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AXAOTHER XL-A Spreadsheet for Determining Doses for Incidents Caused by Tornadoes or High-Velocity Straight Winds

by

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September 1996

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ABSTRACT

AXAOTHER XL is an Excel spreadsheet used to calculated doses associated with tornadoes or high-velocity straight winds. Hand calculations have been performed to ensure proper application of methodologies and equations have been verified. User instructions also are included.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

AXAOTHER XL - A SPREADSHEET FOR DETERMINING DOSES FOR INCIDENTS CAUSED BY TORNADOES OR HIGH-VELOCITY STRAIGHT WINDS

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1.0 INTRODUCTION

AXAOTHER XL is an Excel Spreadsheet used to determine dose to the maximally exposed offsite individual during high-velocity straight winds or tornado conditions. Both individual and population doses may be considered. Potential exposure pathways are inhalation and plume shine. For high-velocity straight winds the spreadsheet has the capability to determine the downwind relative air concentration, however for the tornado conditions, the user must enter the relative air concentration. Theoretical models are discussed and hand calculations are performed to ensure proper application of methodologies. A section has also been included that contains user instructions for the spreadsheet.

2.0 THEORETICAL MODELS

AXAOTHER was originally developed at the Savannah River Site (SRS) in 1983 to estimate dose from tornado winds (Haynes and Taylor, 1983). This methodology was converted to a FORTRAN computer code on the IBM Mainframe in 1985. AXAOTHER XL applies the same methodology as AXAOTHER but has been moved to an Excel spreadsheet and can be executed through the use of Macros.

Methodologies used to determine relative air concentrations within AXAOTHER XL are different for high-velocity straight winds and tornado conditions so the two are discussed separately. Once the relative air concentration is determined, the individual and population dose are determined using the same equations.

2.1 Releases During High-Velocity Straight Winds

High-velocity straight winds usually are associated with severe thunderstorms. The strong winds may cause a nuclear facility to lose its integrity, which may result in the release of radioactivity.

Dispersion associated with a high-velocity straight wind is modeled with a Gaussian plume distribution. The release of radioactivity is treated as a plume since the dispersion in the traveling direction (σ_x) is insignificant relative to transport time. For short-term meteorological conditions, dispersion models have not been verified for distances more than a few tens of kilometers from the release point. However, for high-velocity straight winds analyses, it is assumed that a Gaussian distribution is an adequate representation out to a distance of 80 kilometers.

The equation used to calculate plume centerline, ground-level relative air concentration (χ/Q in sec/m^3) from high-velocity straight winds is:

$$\frac{\chi}{Q}=\frac{1}{2\pi\sigma_y\sigma_z U_{HS}}\left[e^{-\left(\frac{(z-h_e)^2}{2\sigma_z^2}\right)}+e^{-\left(\frac{(z+h_e)^2}{2\sigma_z^2}\right)}\right] \qquad (1)$$

where

χ/Q	dispersion factor (sec/m^3)
z	height above the ground surface (m)
h_e	effective release height (m)
U_{HS}	wind speed at the release height (m/sec)
σ_y	standard deviation of the concentration distribution in the horizontal cross-plume direction (m)
σ_z	standard deviation of the concentration distribution in the vertical direction(m)

For centerline ground-level concentrations (i.e. y=z=0) the above equation reduces to:

$$\frac{\chi}{Q}=\frac{e^{-\left(\frac{(h_e)^2}{2\sigma_z^2}\right)}}{\pi\sigma_y\sigma_z U_{HS}} \qquad (2)$$

For downwind distance such that $\sigma_z > (0.8)L$ relative air concentration is defined as:

$$\frac{\chi}{Q}=\frac{1}{\sqrt{2\pi}\sigma_y U_{HS} L} \qquad (3)$$

where

L depth of the mixing layer (m)

A mixing height of 500 meters is used which is typical of the relatively shallow, cold, and dense air structure near the earth's surface.

The horizontal dispersion coefficient, σ_y, is calculated from the expression derived by Pasquill (1976):

$$\sigma_y = \sigma_a \times f(x) \qquad (4)$$

where

x downwind distance in m; and

σ_a standard deviation of horizontal wind fluctuations in radians. (see Table 2)

$$f(x) = 0.33\left(\frac{10000}{x}\right)^{0.5} \text{ for } x > 10000 \text{ m}$$

$$f(x) = \frac{\left(\frac{x}{1000}\right)^{-0.2}}{1.67 + 0.3\left(\frac{\left|1 - \left(\frac{x}{1000}\right)^{-0.2}\right|}{0.48}\right)^{0.5}} \text{ for } x \le 10000 \text{ m} \qquad (5)$$

Equation 5 is an interpolating formula derived from values of f(x) given by Pasquill (1976).

The vertical diffusion coefficient, σ_z is calculated from Briggs (1973). Table 1 shows the vertical diffusion coefficients as a function of stability class. Table 2 shows the classification of atmospheric stability. The observed values of σ_a and σ_e (the standard deviation of horizontal and vertical wind fluctuations respectively, in radians) are computed from instantaneous (every 1.5 seconds) observations of wind direction made at SRS meteorological towers. The standard deviations of σ_a for the winds typical of those occurring during severe thunderstorms in the area were used (i.e., $\sigma_a = 0.4$ and $\sigma_e = 0.33$ radians). Referring to Table 2 these values correspond to stability class A; therefore, using Briggs approximation for the vertical diffusion coefficient, the following equation is used:

$$\sigma_z = 0.2x \qquad (6)$$

where

x downwind distance (m)

The initial cloud size is assumed to be 10 feet wide and 10 feet deep with a release of 30 seconds duration at a height of 10 meters above ground level.

Table 1. Brigg's Vertical Diffusion Coefficient Formulas

Pasquill Type	σ_z
A	0.20x
B	0.12x
C	$0.08x(1 + 0.0002x)^{-0.5}$
D	$0.06x(1 + 0.0015x)^{-0.5}$
E	$0.03x(1 + 0.0003x)^{-1}$
F	$0.016x(1 + 0.0003x)^{-1}$

Table 2. Classification of Atmospheric Stability

Pasquill Category	σ_a	σ_e
A	>25°	>17.5°
B	20° to 25°	14° to 17.5°
C	15° to 20°	10.5° to 14°
D	10° to 15°	7° to 10.5°
E	5° to 10°	3.5° to 7°
F	<5°	<3.5°

Dispersion factors corresponding to various wind speeds were initially calculated using the above methodologies as coded in the PUFF/PLUME code of the SRL Weather Information and Display (WIND) system (Garrett and Murphy 1981) and are presented in Figure 1. In AXAOTHER XL, for high-velocity straight winds the user can either enter the relative air concentration or have the spreadsheet automatically calculate the concentration using the previously discussed methodologies.

2.2 Releases During Tornadoes

Tornadoes are normally characterized as violently rotating columns of air in contact with the ground. Tornado-induced loading on a structure include aerodynamic wind forces, atmospheric pressure-change forces, and impact forces from windborne debris. If a nuclear facility is incapable of resisting certain tornado wind speeds, the potential exists for a significant release of radioactive material.

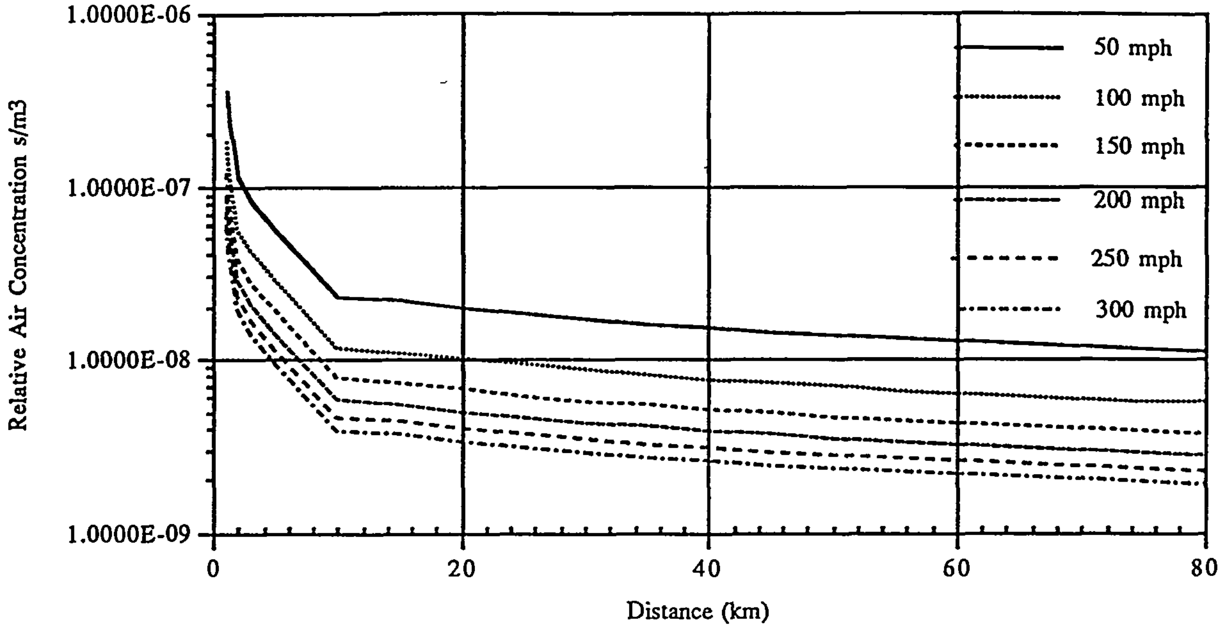

Figure 1. High-velocity Straight Wind Dispersion

A separate set of curves were developed for tornado conditions. Curves have been developed that depict the downwind relative air concentration as a function of distance (Weber and Hunter 1995). The computer model PUFF-PLUME was used to develop the curves. The following conservative assumptions were made for the analysis:

1) The tornado moves with transitional speed in the range of 7.5-22.5 m/s.

2) The released radionuclides are swept into a 100 m diameter vertical tornado vortex that stretches 3500 m in height.

3) The mesocyclone completely mixes the radionuclides.

4) The volume source represented by the mesocyclone is acted upon by a downdraft with vertical velocity in the range of 5-20 m/s.

5) Once the mesocylone's centerline reaches the surface, the down draft ceases its descent.

6) Volume source is converted to Gaussian distribution.

The results of the analysis are shown in Figure 2. The recommended model is depicted as the set of grouped curves. The upper curve represents the previously recommended model. For complete information on the determination of the curves see Weber and Hunter (1995).

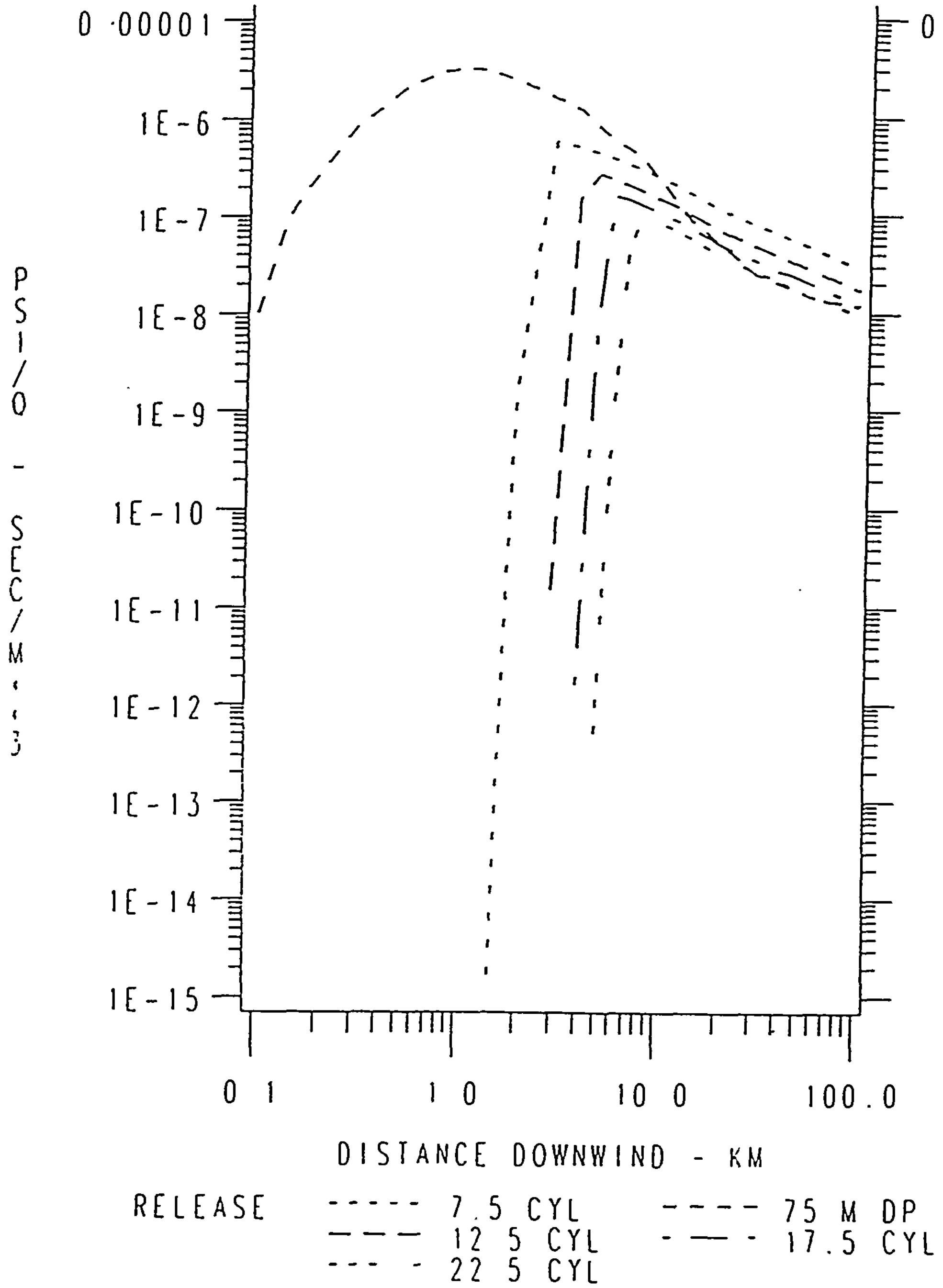

Figure 2. Relative Air Concentrations used for Tornado Conditions (7.5 CYL means 7.5 m/s translational speed for cylindrical mesocyclone)

2.3 Dose Calculations

Doses can be calculated for a hypothetical maximally exposed individual or population or for both. Once the relative air concentration is determined, dose calculations are performed using the same methods for straight wind or tornado conditions.

2.3.1 Individual Dose Calculations

Inhalation dose is estimated by the product of the radionuclide concentration in the air that is breathed, the rate at which the air is breathed, and a factor to convert intake quantities to dose. The inhalation dose to a given individual, assuming exposure during the entire plume passage, is calculated using the following general equation,

$$D = 3.17E-08(Q_n)(\frac{\chi}{Q})(DFI_n)(B)e^{-\lambda_n t} \quad (7)$$

where

3.17E-08	conversion factor (years per second)
Q_n	total release (Ci)
χ/Q	relative concentration at receptor (s/m^3)
DFI_n	effective dose equivalent factor for inhalation (rem/Ci)
B	adult maximum breathing rate, 12,000 m^3/yr (Simpkins 1995)
λ_n	decay constant (1/s)
t	travel time from release to receptor (s)

The uniform plume model assumes that the exposed individual is located in a time integrated uniform concentration of a given nuclide throughout the infinite hemisphere above ground level. The gamma-shine external dose is therefore directly proportional to the integral air concentration and is determined by multiplying the integral concentration by an infinite-plume shine dose factor. The external dose for a given nuclide, n, is expressed as:

$$D_n = (\frac{\chi}{Q})(Q_n)(DFS_n)\ e^{-\lambda_n t} \quad (8)$$

where

χ/Q	relative air concentration at the receptor (s/m^3)
Q_n	total release of nuclide n (Ci)

DFS_n	shine dose factor for nuclide n (mrem/s per Ci/m^3)
λ_n	decay constant for nuclide n (s^{-1})
t	transit time between release and exposure (s)

2.3.2 Population Dose Calculations

Population dose can be determined for an exposed group out to 50 miles from the release location. Dose to the exposed population is determined using the following equation:

$$D_i = \sum_{i=1}^{Inc}\sum_{n=1}^{Nuc}[(f_a BR_a + f_t BR_t + f_c BR_c)e^{-\lambda_n t} DFI_n Q_n (\frac{\chi}{Q})_i P_i 3.17E-08\frac{yr}{s}] \quad (9)$$

where

f_a, f_t, & f_c	fraction of population that is adult, teen and child (unitless)
BR	breathing rate of adult, teen, and child (m^3/yr)
λ_n	decay constant for nuclide of interest (1/s)
t	travel time to location i (s)
DFI_n	inhalation dose factor for radionuclide n (mrem/Ci)
$(\chi/Q)_i$	relative air concentration for radial increment i (s/m^3)
P_i	number of exposed persons in radial segment i
3.17E-08	conversion factor (yr/s)

Plume shine dose for the population is calculated using the following equation:

$$D_i = \sum_{i=1}^{Rad}\sum_{n=1}^{Nuc}[e^{-\lambda_n t} DFS_n Q_n (\frac{\chi}{Q})_i P_i * 0.001\frac{rem}{mrem}] \quad (10)$$

where

DFS_n	uniform plume shine dose factor (mrem/s per Ci/m^3)

3.0 VERIFICATION OF THEORETICAL MODELS

Hand calculations were performed to demonstrate proper use of methodologies. Complete hand calculations are shown in Appendix A.

3.1 High-velocity Straight Winds

The high-velocity straight model was tested for situations where relative air concentration was supplied by the user and calculated by the spreadsheet.

3.1.1 Individual Dose Calculations χ/Q Supplied

Input for the individual dose calculation verification is shown in Table 3. Only input necessary for individual dose calculations is shown.

Table 3. Input for High-Velocity Straight Wind Individual Dose Calculation

Tornado(T) or High-velocity Winds(W)	W
Average Wind Speed (m/s)	20
Offsite Individual Dose(Y or N)	Y
Downwind Distance(m)	13000
Chi/Q at Downwind Distance (s/m**3)	5.00E-07
(If W can Enter C for the Code to Calculate)	
	Activity(Ci)
Pu-238	0.53

Using AXAOTHER XL the resulting individual dose was 46.4 mrem and hand calculations showed exact agreement. See Appendix A, Part 1 for the actual hand calculations.

3.1.2 Individual Dose Calculations χ/Q Calculated

Input for this test was identical to the above input except the spreadsheet calculated the relative air concentration (replace 5.00E-07 with "c"). Using AXAOTHER XL the individual dose was determined to be 2.46 mrem which was in exact agreement with the hand calculations. The hand calculations are shown in Appendix A, Part 2.

3.1.3 Population Dose Calculations χ/Q Supplied

Population dose calculations for high-velocity straight wind conditions were verified using a problem with input parameters as shown in Table 4.

Table 4. Input for High-velocity Straight Wind Population Dose Calculation Verification

Tornado(T) or High-velocity Winds(W)	W	
Average Wind Speed (m/s)	30	
Offsite Individual Dose(Y or N)	N	
Downwind Distance(m)		
Chi/Q at Downwind Distance (s/m**3)		
(If W can Enter C for the Code to Calculate)		
Population Dose (Y or N)	Y	
% Population Adults	50	
% Population Teenagers	40	
% Population Children	10	
Enter Chi/Q Below (C for the code to		
Calculate) and population		
Distance -miles (km)	Chi/Q	People
0.5 (0.8)	1.0E-06	10
1.5 (2.4)	5.0E-07	20
2.5 (4.0)	2.5E-07	30
3.5 (5.6)	1.3E-07	40
4.5 (7.2)	6.5E-08	50
7.5 (12.0)	3.2E-08	60
15 (24.0)	1.6E-08	70
25 (40.0)	1.1E-08	80
35 (56.0)	9.0E-09	90
45 (72.0)	8.0E-09	100
Nuclide	Activity(Ci)	
I-129	0.5	

Using the input shown in Table 4 AXAOTHER XL resulted in a dose of 1.20E-03 person-rem. Hand calculations also yielded 1.20E-03 person-rem. For the actual hand calculations, see Appendix A, Part 3.

3.1.4 Population Dose Calculations χ/Q Calculated

To verify proper calculation of relative air concentration with the high wind model the same problem as above was used except the relative air concentrations were calculated by the spreadsheet (All "c's" were entered). AXAOTHER XL determined a population dose of 3.62E-04 person-rem, and hand calculations resulted in a dose of 3.64E-04 person-rem which is less than 1% error. See Appendix A Part 4 for the hand calculations.

3.2 Tornado Calculations

Doses following hypothetical tornadoes are calculated in a similar manner to doses calculated for high-velocity straight winds. The main difference is that the user must enter the relative air concentration rather than having the spreadsheet calculate it.

3.2.1 Individual Dose Calculations

For a hypothetical release in the event of a tornado, relative air concentration values were taken from Figure 2 for a wind speed of 7.5 m/s. Input used for the calculation is shown in Table 5.

Using AXAOTHER XL an individual dose of 1.27E-05 mrem was calculated. Hand calculations resulted in an individual dose of 1.27E-05 mrem which was in exact agreement with AXAOTHER XL. Hand calculation are shown in Appendix A, Part 5.

Table 5. Input Used to Verify Individual Dose during Tornado

	Tornado(T) or High-velocity Winds(W)	T	
	Average Wind Speed (m/s)	7.5	
	Offsite Individual Dose(Y or N)	Y	
	Downwind Distance(m)	3000	
	Chi/Q at Downwind Distance (s/m**3)	6.00E-07	
	(If W can Enter C for the Code to Calculate)		
	Population Dose (Y or N)	N	
	% Population Adults		
	% Population Teenagers		
	% Population Children		
	Enter Chi/Q Below (C for the code to		
	Calculate) and population		
	Distance -miles (km)	Chi/Q	People
	0.5 (0.8)		
	1.5 (2.4)		
	2.5 (4.0)		
	3.5 (5.6)		
	4.5 (7.2)		
	7.5 (12.0)		
	15 (24.0)		
	25 (40.0)		
	35 (56.0)		
	45 (72.0)		
Nuclide	Curies		
H-3	6.70E-01		
Xe-133	5.60E-03		

3.2.2 Populations Dose Calculations

For population dose verification for tornado conditions, input parameters were used as shown in Table 6.

Table 6. Input Parameters used for Population Dose Verification for Tornado Conditions

	Tornado(T) or High-velocity Winds(W)	T	
	Average Wind Speed (m/s)	7.5	
	Offsite Individual Dose(Y or N)	N	
	Downwind Distance(m)	3000	
	Chi/Q at Downwind Distance (s/m**3)	6.00E-07	
	(If W can Enter C for the Code to Calculate)		
	Population Dose (Y or N)	Y	
	% Population Adults	50	
	% Population Teenagers	30	
	% Population Children	20	
	Enter Chi/Q Below (C for the code to		
	Calculate) and population		
	Distance -miles (km)	Chi/Q	People
	0.5 (0.8)	0.00E+00	1
	1.5 (2.4)	1.00E-08	5
	2.5 (4.0)	5.00E-07	7
	3.5 (5.6)	4.50E-07	6
	4.5 (7.2)	4.00E-07	10
	7.5 (12.0)	2.50E-07	30
	15 (24.0)	1.00E-07	40
	25 (40.0)	7.00E-08	37
	35 (56.0)	5.00E-08	40
	45 (72.0)	4.00E-08	49
Nuclide	Curies		
H-3	3.40E+01		
Pu-238	6.70E+01		

The AXAOTHER XL spreadsheet calculated a population dose of 270 person-rem using the above input parameters. This is identical to the hand calculated dose of 270 person-rem. The hand calculations are shown in Appendix A, Part 6.

4.0 USER INSTRUCTIONS

Use of AXAOTHER is fairly simple and straightforward with several programming techniques that prevent the user from entering incorrect data. Each of the inputs and valid ranges will be discussed.

AXAOTHER XL is a calculational spreadsheet that was created using Microsoft Excel Version 4.0. Macros, the Excel programming language, is used. Later versions of Microsoft Excel will also support this program. The user simply changes the required inputs in the "AXAOTHER DATA" file and clicks a button (CALCULATE) to run the models. "AXAOTHER DATA" and "AXAOTHER MACRO" can only be opened as a "Read Only" file, so when the prompt asks, open as "Read Only." If a window comes up saying "Incorrect Password" press return. Once the calculations are complete, the user can use "Save As" to keep a copy of the results. Certain cells have been locked so inadvertent changes cannot be made by the user.

Table 7 shows a sample page of input. The CALCULATE button is contained in the upper left hand of the computer screen. Once a Macro has begun to execute, the user may work within applications other than Excel by clicking on the desktop. The user may stop execution by holding down the apple key () and the period key (.).

Input parameters are discussed and their ranges of validity are noted. If the user enters a value that is not valid, column E will show "INVALID." The spreadsheet will not execute if there is an "INVALID" anywhere in column E of the data spreadsheet.

Table 7. Input Template for AXAOTHER XL

	AXAOTHER XL	
	Title	
	NAME AND PHONE NUMBER	
Tornado(T) or High-velocity Winds(W)	T	
Average Wind Speed (m/s)	30	
Offsite Individual Dose(Y or N)	Y	
Downwind Distance(m)	1000	
Chi/Q at Downwind Distance (s/m**3)	5.00E-05	
(If W can Enter C for the Code to Calculate)		
Population Dose (Y or N)	Y	
% Population Adults	0	
% Population Teenagers	40	
% Population Children	60	
Enter Chi/Q Below (C for the code to		
Calculate) and population		
Distance -miles (km)	Chi/Q	People
0.5 (0.8)	0.00E+00	4
1.5 (2.4)	1.00E-08	5
2.5 (4.0)	5.00E-07	7
3.5 (5.6)	4.50E-07	6
4.5 (7.2)	4.00E-07	10
7.5 (12.0)	2.50E-07	30
15 (24.0)	1.00E-07	40
25 (40.0)	7.00E-08	37
35 (56.0)	5.00E-08	40
45 (72.0)	4.00E-08	49

Tornado(T) or High-velocity Winds(W)

The user enters "T" if the calculation is for tornado conditions and "W" if the calculation is for high-velocity straight winds. Any other input will result in "INVALID" and the code will not execute.

Average Wind Speed (m/s)

The average wind speed between the release point and the receptor must be entered for either case (Tornado or High Winds). For the both conditions, the wind speed is used to determine the transport time to the receptor and the associated decay of the radionuclide. If high-velocity straight winds are used, the wind speed can be used to determine the relative air concentration. The valid range is from 0 to 140 m/s.

Offsite Individual Dose(Y or N)

The user specifies whether or not the individual dose will be calculated. If the user enters "Y" for yes, the following two inputs must be entered, and if the user enters "N" the following two inputs can be left blank.

Downwind Distance(m)

Enter the downwind distance to the receptor in meters. The valid range is 1000 to 100,000 m.

Chi/Q at Downwind Distance (s/m**3)

The user enters the relative air concentration (χ/Q) at the receptor. For high-velocity straight winds the user may enter "C" and the code will automatically calculate this value. Values for both high-velocity straight winds and tornado conditions may be found in Figures 1 and 2, respectively. The user will not be allowed to enter "C" if tornado conditions have been specified.

Population Dose (Y or N)

The user specifies whether or not population dose is to be calculated.

% Population Adults
% Population Teenagers
% Population Children

If the user enters "yes" to the above question the percentage of population in each age group must be entered. The total of the three must be %100. INVALID will register for all three if the total is not %100.

Enter Chi/Q Below (C for the code to
Calculate) and population

The user enters the relative air concentration at each of the predefined downwind distances. The population at the downwind distance is also entered. For high-velocity straight wind calculations, "C' may be entered and the spreadsheet will automatically calculate the relative air concentrations.

Nuclide Curies

Enter the radionuclide and the relative release amount. If the radionuclide is not contained within the dose factor library, a message will be displayed during execution. The dose factor (DF File) can be opened "Read Only" to look at the possible list of radionuclides.

A sample of the output is shown in Table 8.

Table 8. Sample Output for AXAOTHER XL

		INDIVIDUAL INHALATION (mrem)	INDIVIDUAL PLUME (mrem)	INDIVIDUAL TOTAL (mrem)	POPULATION INHALATION person-rem	POPULATION PLUME person-rem	POPULATION TOTAL person-rem
	TOTAL	3.12E+05	1.87E-02	3.12E+05	1.22E+02	5.29E-06	1.22E+02
Nuclide	Curies						
H-3	3.40E+01	6.15E-02	0.00E+00	6.15E-02	2.41E-05	0.00E+00	2.41E-05
Xe-133	6.70E+01	0.00E+00	1.87E-02	1.87E-02	0.00E+00	5.28E-06	5.28E-06
Cs-137	1.00E+01	6.09E+00	0.00E+00	6.09E+00	2.38E-03	0.00E+00	2.38E-03
Pu-238	3.57E+01	3.12E+05	2.50E-05	3.12E+05	1.22E+02	7.07E-09	1.22E+02

5.0 CONCLUSIONS

A spreadsheet has been developed to calculate dose from high-velocity straight winds and tornado conditions given a limited amount of input. Hand calculations have been performed to ensure that the spreadsheet is properly determining the doses.

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APPENDIX A. HAND CALCULATIONS

APPENDIX A. HAND CALCULATIONS.

Part 1. High-velocity Straight Wind Individual Dose Calculation, χ/Q Supplied

Input data for this calculation is shown in Table 3. The following information is also needed for the calculation:

Decay constant for Pu-238 λ=2.505E-10 1/s

Inhalation dose factor for Pu-238 DFI=4.600E-01 mrem/pCi

Uniform Plume Dose Factor for Pu-238 DFS=1.40E-02 (mrem/Ci)/(s/m^3)

Breathing Rate Adult - 12,000 m^3/yr

Inhalation dose is calculated using the following equation:

$$D = 3.17E-08(Q_n)(\frac{\chi}{Q})(DFI_n)(B)e^{-\lambda_n t}$$

$$D = 3.17E-08(\frac{yr}{s})0.53(Ci)5.00E-07\frac{s}{m^3}12000\frac{m^3}{yr}0.46E12(\frac{mrem}{Ci})e^{(-2.505E-10(1/s)13000(m)/20(m/s))}$$

$$D = 46.4 \text{ mrem}$$

Dose due to plume exposure is calculated using the following equation:

$$D = (\frac{\chi}{Q})(Q_n)(DFS_n)\ e^{-\lambda_n t}$$

$$D = 5.00E-7(\frac{s}{m^3})0.53(Ci)1.40E-2(\frac{mrem/Ci}{s/m^3})e^{(-2.505E-10(1/s)13000(m)/20(m/s))}$$

$$D = 3.71E-09 \text{ mrem}$$

Using AXAOTHER XL the plume shine dose was calculated to be 3.71E-09 mrem which is in exact agreement with the hand calculations.

Summing the inhalation and plume shine dose gives a total dose of 46.4 mrem which is in exact agreement with AXAOTHER XL.

Part 2. High-Velocity Straight Wind Individual Dose Calculation, χ/Q Calculated

Using the input in Table 3 with relative air concentration equal to "C," one of the following two equations is used:

$$\frac{\chi}{Q}=\frac{e^{-\left(\frac{(h_e)^2}{2\sigma_z^2}\right)}}{\pi\sigma_y\sigma_z U_{HS}}$$

For downwind distance such that $\sigma_Z > (0.8)L$ relative air concentration is defined as:

$$\frac{\chi}{Q}=\frac{1}{\sqrt{2\pi}\sigma_y U_{HS} L}$$

The vertical diffusion coefficient σ_Z is calculated using the following relationship:

$\sigma_Z=0.2x = 0.2(13000m)=2600$ m

Since $\sigma_Z > (0.8)L$ the second equation shown above is used to determine the relative air concentration. First the horizontal diffusion coefficient is determined.

$$\sigma_y = \sigma_a x f(x)$$

$$\sigma_y = \sigma_a x[0.33(\frac{10000}{x})^{0.5}]$$

$$\sigma_y = 0.4(13000m)[0.33(\frac{10000}{13000})^{0.5}]$$

$$\sigma_y = 1505 \text{ m}$$

$$\frac{\chi}{Q}=\frac{1}{(2\pi)^{0.5}\sigma_y uL}$$

$$\frac{\chi}{Q}=\frac{1}{(2\pi)^{0.5}(1505m)(20m/s)(500m)}$$

$$\frac{\chi}{Q}=2.65E-08\ \frac{s}{m^3}$$

Inhalation dose is then calculated using the following equation:

$$D = 3.17E-08(Q_n)(\frac{\chi}{Q})(DFI_n)(B)e^{-\lambda_n t}$$

$$D = 3.17E-08(\frac{yr}{s})0.53(Ci)2.65E-08\frac{s}{m^3}12000\frac{m^3}{yr}0.46E12(\frac{mrem}{Ci})e^{(-2.505E-10(1/s)13000(m)/20(m/s))}$$

$$D = 2.46 \text{ mrem}$$

Using AXAOTHER XL inhalation dose was calculated to be 2.46 mrem.

Dose due to plume exposure is calculated using the following equation:

$$D = (\frac{\chi}{Q})(Q_n)(DFS_n)\ e^{-\lambda_n t}$$

$$D = 2.65E-8(\frac{s}{m^3})0.53(Ci)1.402E-2(\frac{mrem/Ci}{s/m^3})e^{(-2.505E-10(1/s)13000(m)/20(m/s))}$$

$$D = 1.97E-10\ \text{mrem}$$

Using AXAOTHER XL the plume shine dose was calculated to be 1.97E-10 mrem. Summing the inhalation and plume shine doses the total dose becomes 2.46 mrem which is in exact agreement with the spreadsheet.

Part 3. High-velocity Straight Wind Population Dose Calculation, χ/Q Supplied

Using the input shown in Table 4, the population dose is determined using the following additional information:

Decay constant for I-129 λ=1.400E-15 1/s

Inhalation dose factor for I-129 DFI=1.800E-04 mrem/pCi

Uniform Plume Dose Factor for I-129 DFS=1.32 (mrem/Ci)/(s/m^3)

Breathing Rate Adult - 10,500 m^3/yr
Teen - 10,500 m^3/yr
Child - 6,840 m^3/yr

Using the above information and the information provided in the input table, inhalation and plume shine doses are calculated using the methodologies shown below. The calculations are summarized in Table A1 for all distances and calculations and are demonstrated for the first downwind distance.

The term $e^{-\lambda t}$ accounts for decay at the downwind distance of interest. The term t is calculated as follows:

t(s)=distance(m)/windspeed (m/s)

For the first downwind distance

t=800/30= 26.7 s

therefore, $e^{-\lambda t}$=1.0.

Inhalation dose is calculated using the following equation:

$$D_i = \sum_{i=1}^{Inc}\sum_{n=1}^{Nuc}[(f_a BR_a + f_t BR_t + f_c BR_c)e^{-\lambda_n t} DFI_n Q_n (\frac{\chi}{Q})_i P_i 3.17E-08 \frac{yr}{s}]$$

For a downwind distance of 800 m

$$D_I = (0.5 \times 10500 \frac{m^3}{yr} + 0.4 \times 10500 \frac{m^3}{yr} + 0.1 \times 6840 \frac{m^3}{yr})1.0 \times 1.8E-04 \frac{mrem}{pCi} 0.5Ci \times$$

$$1E-06 \frac{s}{m^3} \times 10 persons \times 1E9 \frac{rempCi}{mremCi} \times 3.17E-08 \frac{yr}{s}$$

D_I = 2.89E-04 person-rem

For the plume shine dose, calculations are performed as follows:

$$D_{PS} = \sum_{i=1}^{Rad}\sum_{n=1}^{Nuc}[e^{-\lambda_n t} DFS_n Q_n (\frac{\chi}{Q})_i P_i]$$

$$D_{PS} = 1.0E-6(\frac{s}{m^3})0.5(Ci)1.32(\frac{mrem/Ci}{s/m^3})1 * 10 * 0.5 * 0.001 \frac{mrem}{rem}$$

D_{PS} = 3.30E-9 person-rem

Summing these two together, the total dose for the first downwind distance is 2.89E-04 person-rem.

Dose calculations are performed in a similar manner for each of the remaining distances and the results are shown in Table A1.

Table A1. Population Dose Calculation for High-Velocity Straight Winds

Distance (km)	Pop	χ/Q	$e^{-\lambda t}$	Inhalation Dose	Plume Shine Dose	Total Dose
0.8	10	1.0E-06	1	2.89E-04	3.30E-09	2.89E-04
2.4	20	5.0E-07	1	2.89E-04	3.30E-09	2.89E-04
4.0	30	2.5E-07	1	2.17E-04	2.48E-09	2.17E-04
5.6	40	1.3E-07	1	1.50E-04	1.72E-09	1.50E-04
7.2	50	6.5E-08	1	9.40E-05	1.07E-09	9.40E-05
12.0	60	3.2E-08	1	5.55E-05	6.34E-10	5.55E-05
24.0	70	1.6E-08	1	3.24E-05	3.70E-10	3.24E-05
40.0	80	1.1E-08	1	2.55E-05	2.90E-10	2.55E-05
56.0	90	9.0E-09	1	2.34E-05	2.67E-10	2.34E-05
72.0	100	8.0E-09	1	2.31E-05	2.64E-10	2.31E-05
TOTAL				1.20E-03	1.37E-08	1.20E-03

Summing the last column in Table A1, the total dose is 1.20E-03 person–rem which is in exact agreement with AXAOTHER XL.

Part 4. High-velocity Straight Wind Population Dose Calculation χ/Qs Calculated

For this calculation the same information as above is used except the relative air concentrations are calculated by the spreadsheet. For a downwind distance of 800 m the relative air concentration is calculated as follows:

The horizontal and vertical diffusion coefficients are calculated using the following relationship:

$$\sigma_Z=0.2x = 0.2(800\text{m})=160 \text{ m}$$

$$\sigma_y = \sigma_z x \frac{x^{-0.2}}{1.67+0.3\left(\frac{|1-x^{-0.2}|}{0.48}\right)^{0.5}}$$

$$\sigma_y = 0.4\times 800 \frac{0.8^{-0.2}}{1.67+0.3\left(\frac{|1-0.8^{-0.2}|}{0.48}\right)^{0.5}}$$

$$\sigma_y = 197 \text{ m}$$

Since $\sigma_Z < (0.8)L$ the following equation is used to determine the relative air concentration:

$$\frac{\chi}{Q} = \frac{e^{-\left(\frac{(h_e)^2}{2\sigma_z^2}\right)}}{\pi\sigma_y\sigma_z U_{HS}}$$

$$\frac{\chi}{Q} = \frac{e^{-\left(\frac{(10)^2}{2\times160^2}\right)}}{\pi 197\text{m}\times160\text{m}\times30\text{m/s}}$$

$$\frac{\chi}{Q} = 3.36\text{E}-07 \ \frac{\text{s}}{\text{m}^3}$$

Inhalation dose is calculated using the following equation:

$$D_i = \sum_{i=1}^{Inc}\sum_{n=1}^{Nuc}[(f_a BR_a + f_t BR_t + f_c BR_c)e^{-\lambda_n t} DFI_n Q_n (\frac{\chi}{Q})_i P_i 3.17E-08 \frac{yr}{s}]$$

For a downwind distance of 800 m

$$D_I = (0.5 \times 10500 \frac{m^3}{yr} + 0.4 \times 10500 \frac{m^3}{yr} + 0.1 \times 6840 \frac{m^3}{yr})1.0 \times 1.8E-04 \frac{mrem}{pCi} 0.5Ci \times$$

$$3.36E-07 \frac{s}{m^3} \times 10 persons \times 1E9 \frac{rempCi}{mremCi} \times 3.17E-08 \frac{yr}{s}$$

D_I = 9.72E-05 person-rem

For the plume shine dose, calculations are performed as follows:

$$D_{PS} = (\frac{\chi}{Q})(Q_n)(DF_s)_n e^{-\lambda_n t}(P)(SF)$$

$$D_{PS} = 3.36E-7(\frac{s}{m^3})0.5(Ci)1.32(\frac{mrem/Ci}{s/m^3})1 * 10 * 0.5 * 0.001 \frac{mrem}{rem}$$

D_{PS} = 1.11E-9 person-rem

Summing these two together, the total dose for the first downwind distance is 9.72E-05 person-rem.

The results of the calculations at all of the remaining distances are shown in Table A2.

Table A2. Population Dose Calculation for High-Velocity Winds

Distance (km)	Pop	χ/Q	$e^{-\lambda t}$	Inhalation Dose	Plume Shine Dose	Total Dose
0.8	10	3.36E-07	1	9.72E-05	1.11E-09	9.72E-05
2.4	20	5.84E-08	1	3.38E-05	3.86E-10	3.38E-05
4	30	3.99E-08	1	3.47E-05	3.95E-10	3.47E-05
5.6	40	3.10E-08	1	3.59E-05	4.10E-10	3.59E-05
7.2	50	2.57E-08	1	3.71E-05	4.24E-10	3.71E-05
12	60	1.84E-08	1	3.19E-05	3.64E-10	3.19E-05
24	70	1.30E-08	1	2.63E-05	3.00E-10	2.63E-05
40	80	1.01E-08	1	2.33E-05	2.66E-10	2.33E-05
56	90	8.51E-09	1	2.22E-05	2.53E-10	2.22E-05
72	100	7.51E-09	1	2.17E-05	2.48E-10	2.17E-05
				3.64E-04	4.15E-09	3.64E-04

The population dose was determined to be 3.64E-04 person-rem from the hand calculations and 3.62E-04 person-rem using AXAOTHER XL which results in <1% error.

Part 5. Individual Dose Calculation for Tornado Conditions

Input data for this calculation is shown in Table 5. The following information is also needed for the calculation:

Decay constant for H-3 λ=1.790E-09 1/s
Decay constant for Xe-133 λ=1.530E-06 1/s

Inhalation dose factor for H-3 DF_I=9.500E-08 mrem/pCi
Inhalation dose factor for Xe-133 DF_I=0.0 mrem/pCi

Uniform Plume Dose Factor for H-3 DF_P=0.00 (mrem/Ci)/(s/m^3)
Uniform Plume Dose Factor for Xe-133 DF_P=5.58E+00 (mrem/Ci)/(s/m^3)

Breathing Rate Adult - 12,000 m^3/yr

Inhalation dose is calculated using the following equation:

H-3

$$D = 3.17E-08(Q_n)(\frac{\chi}{Q})(DFI_n)(B)e^{-\lambda_n t}$$

$$D = 3.17E-08(\frac{s}{yr})0.67(Ci)6.00E-07\frac{s}{m^3}12000\frac{m^3}{yr}9.50E+04(\frac{mrem}{Ci})e^{(-1.790E-09(1/s)3000(m)/7.5(m/s))}$$

$$D = 1.45E-05 \text{ mrem}$$

Since Xe-133 is a noble gas, the inhalation dose from this radionuclide is zero.

For tritium the plume shine dose is zero and the dose due to plume exposure of Xe-133 is calculated using the following equation:

$$D_n = (\frac{\chi}{Q})(Q_n)(DFS_n)\ e^{-\lambda_n t}$$

$$D_n = 6.00E-7(\frac{s}{m^3})0.0056(Ci)5.58E+00(\frac{mrem/Ci}{s/m^3})e^{(-1.53E-06(1/s)3000(m)/7.5(m/s))}$$

$$D = 1.87E-08 \text{ mrem}$$

Using AXAOTHER XL the plume shine dose was calculated to be 1.87E-08 mrem which is in exact agreement with the hand calculations.

Summing the inhalation and plume shine dose gives a total dose of 1.45E-05 mrem which is in exact agreement with AXAOTHER XL.

Part 6. Population Dose Calculations for Tornado Conditions

The population dose for tornado conditions is calculated using the following additional information:

Decay constant for H-3 λ=1.79E-09 1/s

Decay constant for Pu-238 λ=2.50E-10 1/s

Inhalation dose factor for H-3 DFI=9.5E-08 mrem/pCi
Inhalation dose factor for Pu-238 DFI=0.46 mrem/pCi

Uniform Plume Dose Factor for H-3 DFS=0.00 (mrem/Ci)/(s/m^3)
Uniform Plume Dose Factor for Pu-238 DFS=0.014 (mrem/Ci)/(s/m^3)

Breathing Rate Adult - 10,500 m^3/yr
Teen - 10,500 m^3/yr
Child - 6,840 m^3/yr

Using the above information and the information provided in the input table, Inhalation and Plume Shine Doses are calculated using the methodologies shown below. The calculations are summarized in Table A3.

Calculations are demonstrated for the downwind distance of 2.4 km. All other calculations are performed in the same manner except different downwind distances are used.

The term $e^{-\lambda t}$ accounts for decay at the downwind distance of interest. Due to the long half lives with respect to the time period of interest of both radionuclides, this term is 1.0.

$$D_I = (0.5 \times 10500 \frac{m^3}{yr} + 0.3 \times 10500 \frac{m^3}{yr} + 0.2 \times 6840 \frac{m^3}{yr}) 1.0 \times 9.5E-08 \frac{mrem}{pCi} \times$$

$$34 Ci \times 1E-08 \frac{s}{m^3} \times 5 persons \times 1E9 \frac{rempCi}{mremCi} \times 3.17E-08 \frac{yr}{s}$$

D_I = 5.00E-08 person-rem

For a downwind distance of 2.4 km for Pu-238

$$D_I = (0.5 \times 10500 \frac{m^3}{yr} + 0.3 \times 10500 \frac{m^3}{yr} + 0.2 \times 6840 \frac{m^3}{yr}) 1.0 \times 0.46 \frac{mrem}{pCi} \times$$

$$67 Ci \times 1E-08 \frac{s}{m^3} \times 5 persons \times 1E9 \frac{rempCi}{mremCi} \times 3.17E-08 \frac{yr}{s}$$

D_I = 0.477 person-rem

Summing the above two calculations gives an inhalation dose of 0.477 person-rem from both tritium and plutonium. This is in agreement with the values shown in the following table.

The plume shine dose for tritium is zero.

For a downwind distance of 2.4 km the plume shine dose for Pu-238 is determined as follows:

$$D = (\frac{\chi}{Q})(Q_n)(DF_s)_n e^{-\lambda_n t} \times P \times SF$$

$$D = 1.00E-8(\frac{s}{m^3})67(Ci)0.014(\frac{mrem / Ci}{s / m^3}) * 1.0 * 5persons * 0.5 * \frac{rem}{1000mrem}$$

$D = 2.35E\text{-}11$ person-rem

This number is in exact agreement with the spreadsheet calculations.

For a downwind distance of 2.4 km the total dose is 0.477 person-rem. Calculations are performed in a similar manner for the remaining distances. The results of the calculations at the remaining distances are shown in the Table A3.

Table A3. Population Dose Calculations for Tornado Conditions

Distance (km)	Pop	χ/Q	e-λt	Inhalation Dose	Plume Shine Dose	Total Dose
0.8	1	0.00E+00	1	0.00E+00	0.00E+00	0.00E+00
2.4	5	1.00E-08	1	4.77E-01	2.35E-11	4.77E-01
4.0	7	5.00E-07	1	3.34E+01	1.64E-09	3.34E+01
5.6	6	4.50E-07	1	2.58E+01	1.27E-09	2.58E+01
7.2	10	4.00E-07	1	3.82E+01	1.88E-09	3.82E+01
12.0	30	2.50E-07	1	7.16E+01	3.52E-09	7.16E+01
24.0	40	1.00E-07	1	3.82E+01	1.88E-09	3.82E+01
40.0	37	7.00E-08	1	2.47E+01	1.21E-09	2.47E+01
56.0	40	5.00E-08	1	1.91E+01	9.38E-10	1.91E+01
72.0	49	4.00E-08	1	1.87E+01	9.19E-10	1.87E+01
TOTAL				2.70E+02	1.33E-08	2.70E+02

From the table above the total dose was determined to be 270 person-rem which is in exact agreement with the population dose determined using AXAOTHER XL.

Distribution List

L.M. Papouchado, 773–A
A.L. Boni, 773–A
W.H Carlton, 773–A
M.J. Hitchler, 730–2B
G.T. Jannik, 773–A
K.R. O'Kula, 730–2B
J.M. East, 730–2B
EDG Files(2), 773–A