	Cedar City/Faa Airport	UT	Lat	37.7000	Long	113.1000	For	Data	Years	XXXXXX
STAR	Site	93193	Fresno/Air Terminal	CA	Lat	36.7670	Long	119.7170	For	Data	Years	XXXXXX
STAR	Site	93721	Baltimore/Blt-Washngtn Int'l	MD	Lat	39.1830	Long	76.6670	For	Data	Years	XXXXXX
STAR	Site	93729	Cape Hatteras/WSO	NC	Lat	35.2670	Long	75.5500	For	Data	Years	XXXXXX
STAR	Site	93730	Atlantic City/Airport Nafec	NJ	Lat	39.4500	Long	74.5670	For	Data	Years	XXXXXX
STAR	Site	93738	Washington Dc/Dulles Int'l Ar	VA	Lat	38.9500	Long	77.4500	For	Data	Years	XXXXXX
STAR	Site	93805	Tallahassee/Municipal Arpt	FL	Lat	30.3830	Long	84.3670	For	Data	Years	XXXXXX
STAR	Site	93814	Covington/Greater Cincinnati	KY	Lat	39.0500	Long	84.6670	For	Data	Years	XXXXXX
STAR	Site	93815	Dayton/Int'l Arpt	OH	Lat	39.9000	Long	84.2000	For	Data	Years	XXXXXX
STAR	Site	93817	Evansville/Dress Regional Arp	IN	Lat	38.0500	Long	87.5330	For	Data	Years	XXXXXX
STAR	Site	93819	Indianapolis/Int'l Arpt	IN	Lat	39.7330	Long	86.2670	For	Data	Years	XXXXXX
STAR	Site	93820	Lexington/Bluegrass Field	KY	Lat	38.0330	Long	84.6000	For	Data	Years	XXXXXX
STAR	Site	93821	Louisville/Standiford Field	KY	Lat	38.1830	Long	85.7330	For	Data	Years	XXXXXX
STAR	Site	93822	Springfield/Capital Arpt	IL	Lat	39.8500	Long	89.6830	For	Data	Years	XXXXXX
STAR	Site	93842	Columbus/Metropolitan Arpt	GA	Lat	32.5170	Long	84.9500	For	Data	Years	XXXXXX
STAR	Site	93862	Tupelo	MS	Lat	34.2500	Long	88.7170	For	Data	Years	XXXXXX

STAR	Site	93987	Lufkin/Faa Airport	TX	Lat	31.2330	Long	94.7500	For	Data	Years	XX
STAR	Site	93997	Russell/Faa Airport	KS	Lat	38.8670	Long	98.8170	For	Data	Years	XXXXXX
STAR	Site	94008	Glasgow/Int'l Arpt	MT	Lat	48.2170	Long	106.6170	For	Data	Years	XXXXXX
STAR	Site	94014	Williston/Sloulin Int'l Arpt	ND	Lat	48.1830	Long	103.6330	For	Data	Years	XXXX
STAR	Site	94224	Astoria/Clatsop County Arpt	OR	Lat	46.1500	Long	123.8830	For	Data	Years	XXXXXX
STAR	Site	94240	Quillayute/WSO Airport	WA	Lat	47.9500	Long	124.5500	For	Data	Years	XXXXXX
STAR	Site	94725	Massena/Faa Airport	NY	Lat	44.9330	Long	74.8500	For	Data	Years	XXXXXX
STAR	Site	94789	New York/J F Kennedy Int'l Ar	NY	Lat	40.6500	Long	73.7830	For	Data	Years	XXXXXX
STAR	Site	94822	Rockford/Greater Rockford Arp	IL	Lat	42.2000	Long	89.1000	For	Data	Years	XXXXX
STAR	Site	94823	Pittsburgh/Wscom 2 Airport	PA	Lat	40.5000	Long	80.2170	For	Data	Years	XXXXXX
STAR	Site	94830	Toledo/Express Arpt	OH	Lat	41.6000	Long	83.8000	For	Data	Years	XXXX
STAR	Site	94846	Chicago/O'hare Int'l Arpt	IL	Lat	41.9830	Long	87.9000	For	Data	Years	XXXXXX
STAR	Site	94847	Detroit/Metropolitan Arpt	MI	Lat	42.2330	Long	83.3330	For	Data	Years	XXXXXX
STAR	Site	94849	Alpena/Phelps Collins Ap	MI	Lat	45.0670	Long	83.5670	For	Data	Years	XXXXXX
STAR	Site	94860	Grand Rapids/Kent Co Int'l Ar	MI	Lat	42.8830	Long	85.5170	For	Data	Years	XXXXXX
STAR	Site	94910	Waterloo/Municipal Arpt	IA	Lat	42.5500	Long	92.4000	For	Data	Years	XXXXXX
STAR	Site	94918	North Omaha/Nwsfo Arpt	NE	Lat	41.3670	Long	96.0170	For	Data	Years	XXXXX

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STAR Site 00082  N Wind, Stab F,   Speed 2       Lat    .0000  Long    .0000  For Data Years
STAR Site 00083  N Wind, Stab F,   Speed 3       Lat    .0000  Long    .0000  For Data Years
STAR Site 00084  N Wind, Stab F,   Speed 4       Lat    .0000  Long    .0000  For Data Years
STAR Site 00085  N Wind, Stab F,   Speed 5       Lat    .0000  Long    .0000  For Data Years
STAR Site 00086  N Wind, Stab F,   Speed 6       Lat    .0000  Long    .0000  For Data Years
STAR Site 00091  N Wind, Stab E+F, Speed 1       Lat    .0000  Long    .0000  For Data Years
STAR Site 00092  N Wind, Stab E+F, Speed 2       Lat    .0000  Long    .0000  For Data Years
STAR Site 00093  N Wind, Stab E+F, Speed 3       Lat    .0000  Long    .0000  For Data Years
STAR Site 00094  N Wind, Stab E+F, Speed 4       Lat    .0000  Long    .0000  For Data Years
STAR Site 00095  N Wind, Stab E+F, Speed 5       Lat    .0000  Long    .0000  For Data Years
STAR Site 00096  N Wind, Stab E+F, Speed 6       Lat    .0000  Long    .0000  For Data Years
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Appendix C

DESCRIPTIVE STATISTICS FOR AMBIENT BENZENE CONCENTRATIONS ESTIMATED BY APPLICATION OF ISC2 DISPERSION MODEL TO 348 METEOROLOGICAL STATIONS

Table C-1. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (μg/m³) based on vent velocity = 3.21 ft/sec, vent diameter = 2 inches, and land use = rural.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, μg/m³	Arithmetic std. dev., μg/m³	Geometric mean, μg/m³	Geometric std. dev.	50th percentile, μg/m³	95th percentile, μg/m³	Maximum, μg/m³
10	1	11.9	7.22	10.1	1.768	10.2	26.0	64.3
	7	83.3	50.6	71.0	1.768	71.2	182	450
20	1	8.76	5.24	7.50	1.755	7.52	18.9	43.8
	7	61.3	36.7	52.5	1.755	52.7	133	306
30	1	6.55	3.85	5.63	1.740	5.64	14.0	31.1
	7	45.8	26.9	39.4	1.740	39.5	98.1	218
50	1	3.93	2.32	3.38	1.743	3.39	8.43	18.8
	7	27.5	16.2	23.6	1.743	23.7	59.0	132
100	1	1.66	1.01	1.41	1.774	1.41	3.63	8.06
	7	11.6	7.07	9.86	1.774	9.88	25.4	56.4
200	1	0.617	0.393	0.518	1.813	0.52	1.39	3.23
	7	4.32	2.75	3.63	1.813	3.64	9.75	22.6
300	1	0.333	0.217	0.278	1.834	0.279	0.759	1.81
	7	2.33	1.52	1.95	1.834	1.95	5.31	12.6
500	1	0.146	0.0974	0.121	1.857	0.122	0.336	0.821
	7	1.02	0.682	0.849	1.857	0.853	2.35	5.75
1000	1	0.0479	0.0328	0.0393	1.887	0.0395	0.113	0.280
	7	0.335	0.229	0.275	1.887	0.277	0.789	1.96
2000	1	0.0157	0.0109	0.0129	1.903	0.0130	0.0372	0.0937
	7	0.110	0.076	0.0900	1.903	0.0908	0.260	0.656

Table C-2. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (μg/m³) based on vent velocity = 3.21 ft/sec, vent diameter = 2 inches, and land use = urban.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, μg/m³	Arithmetic std. dev., μg/m³	Geometric mean, μg/m³	Geometric std. dev.	50th percentile, μg/m³	95th percentile, μg/m³	Maximum , μg/m³
10	1	12.0	7.27	10.3	1.765	10.3	26.2	67.6
	7	84.1	50.9	71.8	1.765	72.0	183	473
20	1	8.60	5.01	7.41	1.733	7.42	18.3	40.7
	7	60.2	35.1	51.9	1.733	52.0	128	285
30	1	6.25	3.32	5.50	1.669	5.54	12.7	25.6
	7	43.8	23.2	38.5	1.669	38.7	88.8	179
50	1	3.47	1.89	3.04	1.691	3.06	7.13	14.7
	7	24.3	13.2	21.2	1.691	21.4	49.9	103
100	1	1.06	0.626	0.912	1.748	0.919	2.28	4.98
	7	7.44	4.38	6.38	1.748	6.44	16.0	34.9
200	1	0.292	0.182	0.247	1.793	0.249	0.651	1.49
	7	2.05	1.27	1.73	1.793	1.74	4.56	10.4
300	1	0.136	0.0869	0.114	1.816	0.115	0.307	0.715
	7	0.951	0.608	0.798	1.817	0.802	2.15	5.01
500	1	0.0523	0.0344	0.0435	1.845	0.0437	0.120	0.286
	7	0.366	0.241	0.304	1.845	0.306	0.842	2.00
1000	1	0.0149	0.0101	0.0122	1.880	0.0123	0.0347	0.0846
	7	0.104	0.0710	0.0856	1.880	0.0862	0.243	0.592
2000	1	0.00448	0.00313	0.00365	1.910	0.0369	0.0107	0.0263
	7	0.0313	0.0219	0.0255	1.910	0.0258	0.0746	0.184

Table C-3. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (µg/m³) based on vent velocity = 10.9 ft/sec, vent diameter = 2 inches, and land use = rural.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, µg/m³	Arithmetic std. dev., µg/m³	Geometric mean, µg/m³	Geometric std. dev.	50th percentile, µg/m³	95th percentile, µg/m³	Maximum, µg/m³
10	1	11.2	6.79	9.57	1.767	9.62	24.5	61.2
	7	78.6	47.5	67.0	1.767	67.3	171	429
20	1	8.54	5.16	7.28	1.765	7.31	18.6	47.8
	7	59.8	36.1	51.0	1.765	51.2	130	335
30	1	6.48	3.88	5.54	1.758	5.55	14.0	35.5
	7	45.3	27.2	38.8	1.758	38.9	98.3	249
50	1	3.84	2.31	3.28	1.762	3.29	8.35	20.1
	7	26.9	16.2	23.0	1.762	23.0	58.5	141
100	1	1.60	0.986	1.36	1.784	1.36	3.50	7.84
	7	11.2	6.90	9.52	1.784	9.55	24.5	54.9
200	1	0.603	0.385	0.506	1.819	0.509	1.36	3.15
	7	4.22	2.70	3.54	1.819	3.56	9.54	22.1
300	1	0.329	0.214	0.274	1.838	0.276	0.750	1.78
	7	2.30	1.50	1.92	1.838	1.93	5.25	12.4
500	1	0.145	0.0969	0.120	1.860	0.121	0.334	0.815
	7	1.02	0.678	0.843	1.860	0.847	2.34	5.71
1000	1	0.0478	0.0327	0.0392	1.888	0.0394	0.0597	0.279
	7	0.334	0.229	0.274	1.888	0.276	0.784	1.96
2000	1	0.0157	0.0109	0.0128	1.904	0.0130	0.0371	0.0935
	7	0.110	0.0763	0.0898	1.904	0.0907	0.260	0.655

Table C-4. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (µg/m³) based on vent velocity = 10.9 ft/sec, vent diameter = 2 inches, and land use = urban.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, µg/m³	Arithmetic std. dev., µg/m³	Geometric mean, µg/m³	Geometric std. dev.	50th percentile, µg/m³	95th percentile, µg/m³	Maximum, µg/m³
10	1	11.7	7.00	9.96	1.758	9.97	25.2	70.3
	7	81.6	49.0	69.7	1.758	69.8	176	492
20	1	8.71	5.18	7.47	1.748	7.48	18.8	48.7
	7	60.9	36.3	52.3	1.748	52.4	131	341
30	1	6.26	3.57	5.42	1.718	5.43	13.1	31.0
	7	43.8	25.0	37.9	1.718	38.0	92.0	217
50	1	3.23	1.90	2.78	1.746	2.79	6.93	15.4
	7	22.6	13.3	19.4	1.746	19.5	48.5	108
100	1	1.00	0.621	0.852	1.788	0.858	2.22	5.10
	7	7.03	4.35	5.96	1.788	6.01	15.6	35.7
200	1	0.282	0.181	0.236	1.823	0.238	0.638	1.51
	7	1.97	1.27	1.65	1.823	1.66	4.46	10.5
300	1	0.132	0.0866	0.110	1.840	0.111	0.301	0.722
	7	0.926	0.606	0.771	1.840	0.776	2.11	5.06
500	1	0.0514	0.0343	0.0425	1.861	0.0428	0.118	0.287
	7	0.360	0.240	0.298	1.861	0.300	0.827	2.01
1000	1	0.0148	0.0101	0.0121	1.889	0.0122	0.0346	0.0848
	7	0.103	0.0707	0.0847	1.889	0.0854	0.242	0.594
2000	1	0.00446	0.00312	0.00363	1.915	0.00367	0.0106	0.0263
	7	0.0312	0.0219	0.0254	1.915	0.0257	0.0744	0.184

Table C-5. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (µg/m³) based on vent velocity = 20.3 ft/sec, vent diameter = 2 inches, and land use = rural.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, µg/m³	Arithmetic std. dev., µg/m³	Geometric mean, µg/m³	Geometric std. dev.	50th percentile, µg/m³	95th percentile, µg/m³	Maximum, µg/m³
10	1	10.3	6.22	8.83	1.765	8.83	22.5	54.8
	7	72.4	43.5	61.8	1.765	61.8	158	383
20	1	8.20	4.94	7.00	1.765	7.02	17.9	45.8
	7	57.4	34.6	49.0	1.765	49.2	125	320
30	1	6.33	3.82	5.40	1.763	5.42	13.8	35.2
	7	44.3	26.7	37.8	1.763	38.0	96.4	246
50	1	3.75	2.27	3.20	1.766	3.21	8.18	19.8
	7	26.3	15.9	22.4	1.766	22.5	57.2	139
100	1	1.55	0.950	1.31	1.782	1.32	3.40	7.56
	7	10.8	6.65	9.20	1.782	9.23	23.8	52.9
200	1	0.589	0.375	0.495	1.816	0.496	1.32	3.03
	7	4.12	2.63	3.46	1.816	3.47	9.27	21.2
300	1	0.324	0.211	0.270	1.836	0.272	0.739	1.74
	7	2.27	1.47	1.89	1.836	1.91	5.17	12.2
500	1	0.144	0.0961	0.120	1.859	0.120	0.331	0.807
	7	1.01	0.673	0.837	1.859	0.841	2.32	5.65
1000	1	0.0476	0.0325	0.0390	1.888	0.0393	0.111	0.278
	7	0.333	0.228	0.273	1.888	0.275	0.780	1.94
2000	1	0.0157	0.0109	0.0128	1.903	0.0129	0.0370	0.0932
	7	0.110	0.0761	0.0896	1.904	0.0905	0.259	0.653

Table C-6. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (µg/m^3) based on vent velocity = 20.3 ft/sec, vent diameter = 2 inches, and land use = urban.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, µg/m^3	Arithmetic std. dev., µg/m^3	Geometric mean, µg/m^3	Geometric std. dev.	50th percentile, µg/m^3	95th percentile, µg/m^3	Maximum, µg/m^3
10	1	11.0	6.53	9.38	1.753	9.40	23.5	66.6
	7	76.7	45.7	65.7	1.752	65.8	165	466
20	1	8.60	5.15	7.36	1.755	7.37	18.6	48.8
	7	60.2	36.1	51.5	1.755	51.6	130	342
30	1	6.13	3.63	5.26	1.748	5.27	13.2	31.5
	7	42.9	25.4	36.8	1.748	36.9	92.3	220
50	1	3.13	1.91	2.66	1.777	2.67	6.88	15.3
	7	21.9	13.4	18.6	1.777	18.7	48.2	107
100	1	0.978	0.620	0.822	1.811	0.827	2.21	5.06
	7	6.84	4.34	5.75	1.811	5.79	15.5	35.4
200	1	0.277	0.181	0.231	1.839	0.232	0.634	1.51
	7	1.94	1.27	1.62	1.839	1.62	4.44	10.5
300	1	0.131	0.0867	0.109	1.852	0.109	0.299	0.723
	7	0.917	0.607	0.760	1.853	0.763	2.09	5.06
500	1	0.0511	0.0344	0.0422	1.869	0.0425	0.118	0.288
	7	0.358	0.241	0.295	1.869	0.297	0.827	2.01
1000	1	0.0147	0.0101	0.0120	1.893	0.0122	0.0346	0.0849
	7	0.103	0.0708	0.0843	1.893	0.0851	0.242	0.594
2000	1	0.00445	0.00313	0.00362	1.917	0.00367	0.0106	0.0263
	7	0.0312	0.0219	0.0253	1.917	0.0257	0.0743	0.184

Table C-7. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (µg/m^3) based on vent velocity = 3.21 ft/sec, vent diameter = 4 inches, and land use = rural.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, µg/m^3	Arithmetic std. dev., µg/m^3	Geometric mean, µg/m^3	Geometric std. dev.	50th percentile, µg/m^3	95th percentile, µg/m^3	Maximum, µg/m^3
10	1	11.7	7.10	9.99	1.768	10.0	25.6	64.3
	7	82.0	49.7	69.9	1.768	70.2	179	450
20	1	6.68	5.23	7.42	1.760	7.45	18.8	47.3
	7	60.8	36.6	51.9	1.760	52.1	132	331
30	1	6.51	3.86	5.58	1.747	5.60	14.0	34.3
	7	45.6	27.0	39.1	1.747	39.2	98.0	240
50	1	3.86	2.29	3.31	1.750	3.32	8.35	19.6
	7	27.0	16.0	23.2	1.750	23.3	58.4	137
100	1	1.60	0.976	1.36	1.774	1.37	3.49	7.71
	7	11.2	6.83	9.54	1.774	9.58	24.4	54.0
200	1	0.601	0.382	0.505	1.812	0.507	1.35	3.11
	7	4.21	2.67	3.54	1.812	3.55	9.46	21.8
300	1	0.327	0.213	0.273	1.834	0.275	0.746	1.76
	7	2.29	1.49	1.91	1.834	1.92	5.22	12.3
500	1	0.145	0.0963	0.120	1.857	0.121	0.332	0.809
	7	1.01	0.674	0.841	1.857	0.844	2.32	5.67
1000	1	0.0477	0.0326	0.0391	1.887	0.0394	0.112	0.278
	7	0.334	0.228	0.274	1.887	0.276	0.782	1.95
2000	1	0.0157	0.0109	0.0128	1.903	0.0129	0.0371	0.0934
	7	0.110	0.0762	0.0898	1.903	0.906	0.260	0.654

Table C-8. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (μg/m³) based on vent velocity = 3.21ft/sec, vent diameter = 4 inches, and land use = urban.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, μg/m³	Arithmetic std. dev., μg/m³	Geometric mean, μg/m³	Geometric std. dev.	50th percentile, μg/m³	95th percentile, μg/m³	Maximum, μg/m³
10	1	12.0	7.23	10.2	1.763	10.2	26.0	71.0
	7	83.9	50.6	71.6	1.763	71.7	182	497
20	1	8.65	1.81	7.44	1.740	7.47	18.6	46.7
	7	60.6	35.7	52.1	1.740	52.3	130	327
30	1	6.25	3.42	5.47	1.688	5.50	12.9	29.4
	7	43.8	24.0	38.3	1.688	38.5	90.2	206
50	1	3.34	1.87	2.90	1.708	2.91	6.92	14.8
	7	23.4	13.1	20.3	1.708	20.4	48.4	104
100	1	1.03	0.616	0.880	1.760	0.886	2.24	4.98
	7	7.20	4.31	6.16	1.760	6.20	15.7	34.9
200	1	0.286	0.180	0.241	1.803	0.243	0.643	1.49
	7	2.00	1.26	1.69	1.803	1.70	4.50	10.4
300	1	0.134	0.0864	0.112	1.825	0.113	0.304	0.717
	7	0.938	0.605	0.785	1.825	0.789	2.13	5.02
500	1	0.0518	0.0343	0.0430	1.851	0.0432	0.119	0.286
	7	0.363	0.240	0.301	1.851	0.302	0.836	2.00
1000	1	0.0148	0.0101	0.0122	1.883	0.0123	0.0347	0.0847
	7	0.104	0.0707	0.0851	1.883	0.0858	0.243	0.593
2000	1	0.00447	0.00312	0.00364	1.912	0.00368	0.0106	0.0263
	7	0.0313	0.0219	0.0255	1.912	0.0258	0.0745	0.184

Table C-9. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (μg/m³) based on vent velocity = 10.9 ft/sec, vent diameter = 4 inches, and land use = rural.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, μg/m³	Arithmeticstd. dev., μg/m³	Geometric mean, μg/m³	Geometric std. dev.	50th percentile, μg/m³	95th percentile, μg/m³	Maximum, μg/m³
10	1	10.2	6.12	8.70	1.764	8.73	22.1	53.5
	7	71.3	42.8	60.9	1.764	61.1	155	374
20	1	8.06	4.84	6.88	1.762	6.89	17.6	44.8
	7	56.4	33.9	48.2	1.762	48.2	123	313
30	1	6.20	3.72	5.30	1.759	5.31	13.5	34.3
	7	43.4	26.0	37.1	1.759	37.2	94.7	240
50	1	3.62	2.17	3.10	1.759	3.10	7.83	19.0
	7	25.4	15.2	21.7	1.759	21.7	54.8	133
100	1	1.45	0.879	1.24	1.770	1.24	3.15	6.97
	7	10.2	6.15	8.67	1.770	8.68	22.1	48.8
200	1	0.557	0.350	0.470	1.805	0.471	1.24	2.75
	7	3.90	2.45	3.29	1.805	3.30	8.68	19.2
300	1	0.311	0.200	0.260	1.828	0.262	0.708	1.62
	7	2.18	1.40	1.82	1.828	1.83	4.96	11.4
500	1	0.141	0.0934	0.117	1.854	0.118	0.323	0.777
	7	0.988	0.654	0.820	1.854	0.824	2.26	5.44
1000	1	0.0470	0.0321	0.0386	1.885	0.0389	0.110	0.273
	7	0.329	0.225	0.270	1.885	0.272	0.773	1.91
2000	1	0.0156	0.0108	0.0127	1.902	0.0129	0.0368	0.0925
	7	0.109	0.0756	0.0892	1.902	0.0901	0.258	0.647

Table C-10. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (µg/m³) based on vent velocity = 10.9 ft/sec, vent diameter = 4 inches, and land use = urban.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, µg/m³	Arithmetic std. dev., µg/m³	Geometric mean, µg/m³	Geometric std. dev.	50th percentile, µg/m³	95th percentile, µg/m³	Maximum, µg/m³
10	1	10.8	6.44	9.28	1.751	9.29	23.3	65.8
	7	75.8	45.1	65.0	1.751	65.1	163	460
20	1	8.48	5.06	7.27	1.752	7.26	18.3	48.0
	7	59.4	35.4	50.9	1.752	50.8	128	336
30	1	6.00	3.53	5.16	1.744	5.16	12.8	30.6
	7	42.0	24.7	36.1	1.744	36.1	89.9	214
50	1	3.05	1.85	2.60	1.771	2.60	6.64	14.7
	7	21.4	12.9	18.2	1.771	18.2	46.5	103
100	1	0.953	0.600	0.804	1.805	0.808	2.14	4.82
	7	6.67	4.20	5.62	1.805	5.65	15.0	33.7
200	1	0.274	0.179	0.229	1.837	0.230	0.627	1.48
	7	1.92	1.25	1.60	1.837	1.61	4.39	10.4
300	1	0.130	0.0861	0.108	1.851	0.108	0.297	0.717
	7	0.911	0.603	0.756	1.851	0.759	2.08	5.02
500	1	0.0510	0.0343	0.0421	1.868	0.424	0.118	0.287
	7	0.357	0.240	0.294	1.868	0.297	0.826	2.01
1000	1	0.0147	0.0101	0.0120	1.893	0.0121	0.0345	0.0848
	7	0.103	0.0707	0.0842	1.893	0.0850	0.242	0.593
2000	1	0.00445	0.00312	0.00362	1.917	0.00367	0.0106	0.0263
	7	0.0312	0.0219	0.0253	1.917	0.0257	0.0743	0.184

Table C-11. Descriptive statistics for dispersion model estimates of outdoor benzene concentration (μg/m³) based on vent velocity = 20.3 ft/sec, vent diameter = 4 inches, and land use = rural.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, μg/m³	Arithmetic std. dev., μg/m³	Geometric mean, μg/m³	Geometric std. dev.	50th percentile, μg/m³	95th percentile, μg/m³	Maximum, μg/m³
10	1	8.24	4.91	7.04	1.765	7.11	17.5	41.1
	7	57.7	34.4	49.3	1.765	49.7	123	288
20	1	7.12	4.22	6.10	1.753	6.13	15.1	38.9
	7	49.8	29.5	42.7	1.753	42.9	106	272
30	1	5.68	3.36	4.87	1.749	4.87	12.1	31.0
	7	39.7	23.5	34.1	1.749	34.1	84.6	217
50	1	3.34	1.97	2.86	1.748	2.87	7.10	17.1
	7	23.4	13.8	20.1	1.748	20.1	49.7	120
100	1	1.31	0.783	1.12	1.757	1.12	2.80	6.42
	7	9.19	5.48	7.87	1.757	7.86	19.6	44.9
200	1	0.508	0.313	0.431	1.787	0.432	1.11	2.43
	7	3.56	2.19	3.02	1.787	3.03	7.78	17.0
300	1	0.292	0.185	0.245	1.813	0.246	0.649	1.44
	7	2.04	1.29	1.72	1.813	1.72	4.54	10.1
500	1	0.136	0.0894	0.114	1.846	0.114	0.312	0.732
	7	0.955	0.626	0.795	1.846	0.801	2.18	5.12
1000	1	0.0462	0.0314	0.0380	1.881	0.0383	0.108	0.265
	7	0.324	0.220	0.266	1.881	0.268	0.758	1.86
2000	1	0.0155	0.0107	0.0126	1.900	0.0128	0.0364	0.0913
	7	0.108	0.0749	0.0885	1.900	0.0895	0.255	0.639

Table C-12. Descriptive statistics for dispersion model estimates of outdoor benzene concentration ($\mu g/m^3$) based on vent velocity = 20.3 ft/sec, vent diameter = 4 inches, and land use = urban.

Distance, m	Benzene emis. rate, tons/year	Outdoor benzene concentration						
		Arithmetic mean, $\mu g/m^3$	Arithmetic std. dev., $\mu g/m^3$	Geometric mean, $\mu g/m^3$	Geometric std. dev.	50th percentile, $\mu g/m^3$	95th percentile, $\mu g/m^3$	Maximum, $\mu g/m^3$
10	1	9.23	5.41	7.95	1.741	7.96	19.6	57.1
	7	64.6	37.9	55.6	1.741	55.7	137	399
20	1	7.91	4.66	6.80	1.743	6.78	16.8	44.2
	7	55.3	32.6	47.6	1.743	47.5	118	309
30	1	5.53	3.30	4.73	1.756	4.73	11.8	28.0
	7	38.7	23.1	33.1	1.756	33.1	82.6	196
50	1	2.85	1.75	2.42	1.783	2.42	6.23	13.9
	7	19.9	12.2	16.9	1.783	17.0	43.6	97.5
100	1	0.906	0.574	0.762	1.812	0.765	2.02	4.52
	7	6.34	4.02	5.33	1.812	5.35	14.2	31.6
200	1	0.269	0.176	0.224	1.844	0.225	0.618	1.45
	7	1.88	1.23	1.56	1.844	1.57	4.33	10.1
300	1	0.129	0.0856	0.107	1.857	0.107	0.295	0.711
	7	0.901	0.599	0.746	1.857	0.749	2.06	4.98
500	1	0.0507	0.0342	0.0418	1.873	0.0422	0.117	0.286
	7	0.355	0.240	0.293	1.873	0.295	0.822	2.00
1000	1	0.0147	0.0101	0.0120	1.895	0.0121	0.0345	0.0847
	7	0.103	0.0707	0.0840	1.895	0.0849	0.242	0.593
2000	1	0.00445	0.00312	0.00361	1.918	0.00366	0.0106	0.0263
	7	0.0311	0.0219	0.0253	1.918	0.0256	0.0742	0.184

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