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User Guide for the Air Force Nuclear Weapons Center Dust Cloud Calculator Version 1.0

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User Guide for the Air Force Nuclear Weapons Center Dust Cloud Calculator Version 1.0

John W St. Ledger

Abstract

The Air Force Nuclear Weapons Center (AFNWC) Dust Cloud Calculator is a Java™ application that can calculate the dust loading and radiation dose for an aircraft or cruise missile flying through a dust cloud created by a nuclear detonation. The dust cloud model is based upon the Air Force Institute of Technology (AFIT) dust cloud and fallout model. The AFIT model uses a combination of algorithms from the Weapons System Evaluation Group (WSEG) model 10 fallout code, the Defense Land Fallout Interpretive Code (DELFIC), and algorithms developed at AFIT to calculate the nuclear dust cloud.

The Dust Cloud Calculator uses a stationary cloud, that grows with time, but that doesn't move with a wind. The Calculator can calculate the dust loading and radiation dose using 14 different particle size distributions. The particle fall mechanics can be calculated for the United States 1962 or United States 1976 standard atmospheres, as well as for any of the United States 1966 Supplemental Atmospheres. The fly-through mass loading can be calculated for any straight-line path through the dust cloud. The total mass loading, and the intercepted particle size distributions are reported. The fly-through dose can be calculated at the aircraft skin in rad(Si). The accumulated dose inside the aircraft can be reported for the B-1B, B-52H, E-3, E-4B, EC-135, and the KC-135 aircraft. The vertical dust mass, and activity distributions can be plotted and shown for any time after cloud stabilization. In addition, there is a tab in the Calculator to present the probability of flying through dust clouds that are contained within an area.

User Guide for the
Air Force Nuclear Weapons Center
Dust Cloud Calculator
Version 1.0

Introduction

Since the Mount St. Helen's volcanic eruption, the effects of dust clouds from nuclear detonations and volcanoes have become of much more interest to the Air Force (AF) acquisition community. This nuclear Dust Cloud Calculator can calculate the areal dust mass and the radiation dose to aircraft flying through nuclear dust clouds. The dust cloud is allowed to grow in size with time, to simulate the effects of wind shear on the cloud, but the cloud is stationary. It is not transported by the wind. Up to 14 different particle size distributions can be selected for the cloud. The stabilized cloud is based upon fits to a DELFIC cloud rise in a dry 1976 United States Standard Atmosphere. The particle fall can be calculated for the United States (US) 1962 Standard Atmosphere, the US 1976 Standard Atmosphere, or any of the 1966 US Supplemental Atmospheres (NOAA, 1976, 1962, 1966). In addition the vertical dust mass, and vertical cloud activity can be plotted as a function of altitude, and time after the detonation. Finally, there is a tab in the application that can be used to calculate the probability of flying through a dust cloud.

The dust cloud model uses the Air Force Institute of Technology (AFIT) dust cloud and fallout model. (Bridgman, 1982, Hopkins, 1984, Conners, 1985, among others) The model is relatively easy to implement, and has been validated for use in Air Force survivability studies. (Palmer, 1987) The Air Force adapted the AFIT dust cloud model into the Residual Dust and Radiation Model (REDRAM), which was developed by Palmer at the AF Nuclear Criteria Group Secretariat (NCGS), by Brown at the Aeronautical Systems Division, and by Hopkins at the Air Force Center for Studies and Analysis. (Palmer, 1987) The source code and executables for REDRAM no longer exist. In 2011, the AFNWC started an effort to resurrect the Air Force's nuclear dust cloud modeling capability. Dr. Michael Clemens wrote the core Java code for the dust cloud calculator, and then Alex Stevenson, and John St. Ledger developed the application into the form it exists today.

The AFNWC Dust Cloud Calculator is written entirely in the Java™ language, and can be executed on any computer with a suitable Java runtime environment (JRE) of version 1.7 or higher. The application has been tested on Windows 7 computers, and on Linux based computers running Red Hat Linux. It has been tested on Mac OS X computers.

The Clemens or Palmer reference can be used to understand the workings of the dust cloud model. The model was validated by Palmer. (Clemens, 2011, Palmer, 1987) The stabilized clouds use the WSEG10 formulas for cloud height and growth after stabilization time. The dust particles are gravity sorted in the stabilized cloud with the smaller particles being lofted to higher altitudes. The particle heights are calculated with fits to DELFIC particle starting heights in a 1976 Standard Atmosphere. (NOAA, 1976)

The cloud is assumed to be a vertical cylinder, with the dust density for each particle size being described as a 3 dimensional Gaussian spheroid. The standard deviations of the spheroids are fits to DELFIC stabilized cloud sizes. In this Calculator the wind shear is always a constant of 1 per hour. The cloud model can calculate the cloud growth using other shear values, but the Calculator uses a constant shear.

This is the first version of the AFIT dust cloud model that has different standard atmospheres selectable to use for the fall rate of the dust particles. It is best to just use the 1976 Standard Atmosphere. Surprisingly, there is no practical difference in the particle fall rates when different atmospheres are selected. Also, the cloud dimensions at stabilization are the same no matter what atmosphere is selected. The particle fall velocities are calculated using Stokes Law, with corrections for the aerodynamic drag of larger particles using a method developed by McDonald and Davies. (Bridgman, 1982)

The rest of this user guide explains how to install and use the Dust Cloud Calculator software.

Software Distribution DVD

The AFNWC Dust Cloud Calculator is one application in the Los Alamos National Laboratory (LANL) Nuclear Weapon Analysis Tools. The software may be ordered from the Defense Threat Reduction Information Analysis Center (DTRIAC) at Kirtland AFB. Please contact Janet Ortiz at 505-846-9420 or JANET.ORTIZ_CONTRACTOR @abq.dtra.mil. If Janet is not available, then call 505-853-1789, or send an email to: dtriac@abq.dtra.mil. Ask to be put on distribution for the LANL Nuclear Weapon Analysis Tools. The thirteen applications comprising the analysis tools will be shipped on a DVD. Figure 1 shows the directory structure of the distribution DVD.

Figure 1—Distribution DVD Contents

Copyrights and Distribution

The copyrights.txt file has copyright information on software written by non-LANL authors that is included with the open source libraries, or that is included directly in the source code. The Distribution.txt file has the limited distribution caveats for the software. The software is Official Use Only, because it is Export Controlled as critical technology.

Documentation Directory

The documentation directory has user guides for each application, and other reports describing the use or capabilities of the applications. In addition there is a user guide for the LANL Plotting software, which is used by all of the applications to display data plots. There is also a developer directory that has the JavaDoc information for the Java source code.

Geologies Directory

The geologies directory has 38 predefined geologies that can be used by the Dug1c, Dug2d, and Tunnel Damage ground shock codes. The files ending in .doc have the geologies in a textual form. The .obj files can be imported into the ground shock codes, rather than the user having to manually build up the geology definition one layer at a time.

Java Tools For… Directories

The Java Tools for Mac OS X, Windows, and Linux contain the command (batch), library, and executable jar files for each application. The library directory is discussed in the “Libraries” section below.

ReadMe… Directory

The ReadMe 30 Dec 2016 Tools vsn 5.6 directory has a text file with a running commentary on changes made to the Analysis Tools over the years.

Installation.txt File

The Installation.txt file has the installation instructions for all operating systems.

Source Code Directory

The source code directory has the Java source files.

Wind Data

The Wind Data folder has a collection of wind files used by the Dust Cloud Simulation model. The winds are for every month for the years 2000 to 2010. There is a wind pattern for the first, tenth, and twentieth day of each month. The winds cover the entire world from 0 to 50 km altitude.

WorldWindCache

The WorldWindCache has information needed by the NASA World Wind software to draw such things as national borders. This cache directory is used by World Wind to draw map information if the computer running the Base Escape Simulator or the Dust Cloud Simulation Model is not connected to the Internet.

Software Installation

To install the applications on a Macintosh computer, drag the “Java Tools for Mac OS X” folder, the “Wind Data” folder, and the “WorldWindCache” folder to a convenient directory on your hard drive. To install the applications on a Windows computer, drag the “Java Tools for Windows”, the “Wind Data” folder, and the “WorldWindCache” folder to a convenient directory on your hard drive. Dragging these folders to your hard drive copies the Java executables, the Fortran executables, and supporting files and libraries to your hard drive. It does not copy the documentation, or the geology files. These two directories should also be copied to your hard drive, and placed in the same directory as the “Java Tools for…” directory.

To install the applications on a Linux computer with Red Hat Linux™ , drag the “Java Tools for Linux”, the “Wind Data” folder, and the “WorldWindCache” folder to a convenient directory on your hard drive. This installs the executables that have been compiled for Red Hat Linux™ .

Launching an Application

This version of the Nuclear Weapon Analysis Tools has been tested with version 1.7 of the Java virtual machine for the Windows™ operating system, the Mac OS X operating system, and the Red Hat Linux operating system. It will probably run with later versions of the virtual machine, but there have been cases in the past when a new virtual machine will cause an application to fail. Versions of the Java Runtime Environment for Mac, Windows, and Linux machines may be downloaded from the Oracle Corporation Java web site.

On Windows each application directory has a file name Run_*.bat. For Mac OS X and Linux each application directory has a file named Run_*.command. These files control the version of the JRE that is used by the applications, and set other parameters such as the amount of memory that the application needs. The user should double click these files to launch the applications. If double clicking on these files does not successfully launch the application, try double clicking on the appName.jar file in the application directory. For this option to work, the Java Runtime Environment must have been downloaded from the Oracle Corporation web site, and installed on the computer.

Logging

The Calculator creates a log file every time it is started. The beginning of the file has information written when the application is started. The time of day, operating system, JRE version, etc. are written to a header. Each time the "Calculate" button is clicked, the data that the user input, all error messages displayed to the user, and the results of the calculation are written to the file. Each day after midnight, the previous log file is saved with the date, and a new log_file.txt file is created. The six latest log files are saved by the application. Any older logs are deleted when the application is started. If the application is started multiple times in a day, one log file for that day will have multiple entries.

Input Errors and Output Information

If the user enters invalid data, or if there is some information about the calculation that the user should be aware of, a window will be shown with the information. Figure 2 shows an error message when the cloud penetration time was entered as a negative value. The earliest time allowed is zero, which is the cloud stabilization time. In Figure 3, the user entered 1,000 as the aircraft altitude, but commas are not allowed for numerical inputs. Figure 4 shows that some input errors may be shown in a Run Time Exception dialog.

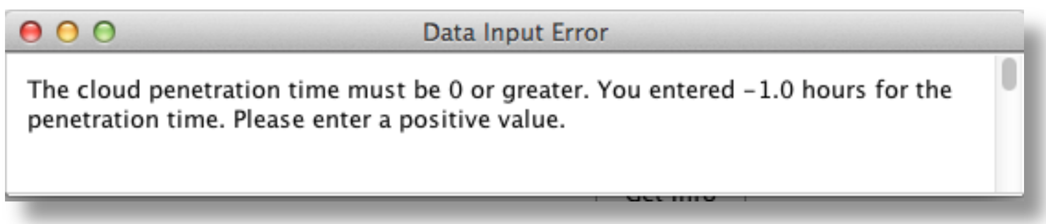

Figure 2—User Receiver Altitude Input Error

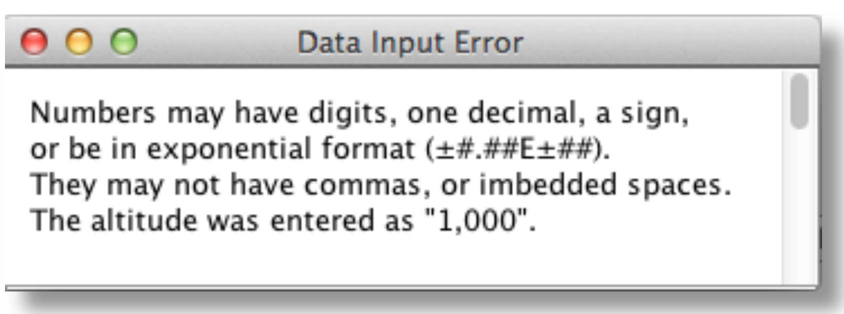

Figure 3— User Numerical Input Error

Figure 4—Run Time Exception Dialog

Particle Size Distributions Tab

Figure 5 shows the beginning tab when the Calculator is started. If the "Get Info" button is clicked, a window will appear that describes the tab's function, and which gives a short description of each of the particle size distributions (PSDs).

Historically, either a power law, or a log-normal distribution have most commonly been used to model the measured distributions from nuclear tests. Baker showed that the power law distribution was just a subset of a log-normal distribution, when the nuclear dust cloud particles were sampled by aircraft at low and medium altitudes. (Baker, 1987)

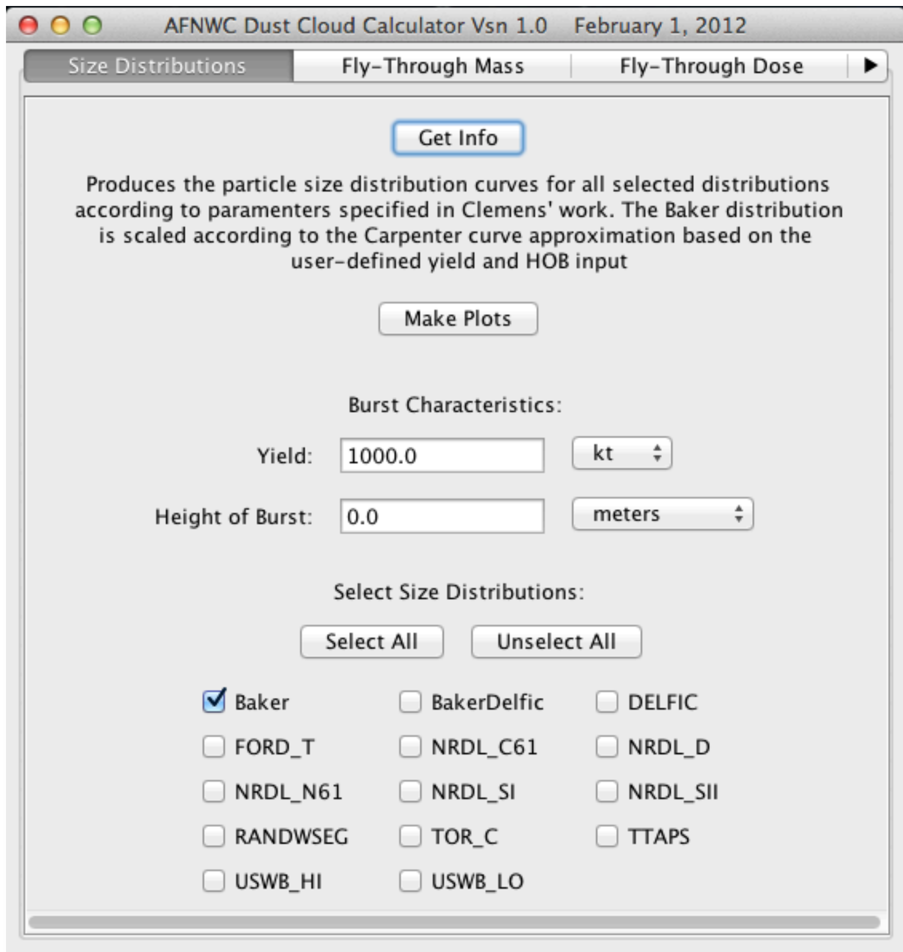

Figure 5—The Application Screen on Start Up

A log-normal distribution is shown in Equation 1:

$$F(r) = \frac{1}{\sqrt{2\pi}\,\beta r}\, e^{-\frac{1}{2}\left[\frac{\ln(r) - \alpha_n}{\beta}\right]^2} \qquad (1)$$

where:
$\alpha_0 = \ln(rm)$, or the log of the median particle radius
$\beta = \ln(\sigma)$, and
$\alpha_n = \alpha_0 + n\beta^2$

and F(r)dr is the fraction of particles with a radius of r, rm is the median particle radius, β is the natural log of the standard deviation of the particle radius distribution, and r is the particle radius in microns. The n determines the type, or moment, of the distribution. For $n = 3$ Equation (1) represents a volumetric distribution, or a mass particle size distribution, for $n = 2$ it represents a surface distribution and $n = 0$ gives the particle radius distribution, or size distribution. Equation (1) then can be used to determine both the activity particle distribution (depending on whether the radioactive material in the particles is volumetrically or surface distributed) and the mass distribution (assuming a uniform particle density, $n = 3$) given the distribution's median radius and standard deviation. The mean radius and standard deviation of the particle size distribution will vary depending on the bomb type, the detonation altitude, and the soil. These quantities are listed Table 1 for the particle size distributions in Figure 5. Most of the PSDs in Table 1 are from Conners. (Conners, 1985) The Baker and BakerDelfic PSDs are from Clemens. (Clemens, 2011)

Table 1—Particle Size Distributions

PSD Name	Median Particle Radius (microns)	PSD Sigma	Source	Remarks
Baker	--	--	Baker	2 log-normal distributions
BakerDelfic	--	--	Clemens	2 log-normal distributions
TTAPS	0.25	2.0	Turco	Uses log-normal to approximate TTAPS, with no small tail
NRDL-N61	0.00039	7.24	Freiling	Nevada Soil
NRDL-C61	0.103	5.38	Freiling	Coral
NRDL-D	0.01	5.42	Polan	Nevada Dynamic
DELFIC	0.204	4.0	Bridgman	Activity Volume Fractionation = 0.68
USWB-HI	3.48	2.72	Polan	Hicap
USWB-LO	3.84	3.0	Polan	Locap
FORD-T	5.98	3.23	Polan	
RANDWSEG	10.6	2.0	WSEG	Activity Volume Fractionation = 1.0
NRDL-SII	27.1	1.48	Polan	Saltwater II
NRDL-SI	36.8	1.51	Polan	Saltwater I
TOR-C	50.6	1.36	Polan	Coral

When the "Make Plots" button is clicked in Figure 5, a plot will be shown of the number size distribution, the activity size distribution, and the mass size distribution of the selected PSDs. Figure 6 shows the Baker PSD, the activity size, and mass size distributions for a 1 kt surface burst.

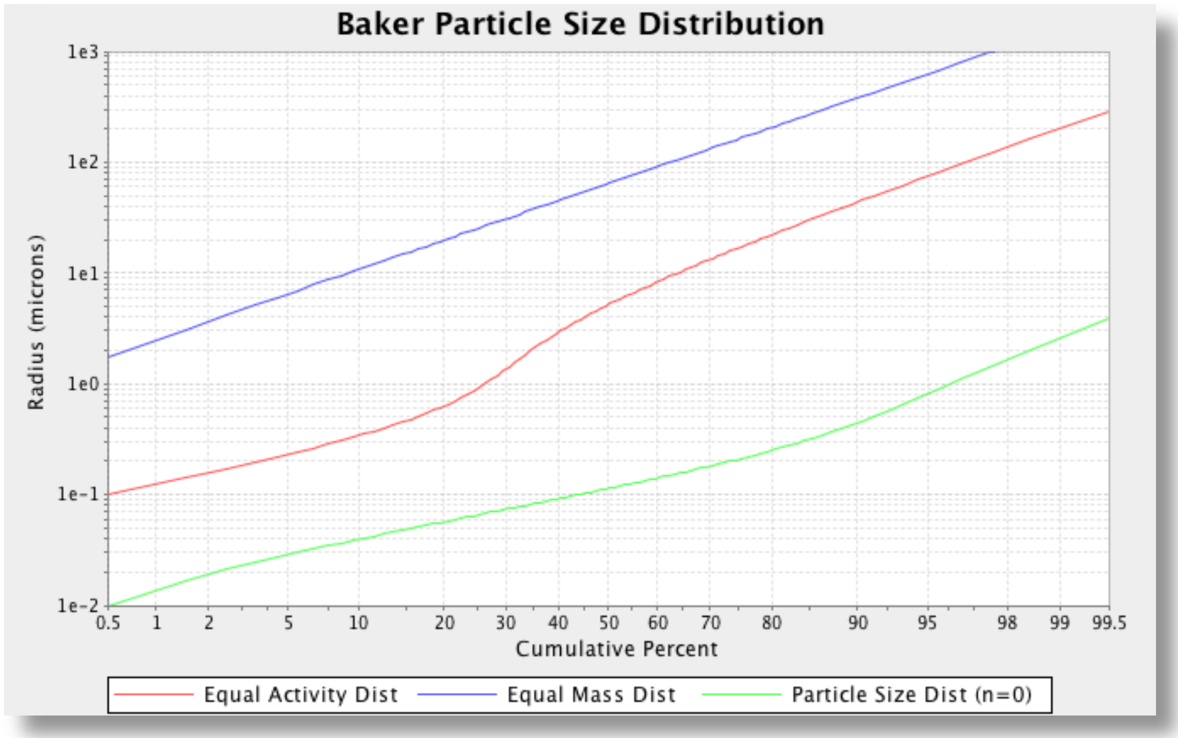

Figure 6—Surface Burst Baker Particle Size Distribution

A log-normal distribution should show as a straight line in Figure 6. However, Baker showed that a bi-modal log-normal particle size distribution gives the most reasonable description of the PSD for a nuclear dust cloud. Equation (2) gives the equation for a bi-modal distribution:

$$F_{Baker}(r) = \frac{N_1}{\sqrt{2\pi}\,\beta_1 r}\, e^{-\frac{1}{2}\left[\frac{\ln(r) - \alpha_{n1}}{\beta_1}\right]^2} + \frac{N_2}{\sqrt{2\pi}\,\beta_2 r}\, e^{-\frac{1}{2}\left[\frac{\ln(r) - \alpha_{n2}}{\beta_2}\right]^2} \qquad (2)$$

where α_n and β are the same as in Equation (1), and $N_1 + N_2 = 1$ so that the function remains normalized. Baker found that the N_1 particles were small, spherical particles with the activity distributed volumetrically while the N_2 particles were larger, irregularly shaped particles with the activity distributed over the surface. N_2 particles were found to be responsible for local fallout and N_1 particles were responsible for global fallout since they were smaller and stayed in the atmosphere longer. Baker observed that the N_2 type particles were absent for air bursts, and less numerous for tower bursts. Thus the ratio N_1/N_2 increased for an increased height of burst. The characteristics for the particle types N_1 and N_2 are summarized in Table 2.

Table 2 – Characteristics of N_1 and N_2 Particles

Type	N_1	N_2
Shape	Spherical	Irregular
Activity	High Specific Activity $\propto r^3$	Low Specific Activity $\propto r^2$
Origin	Vaporized material, weapon mass + soil	Unmelted/partially melted material, soil
Present in Air Burst?	Yes	No
rm (μm)	≈0.1	≈0.2
β	≈ln(2.0)	≈ln(3.0 – 5.0)
	Surface Burst Distributions	
Size (n=0)	$N_1 = 2.2/3.2$	$N_2 = 1/3.2$
Mass (n=3)	$M_1 = 0.017/1.017$	$M_2 = 1/1.017$
Activity (n=2 and n=3)	$F_1 = 0.25$	$F_2 = 0.75$

Baker gives the values for N_1 and N_2 (number fractions), M_1 and M_2 (mass fractions), and F_1 and F_2 (activity fractions) for surface bursts. For an air burst $N_1 = 1.0$ and $N_2 = 0$. Figure 7 shows the Carpenter curve of total dust mass lofted as a function of scaled height of burst (SHOB), except that the curve has been adjusted to show an activity fraction of 0.75 for a surface burst, rather than a mass lofted of 0.33 kiloton of dust per kiloton of yield. Notice that the SHOB is in ft/Mt$^{1/3}$, rather than the more typical ft/kt$^{1/3}$. Also plotted in Figure 7 is F_2 for 16 different above ground nuclear tests. The values of F_2 are provided by Baker. (Baker, 1987)

For the Baker PSD, the F_2 is calculated using the solid line in Figure 7 as a function of the SHOB. Once F_2 is known, then the size fractions (N_1 and N_2), and the mass fractions (M_1 and M_2) can be calculated using relations provided by Baker.

The Baker PSD is the only PSD in the dust cloud calculator that changes with the height of the burst above the ground. It is the default PSD, and should normally be preferred over the other PSDs in Table 1. The other PSDs are included in the calculator for parametric studies, and comparisons with other dust cloud models.

The TOR-C PSD is an example of a PSD with very large particles, and the NRDL-N61 is an example of a PSD with very small particles. Figure 8 shows the number size distributions for the TOR-C PSD, the Baker PSD for a surface burst, and the NRDL-N61 PSD. This shows the particle size variation that is possible in different PSDs.

Figures 9, 10, and 11 show the Baker particle number size distribution for a surface burst, an air burst at 30 scaled meters, and an air burst above 215 scaled meters.

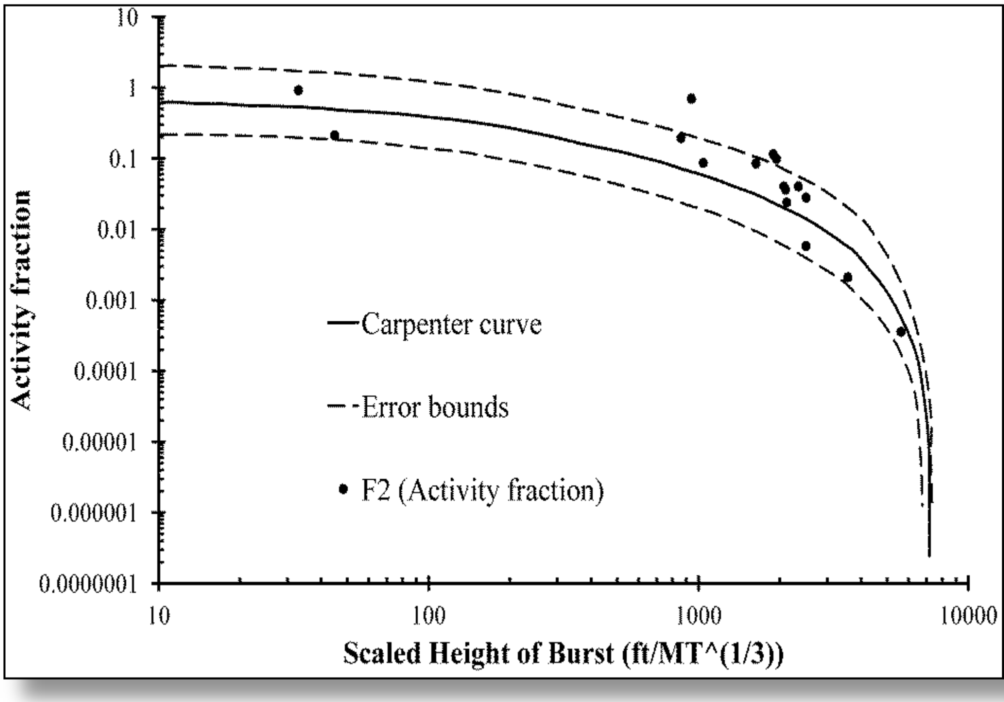

Figure 7—Activity Fraction as a Function of Scaled Burst Height

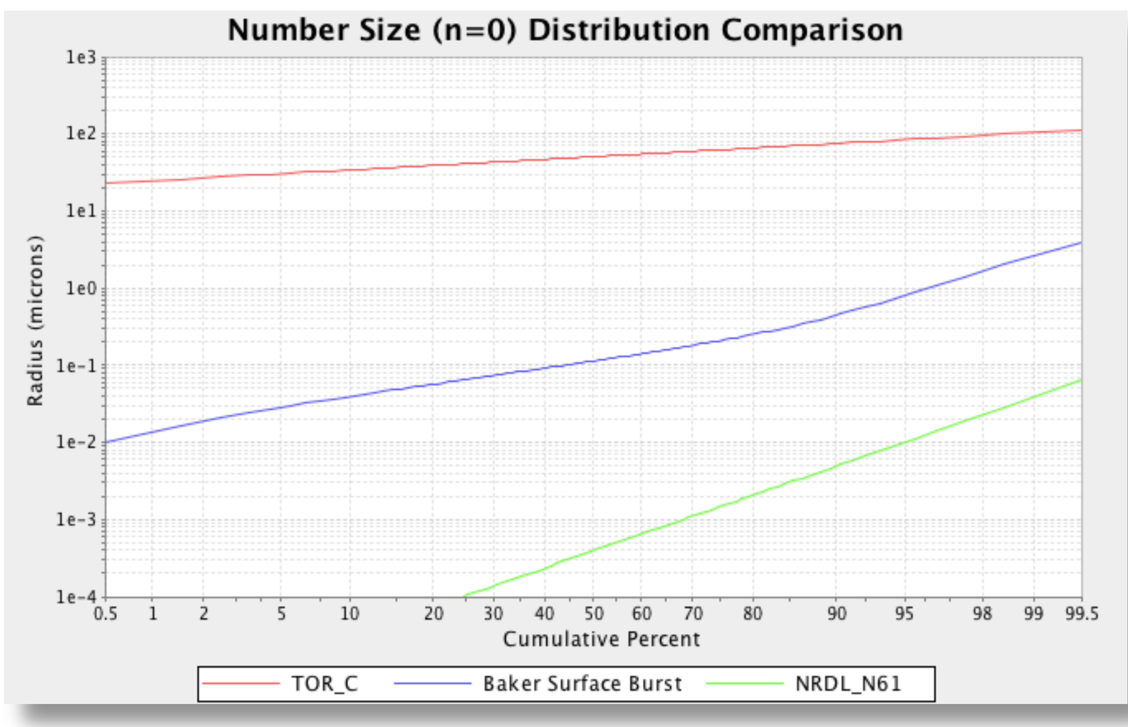

Figure 8—Large, Medium, and Small Number Size Distribution Comparison

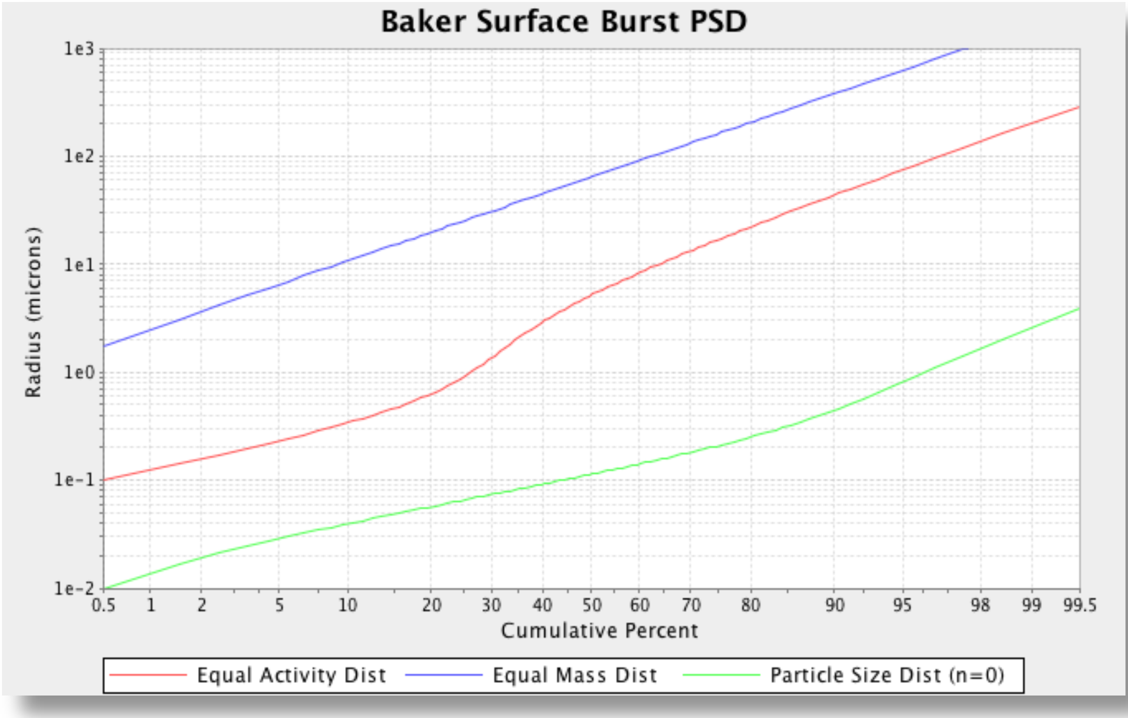

Figure 9—Baker Surface Burst PSD

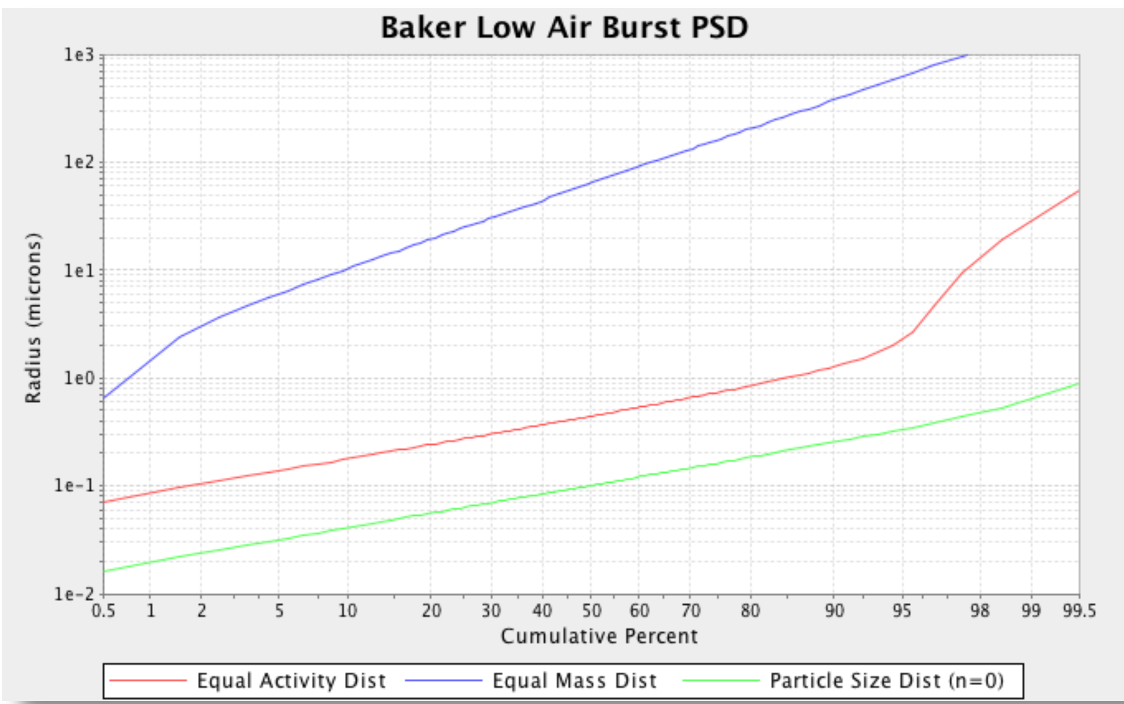

Figure 10—Baker Low Air Burst PSD

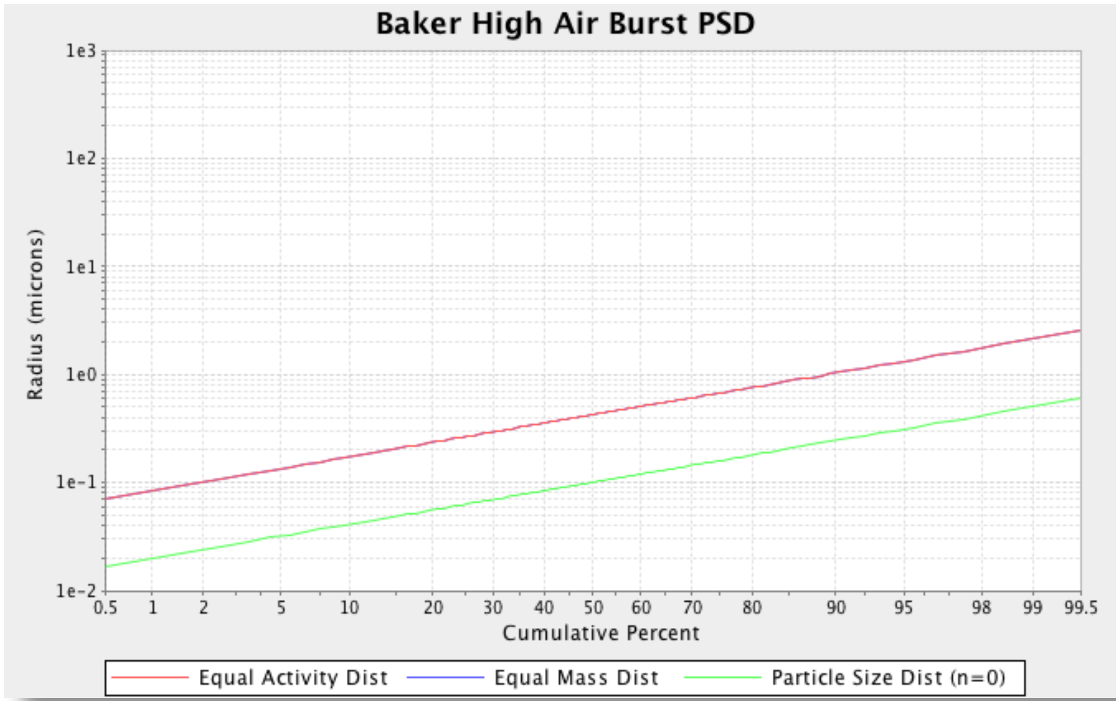

Figure 11—Baker High Air Burst PSD

Fly-Through Mass Tab

Figure 12 shows the "Fly-Through Mass" tab after a calculation has been performed using the default tab inputs. The results of the calculation are shown in the two result lines at the bottom of the tab. Vertical dust mass is the areal dust mass for a receiver diving from the user input altitude (8,000 meters) to the ground, vertically through the cloud center. The horizontal dust mass is for a receiver flying a horizontal flight path through the center of the cloud. In addition to the areal dust mass, Figure 13 shows the dust mass as a function of particle radius for the fly-through calculation in Figure 12. At the time of cloud fly-through, which is one hour after the detonation, this figure shows that particles with a radius of about 225 microns are the largest particles still within the dust cloud. Larger particles have already settled to the ground.

The atmosphere select field in Figure 12 has 14 different standard atmospheres for the dust cloud particles to fall through. Figure 14 shows the particle size distributions for the same inputs as in Figure 12, except the cloud penetration time is 6 hours after the detonation, and three different atmospheres were used for the particles to fall through. As a general rule, different atmospheres have only a small effect on the dust mass intercepted, and the 1976 Standard Atmosphere can be used for all calculations.

The dust cloud stabilizes at about 10 minutes after the detonation. If the penetration time entered is less than the cloud stabilization time, the penetration time is adjusted to be the cloud stabilization time.

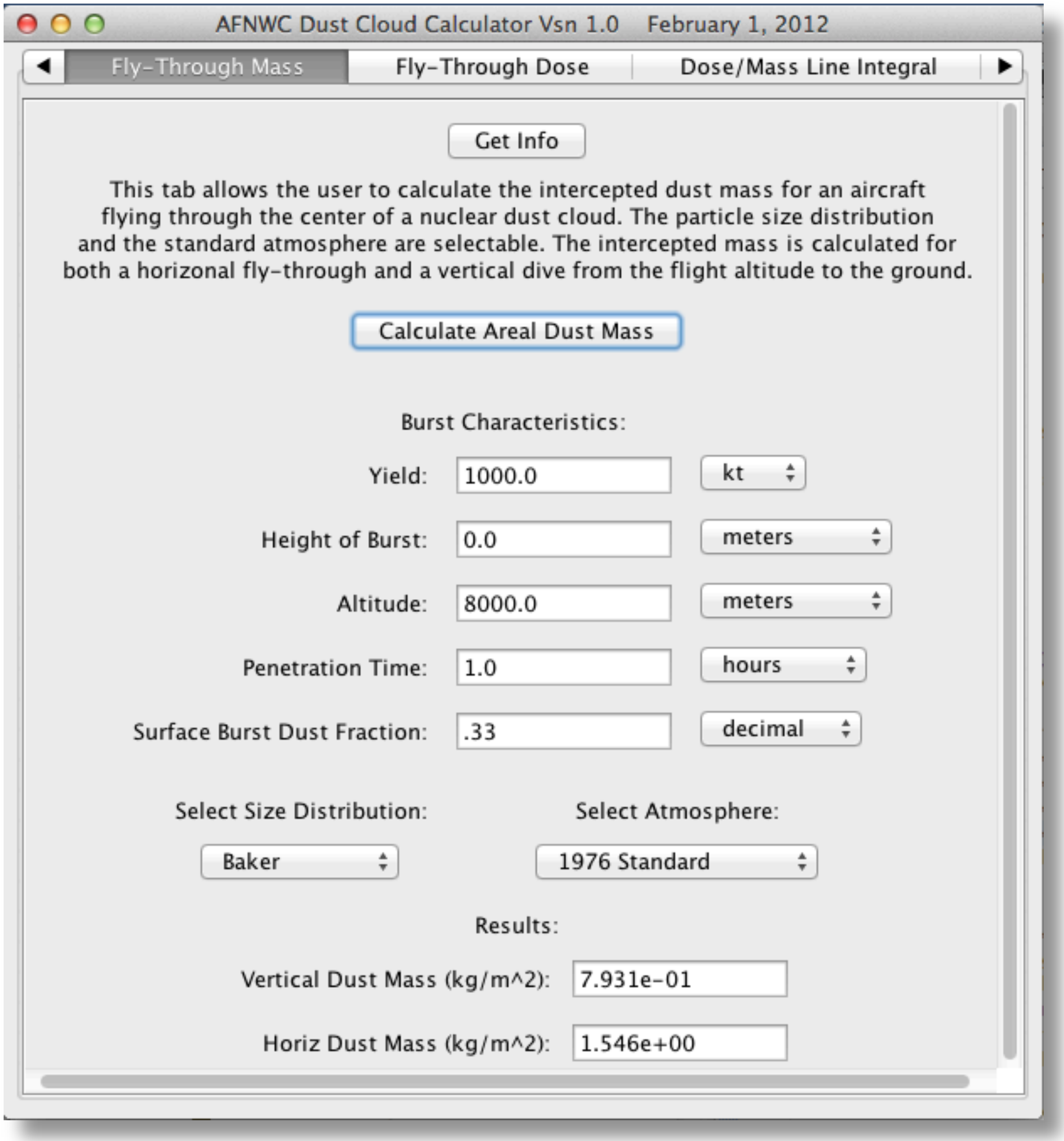

Figure 12—The Fly-Through Mass Tab

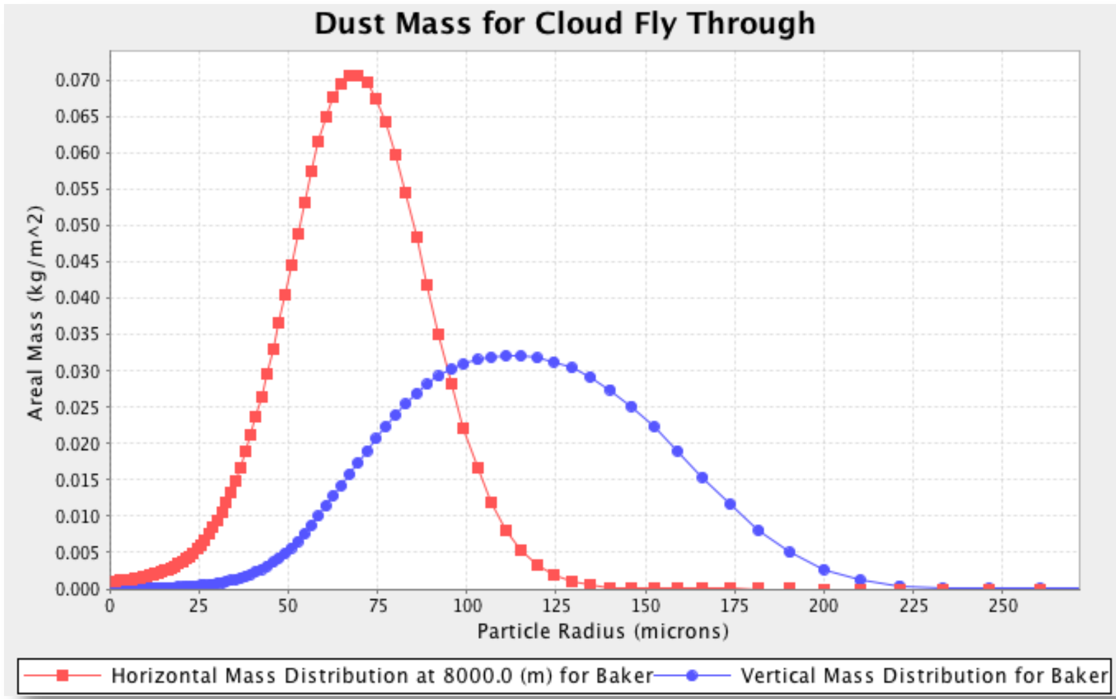

Figure 13—Fly-Through Particle Sizes

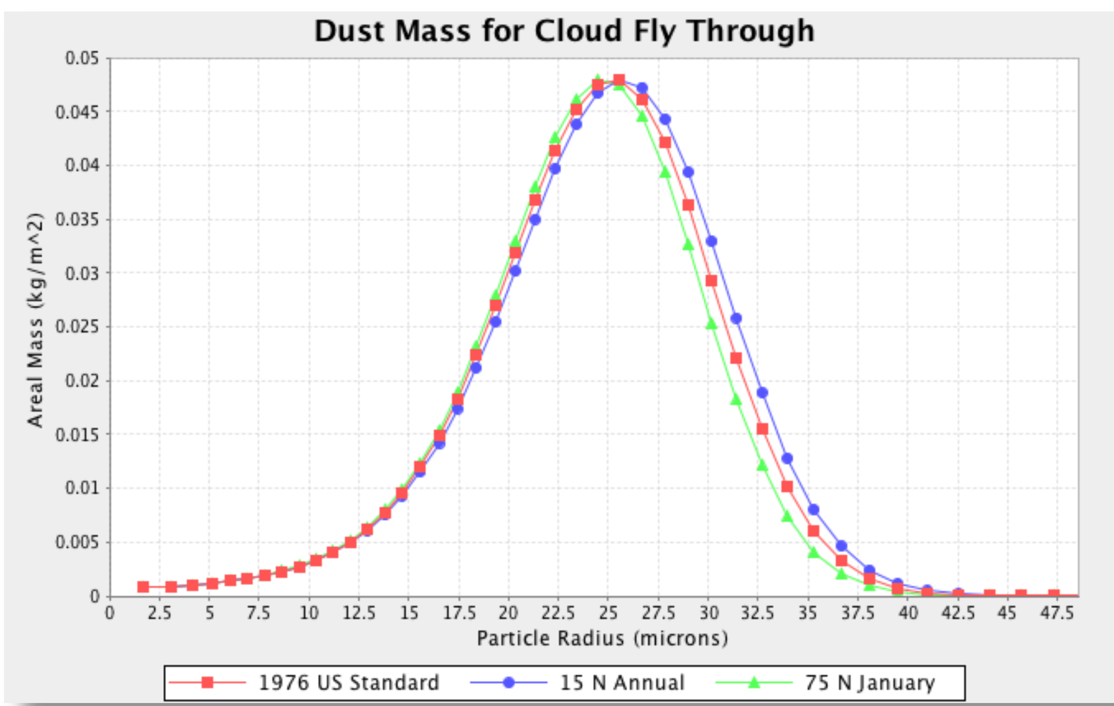

Figure 14—Fly Through Particle Sizes for Different Atmospheres

Fly-Through Dose Tab

Figure 15 shows the "Fly-Through Dose" tab after a calculation has been performed using the default tab inputs. The results of the calculation are shown in the four result lines at the bottom of the tab. The user can select the PSD, the aircraft type, and the standard atmosphere. The vertical sky-shine dose is the dose received during a vertical dive from the entered altitude to the ground, from the radioactive particles outside of the aircraft. The horizontal sky-shine dose is the dose received when flying through the center of the cloud at the entered altitude, from the radioactive particles outside of the aircraft. The cabin dose is the dose received by the aircrew, caused by radioactive dust particles that are pulled into the aircraft by the cabin pressurization system. It is assumed that all dust particles pulled into the cabin remain in the cabin, and are evenly distributed throughout the pressurized volume. The cabin dose is integrated over the aircraft mission time entered by the user. The total dose is the sum of the cabin dose, and the sky-shine dose received by flying through the cloud.

The aircraft select field in Figure 16 shows the type of aircraft that can be selected for the dose calculations. The "Free Field" selection is the default "aircraft". This aircraft type should be selected for all aircraft other than those shown in the pull down menu in Figure 16. The free field dose in rad(Si) is calculated at the skin of the aircraft, and does not include shielding that would be provided by the aircraft structure. The cabin dose is zero, because the cabin dose is not a free field environment. The total dose is the total free field dose for a flight through the cloud. Notice that the "Free Field Horizontal Shy-Shine" dose is given in rad(Si), and the "Horizontal total dose" is given in rem, so that the two doses will not be numerically the same.

Figure 17 shows the results of a calculation using the default inputs, except that the aircraft type selected was the B-52H. Now all doses are to the aircrew inside the aircraft, and the total dose is the sum of the sky-shine and cabin doses. The details of how the sky-shine and cabin doses are calculated for the different aircraft are given in Conners and Clemens. (Conners, 1985 and Clemens, 2011)

The "Cabin Filter" in the Fly-Through dose tab is based upon the dust filter in the B-1B. The filter transmission factor as a function of the dust size is shown in Equation (3). The filter traps all dust particles larger than 10 microns radius. All particles less than 5 microns radius pass through the filter, and 10 percent of the particles between 5 and 10 microns pass through the filter. The aircraft would have to fly through more than 10 nuclear dust clouds before the filter will become clogged. (Conners, 1985)

$$T_f = \begin{cases} 0, & rm > 10\ \mu\text{m} \\ 0.1, & 10\ \mu\text{m} > rm > 5\ \mu\text{m} \\ 1, & rm < 5\ \mu\text{m} \end{cases} \tag{3}$$

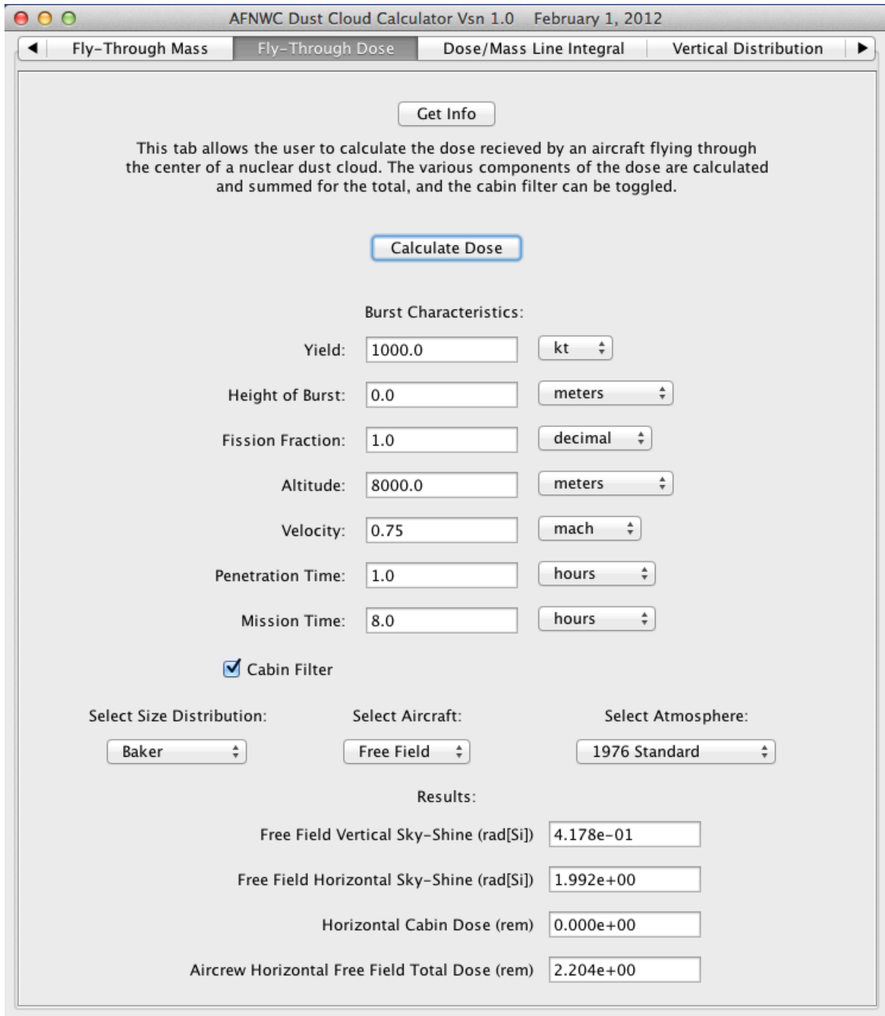

Figure 15—The Fly-Through Dose Tab

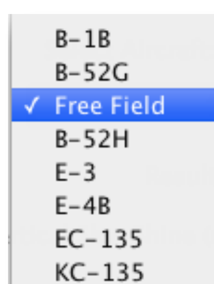

Figure 16—Fly-Through Dose Tab Aircraft Selections

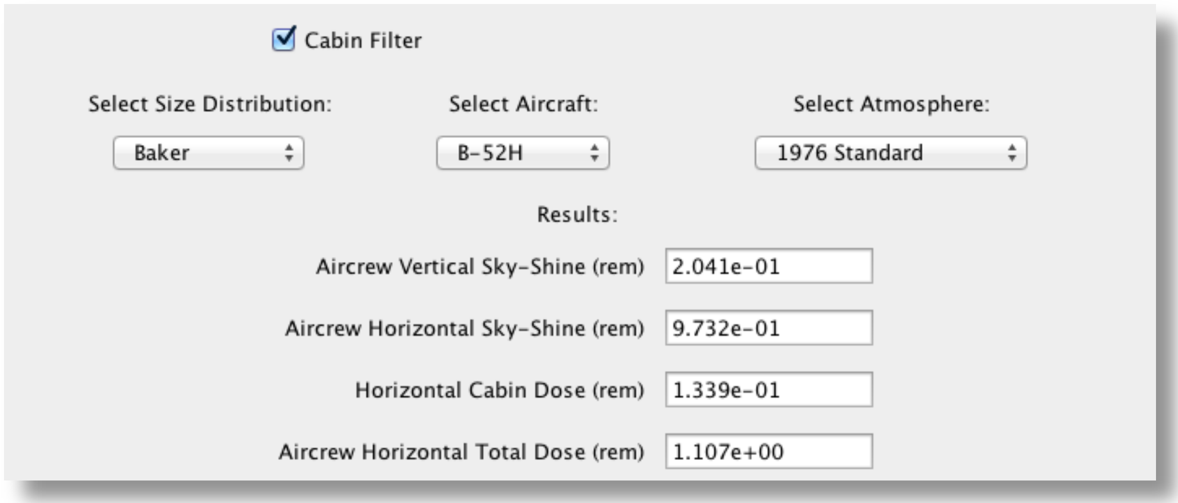

Figure 17—Fly-Through Dose for a B-52H

Dose/Mass Line Integral Tab

Figure 18 shows the "Dose/Mass Line Integral" tab after a default calculation has been performed. This tab calculates the sky-shine dose and dust mass intercepted for any arbitrary flight path through the dust cloud.

In Figure 18, the "Free Field" "aircraft" has been selected. The aircraft flight path is defined by the initial and final points, which define a straight-line path. The x-axis is in the East-West direction. The y-axis is in the North/South direction, and the z-axis is vertical. The coordinate origin is at ground zero. The flight path is at a constant 8,000 meters altitude MSL. The "y" coordinate is zero for both points, so the flight path is through the center of the cloud. The initial point is 22,000 meters left, or West, of the cloud center. The final point is 22,000 meters right, or East, of the cloud center. This means the flight path is horizontal, from West to East, through the center of the cloud. This is the same flight path as is used in the "Fly Through Mass", and "Fly Through Dose" tabs. In Figure 18, the free field sky shine dose is reported in rad(Si), at the surface of the aircraft. No shielding is provided by the aircraft skin.

Figure 19 shows the results for a default calculation, with the same flight path, except that the aircraft is the B-52H. The calculated dose is now the sky-shine dose for the aircrew inside the aircraft. Credit is taken for the shielding provided by the aircraft skin.

When a calculation is performed, the total dust mass, as a function of particle radius is shown. This is the same type of plot as is shown in Figure 13, except there is only one line for the actual flight path through the cloud.

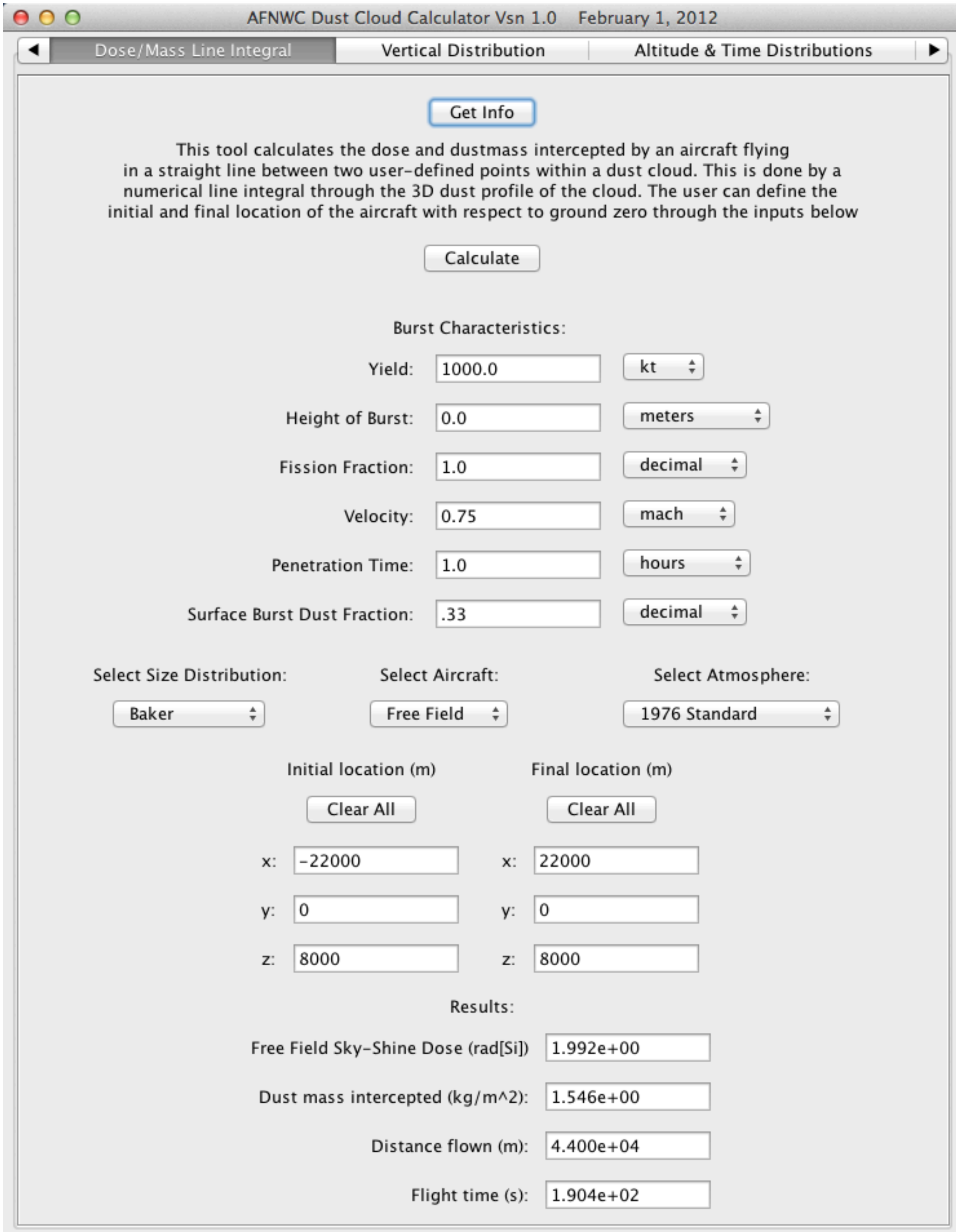

Figure 18—Dose/Mass Line Integral Tab With Default Calculation

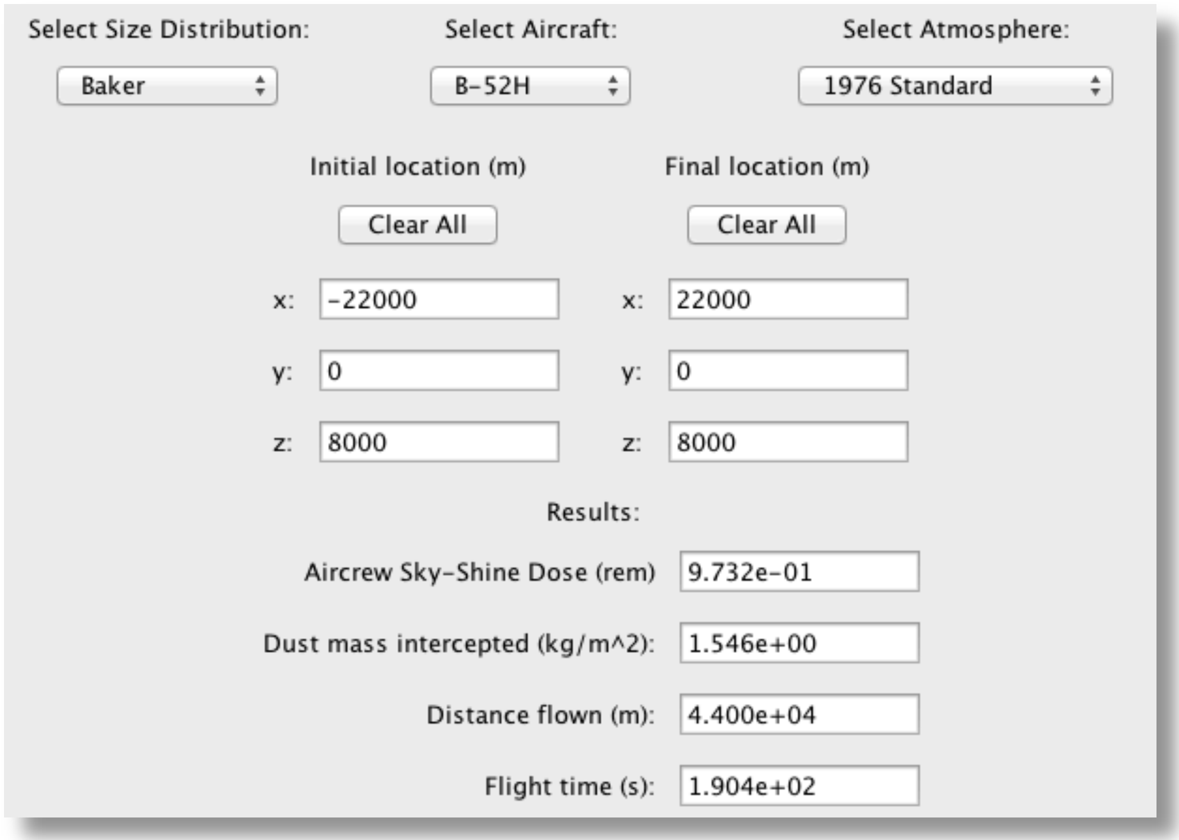

Figure 19—Dose/Mass Line Integral Results for B-52H

Vertical Distribution Tab

Figure 20 shows the "Vertical Distribution" tab. This tab can be used see how the dust mass and activity are vertically distributed at different times after a detonation. It can be used to quickly understand how different particle size distributions affect the distribution of dust and activity within the cloud as the dust particles settle with time.

Figure 21 shows the vertical distribution of mass for a default calculation, using the inputs in Figure 20. Figure 22 shows the vertical distribution of activity. The y-axis of the plots is labeled as the altitude in kilometers. This is the MSL altitude, with the ground at sea level. The x-axis in Figure 21 is labeled as kg/m. This is the total dust mass in kilograms, contained in one vertical meter of the cloud. The different lines labeled with the time after detonation, show how the dust mass changes with time, as the dust particles fall from their initial heights at cloud stabilization time. The 0 time curve is actually for the cloud stabilization time of about 10 minutes. In Figure 22 the x-axis is labeled Ci/m. This is the total activity in Curies contained in one vertical meter of the cloud. The activity distribution typically decreases much more rapidly than the dust distribution with time, because activity is removed due to the dust particles settling, and the activity decays with time according to the Way-Wigner approximation, where the cloud activity at any time can be calculated from:

$$A(t) = A_1 t^{-1.2} \quad (4)$$

where:
A is the activity in Curies,
t is the time after detonation in hours, and
A_1 is the activity at one hour after the detonation, which is 530 gamma mega-Curies per kt of fission.

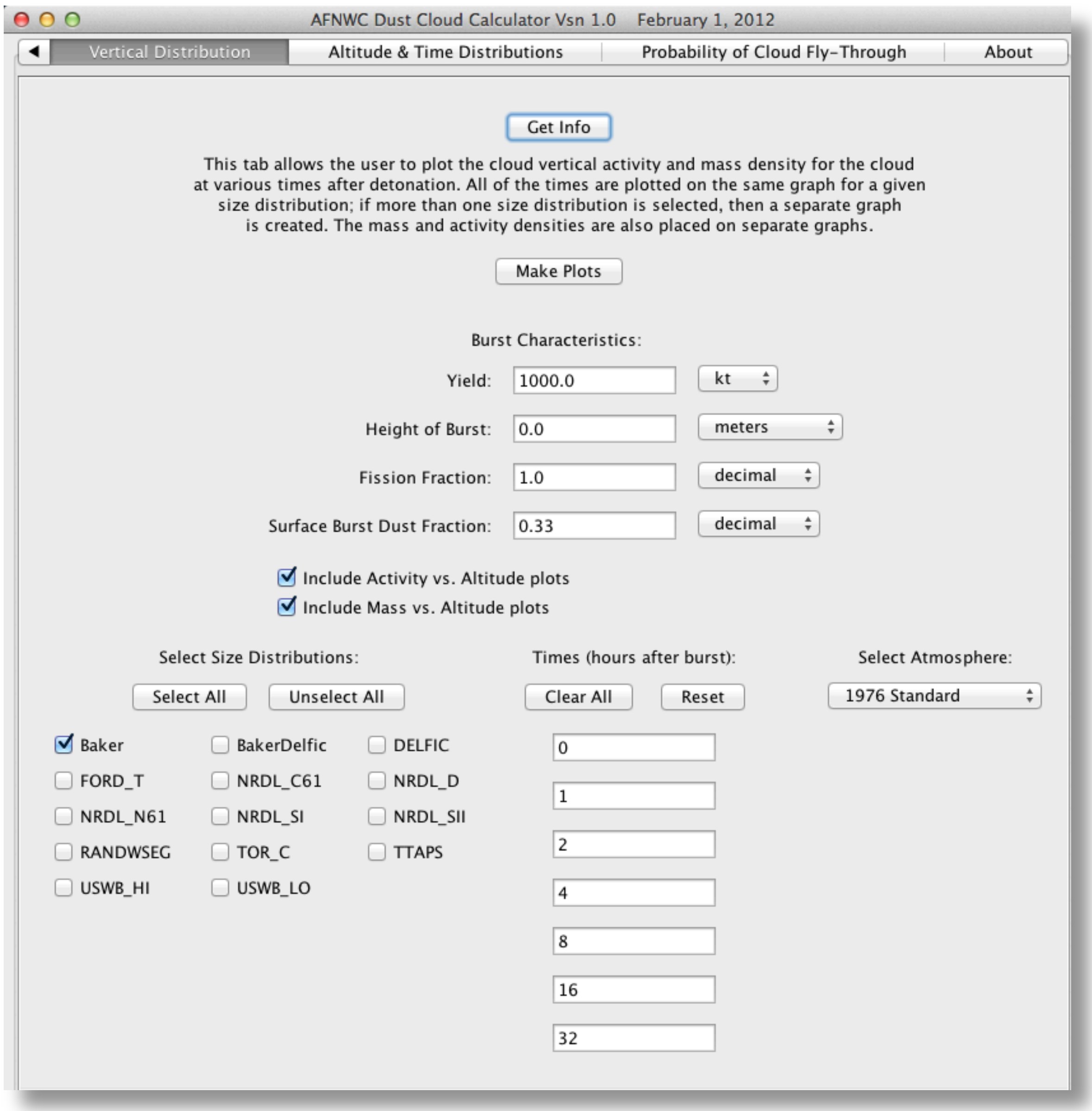

Figure 20—The Vertical Distribution Tab

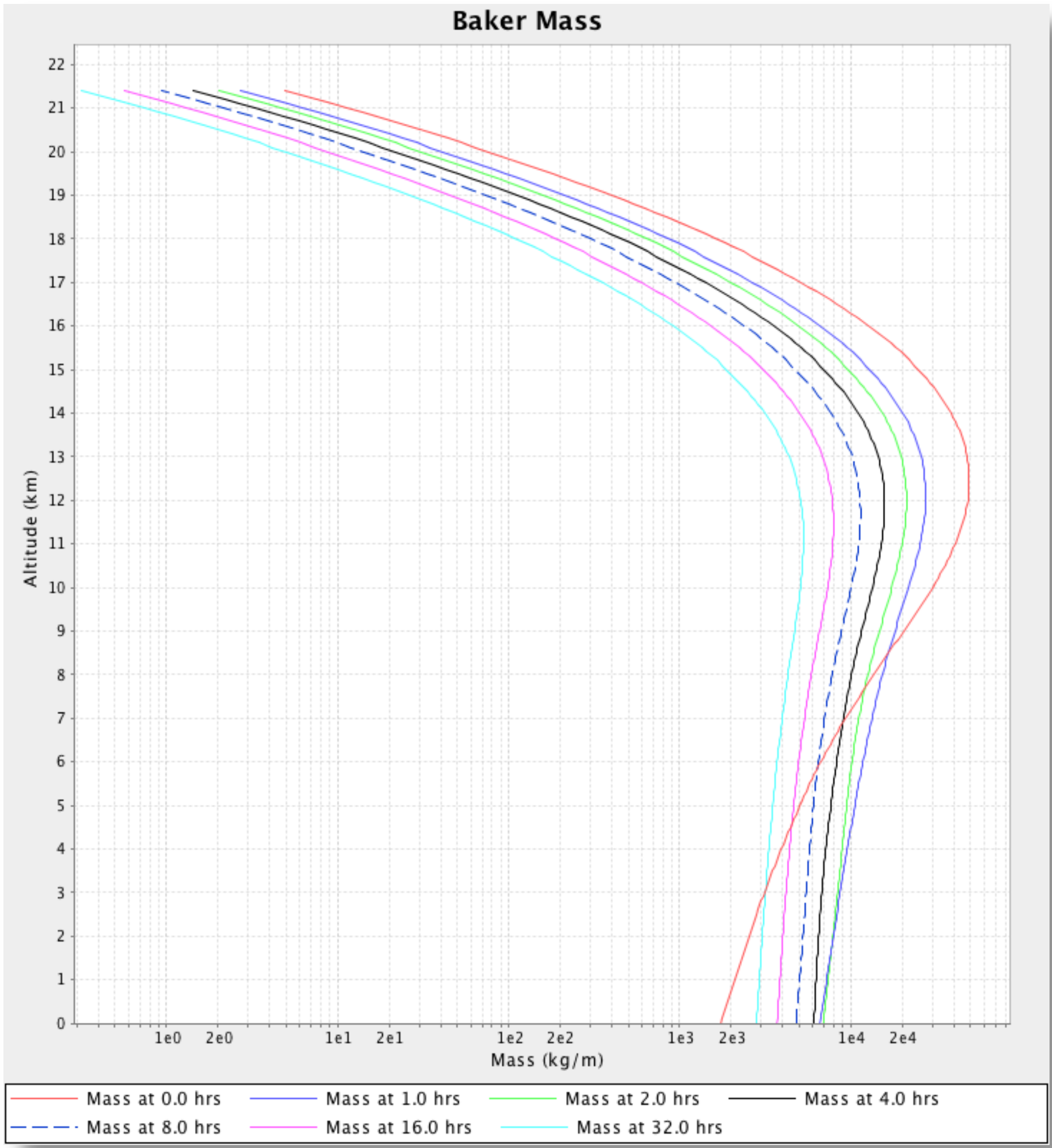

Figure 21—Baker Surface Burst Vertical Mass Distribution

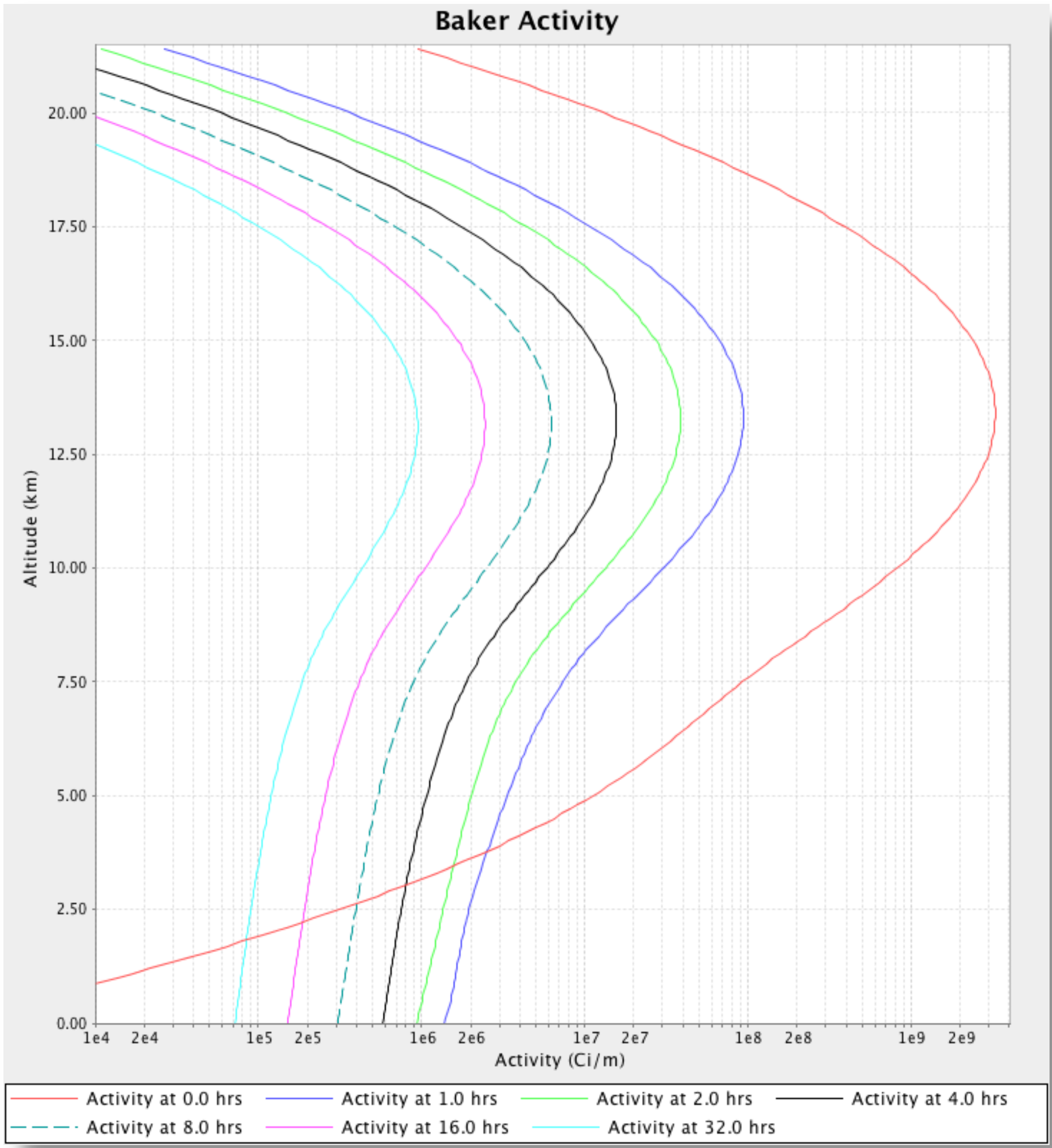

Figure 22—Baker Surface Burst Vertical Activity Distribution

Altitude and Time Distributions Tab

This tab produces graphs that quickly show how the dust mass and dose vary with time and altitude, as aircraft fly through the dust cloud both horizontally, and vertically. Figure 23 show the “Altitude and Time Distribution” tab with the default settings. If “Free Field” is selected as the aircraft type, the doses are given as the free field sky shine dose, with the dose calculated at the aircraft skin, with no credit taken for shielding by the aircraft skin. If an actual aircraft is selected, the dose calculated is the aircrew sky shine dose internal to the aircraft.

Figures 24 and 25 show the plots of horizontal and vertical dose as a function of time and altitude, for the default inputs in Figure 23. The dose is given as the free field sky shine dose. If an actual aircraft type were selected, the dose would be reported as the aircrew sky shine dose.

Figures 26 and 27 show the plots of horizontal and vertical dust mass as a function of time and altitude, for the default inputs in Figure 23. The vertical values in Figures 24 to Figure 27 are calculated from the altitude to the ground.

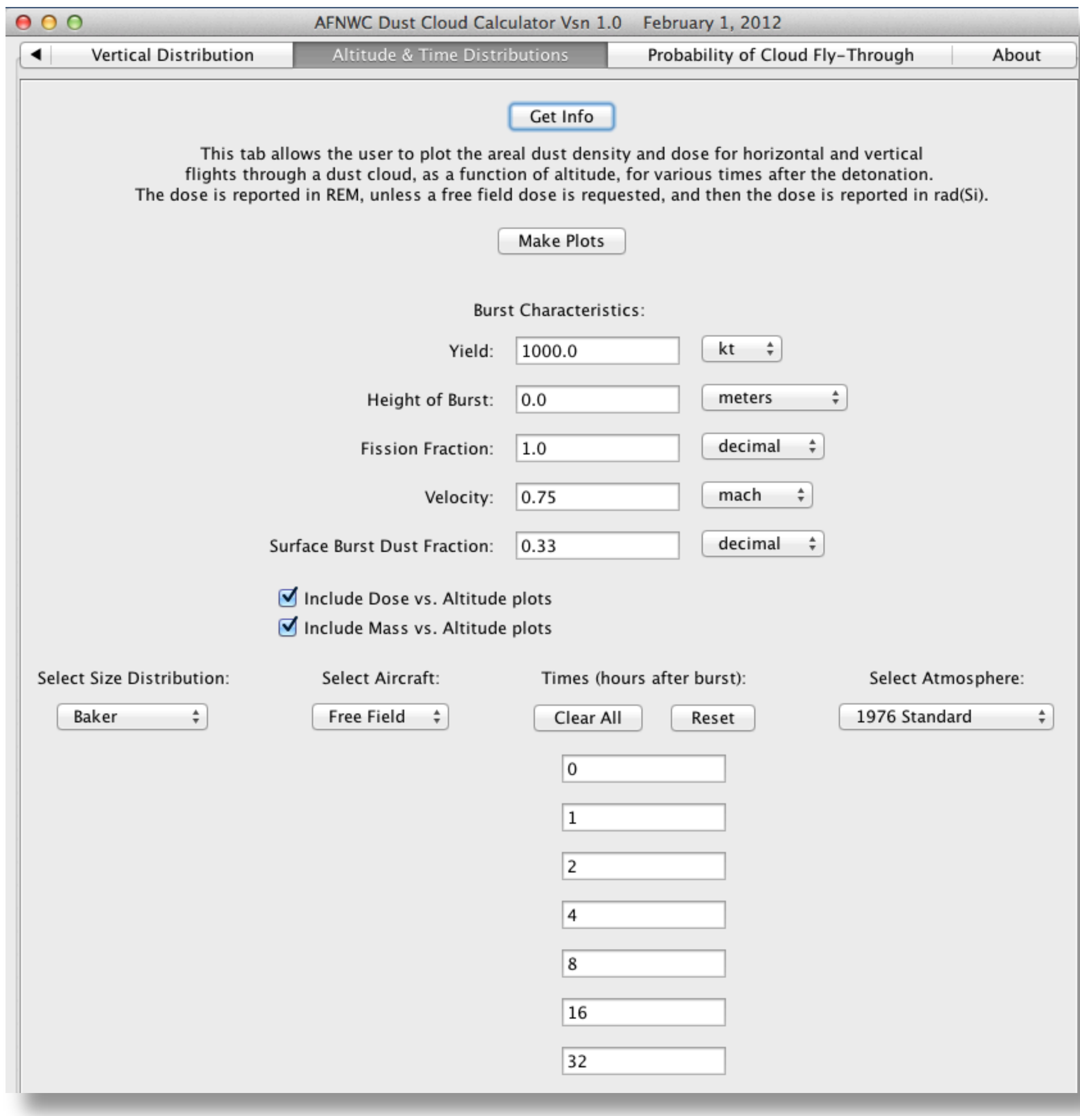

Figure 23—The Altitude and Time Distributions Tab

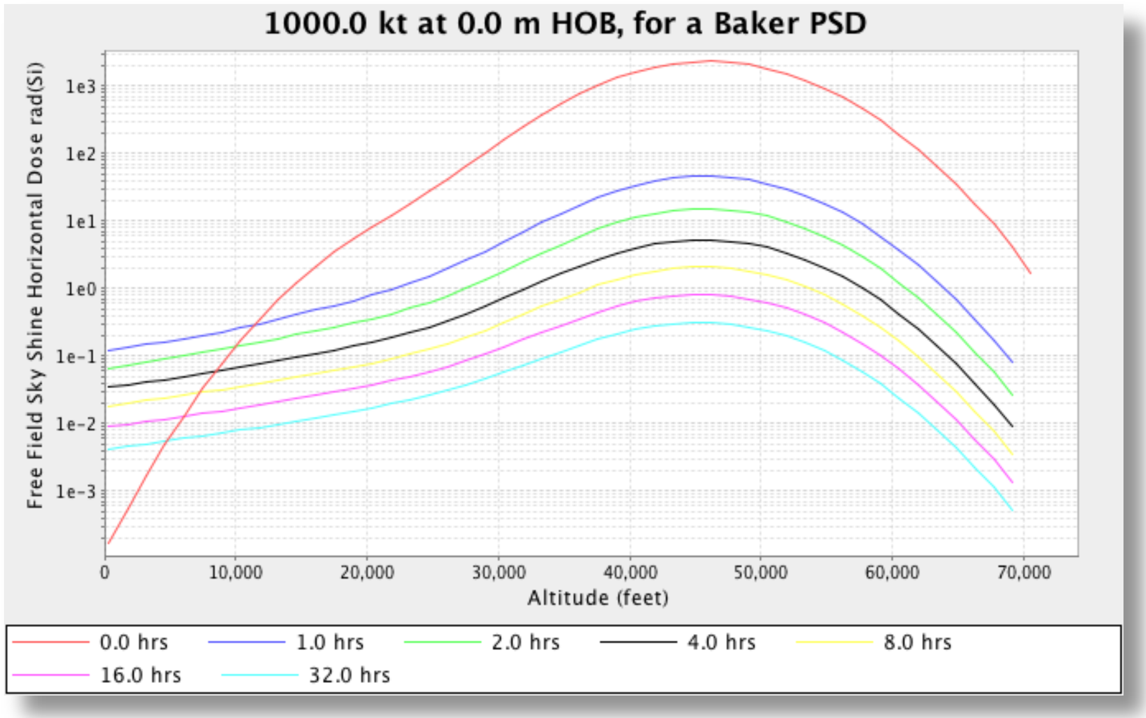

Figure 24—Baker Horizontal Dose by Time and Altitude

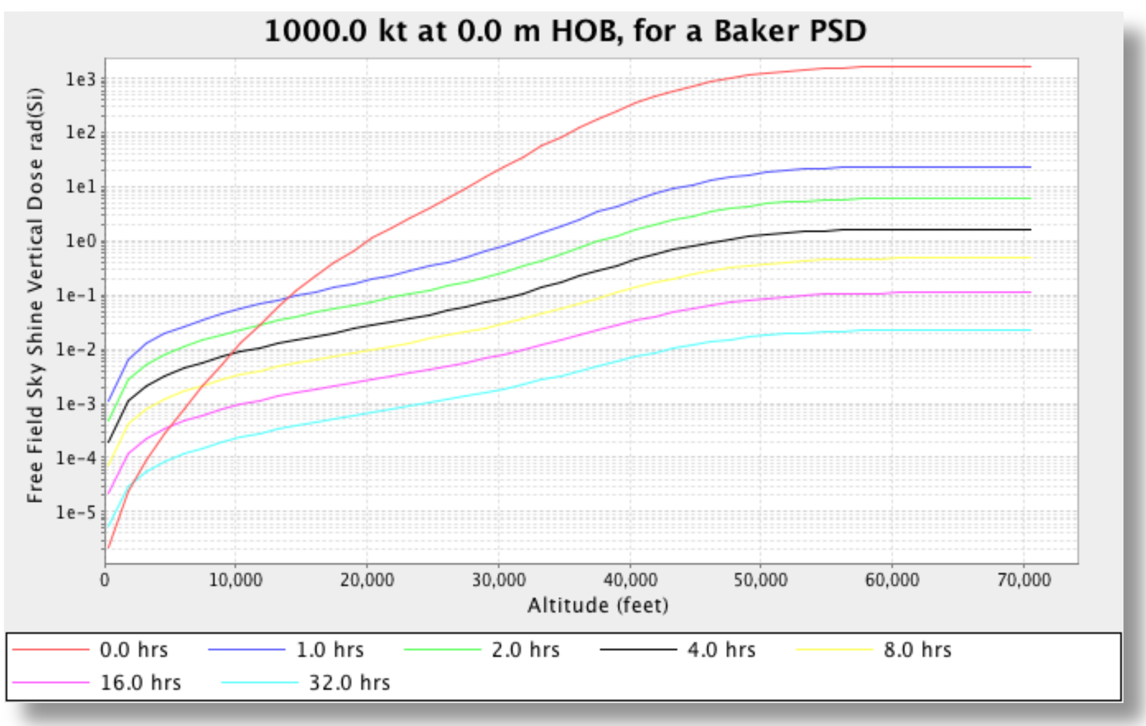

Figure 25—Baker Vertical Dose by Time and Altitude

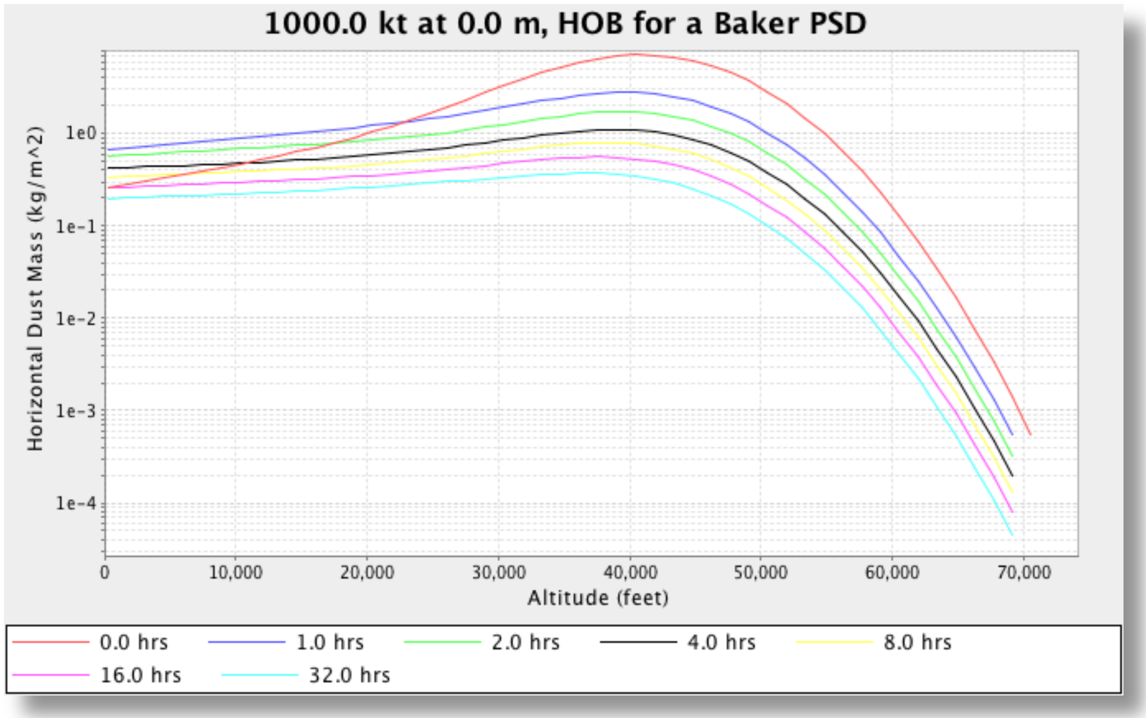

Figure 26—Baker Horizontal Mass by Time and Altitude

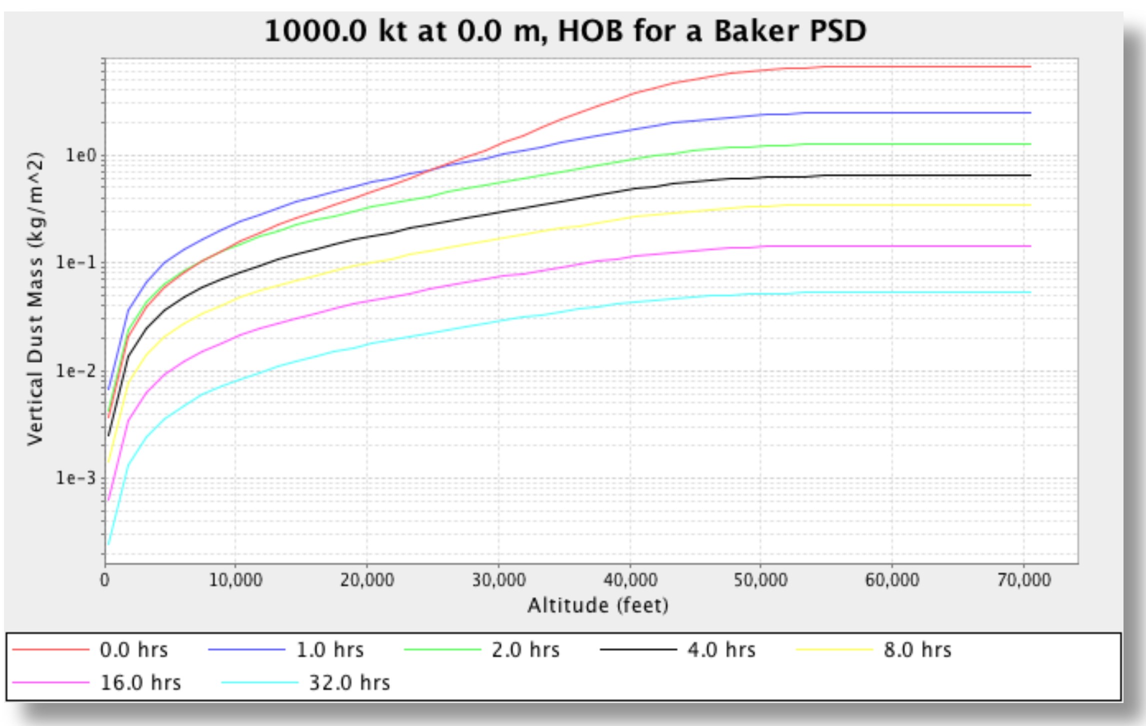

Figure 27—Baker Vertical Mass by Time and Altitude

Probability of Cloud Fly-Through Tab

It is relatively easy to model the dust cloud environment from a single nuclear detonation. It requires a few weeks to develop the model, and a few seconds to calculate the effects of flying through the cloud. It is not so easy to model the probability of flying through a cloud. (See Rausch, 1988, for instance.) The model must use a large selection of wind patterns to build a statistically significant database of cloud encounters, and the location of hundreds to thousands of dust clouds must be compared to the flight paths of hundreds of cruise missiles to calculate the probability of encounter, and the effects of the encounters.

The "Probability of Cloud Fly-Through" tab in Figure 28 can be used to make very rapid calculations of the probability of flying through a given number of dust clouds within an area. The basic problem being solved is shown in Figure 29.

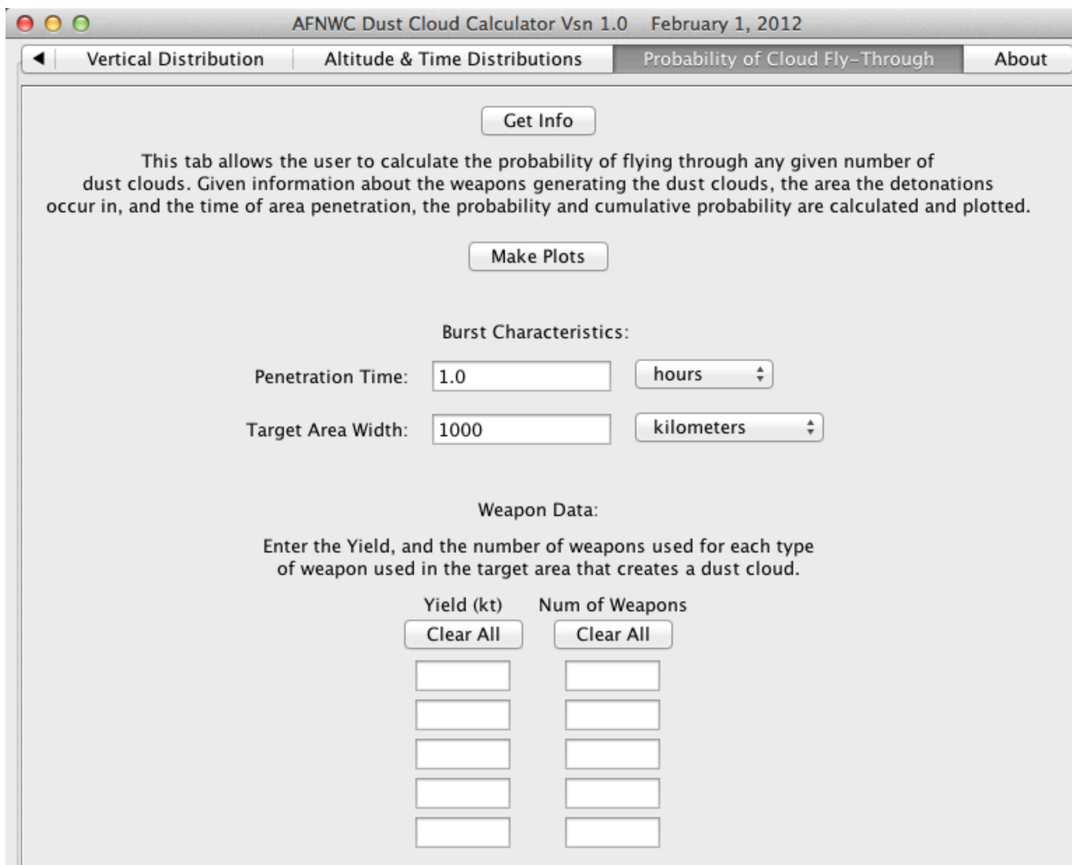

Figure 28—The Probability of Cloud Fly-Through Tab

The red circles represent dust clouds that have been randomly placed within a rectangular target area represented by the rectangle with a width of W, and a length of L. The aircraft or cruise missile is constrained to fly completely through the target area, parallel to the long side of the target area. The probability of flying through one particular dust cloud is the cloud diameter, divided by the target area width. The probability of flying through any number of dust clouds can be calculated using the binomial distribution. St. Ledger and Hockersmith present the development of the probability of encounter model, with examples. (St. Ledger, 2012)

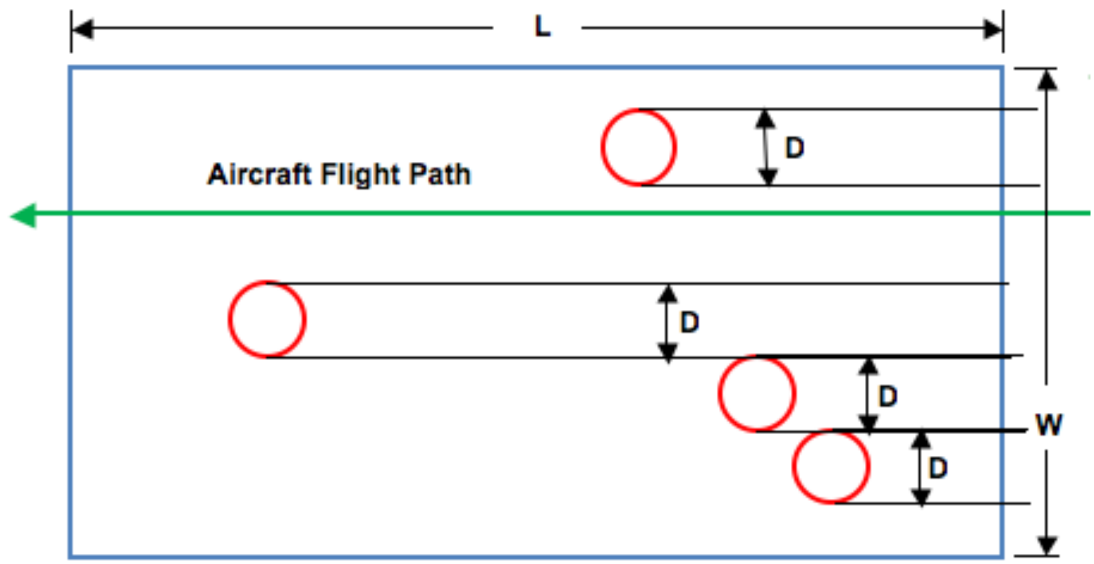

Figure 29—Flight Path Through Randomly Placed Clouds

In Figure 28, the penetration time is the time after an ICBM or SLBM laydown that aircraft or cruise missiles enter the target area. The target area width is the side with length W in Figure 29.

Figure 30 shows three example weapon entries in the weapon data. Figures 31 to 34 show the plots with a calculation performed for these weapons, an entry time of 1.0 hour after the detonations, and a target area width of 1,000 km. In Figure 31, there is about a 12 percent chance that an aircraft flying through the area will fly through 11 clouds. This is the most likely number of clouds that an aircraft will fly through. There is a 99 percent chance that the aircraft will fly through 20 or fewer clouds. Conversely, there is only a 1 percent chance that an aircraft will fly through more than 20 clouds. Figure 31 tells us how many clouds are likely to be flown through, but it does not show which clouds are likely to be flown through.

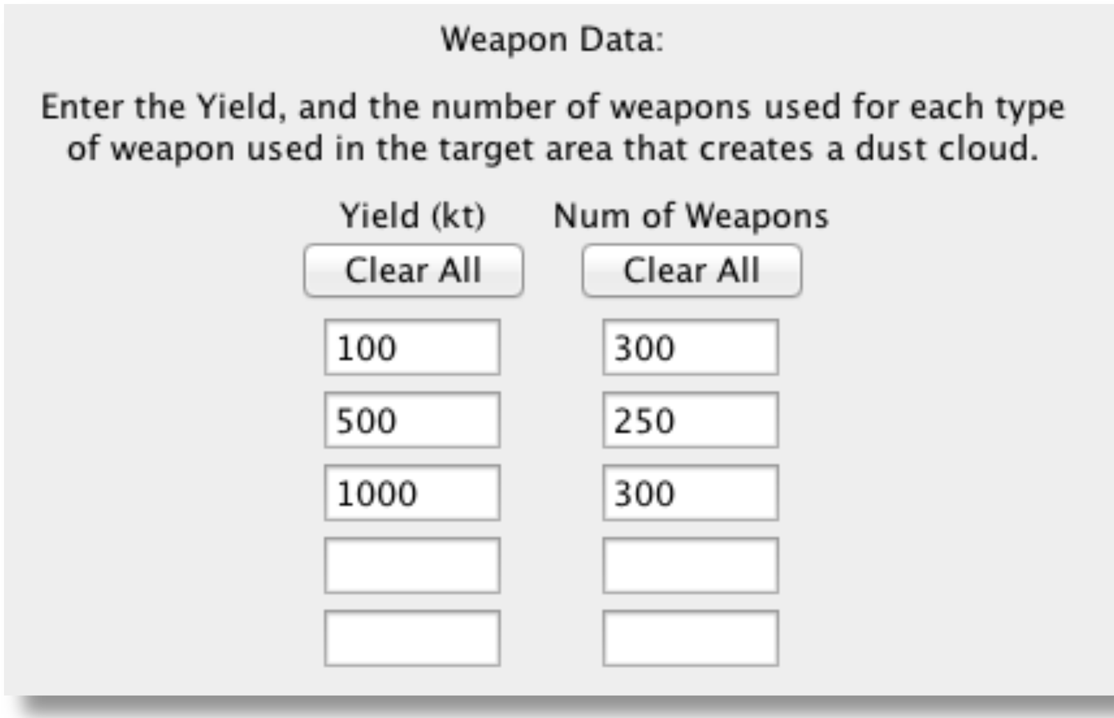

Figure 30—Weapon Data for Three Weapon Types

Figure 32 shows the probability of flying through the 300 clouds with a yield of 100 kt. The most likely number of clouds is 3, and there is a 99 percent chance that 8 or fewer clouds will be flown through. Figure 33 shows that the most likely number of 500 kt clouds to be flown through is 3, and there is a 99 percent chance that 8 or fewer 500 kt clouds will be flown through. Figure 34 is for the 200 dust clouds from the 1,000 kt detonations. The most likely number of 1,000 kt clouds that will be flown through is 4 with a probability of 18 percent. There is a 99 percent chance that 10 or fewer clouds will be flown through. The 99 percent can be thought of as a 1 percent risk that the number of cloud encounters will be exceeded. We could just as easily used the 90^{th} percentile for a 10 percent risk that the number of cloud encounters would be exceeded.

The total number of clouds at the 99^{th} percentile in Figures 32, 33, and 34 is 26. This is more than the 99^{th} percentile of clouds shown in Figure 31 as 20 total cloud encounters. The sum of the three values is larger, because the cumulative probability is larger than 0.99 that the 99^{th} percentile number of clouds would be flown through for *all three cloud types*. The two numbers being different is not an error in the methodology.

To calculate the cumulative risk, just multiply the cloud encounters for each cloud type, by the dust mass or dose that is accumulated for a single pass through the cloud, and then sum all of the accumulated values together. Table 3 shows the accumulated dust mass for a 1% risk, and 10% risk calculation. The 1% risk level means that there is about a 1% chance that the number of dust cloud encounters will be exceeded. The 10% risk level means that there is about a 10% chance that the number of dust cloud encounters will be exceeded.

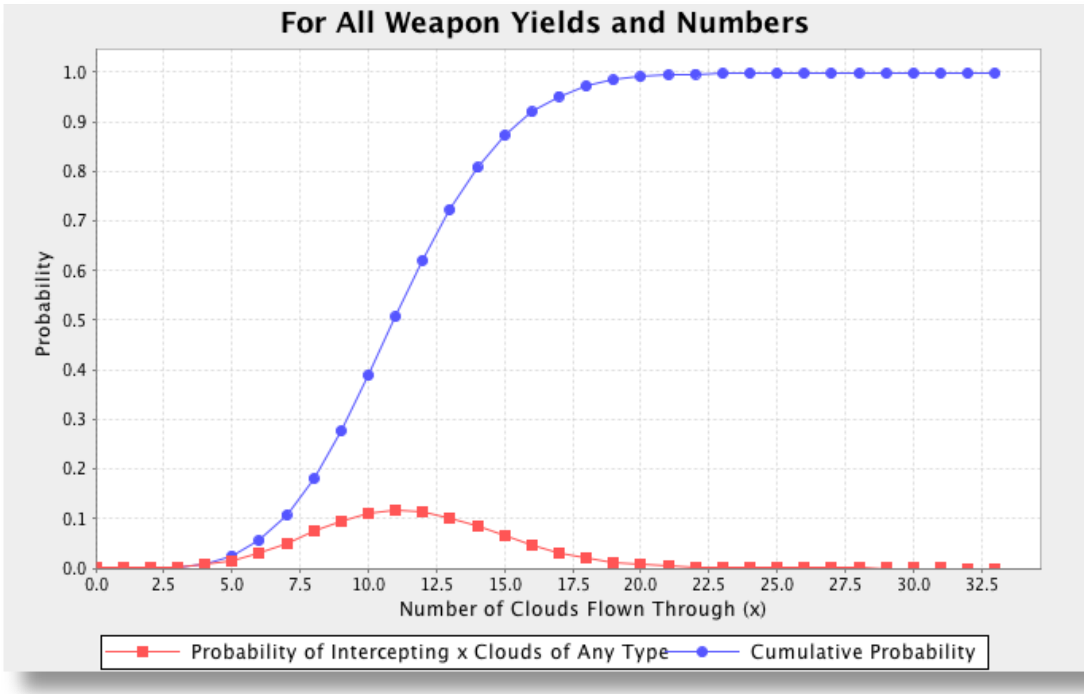

Figure 31—Probability of Flying Through All Cloud Types

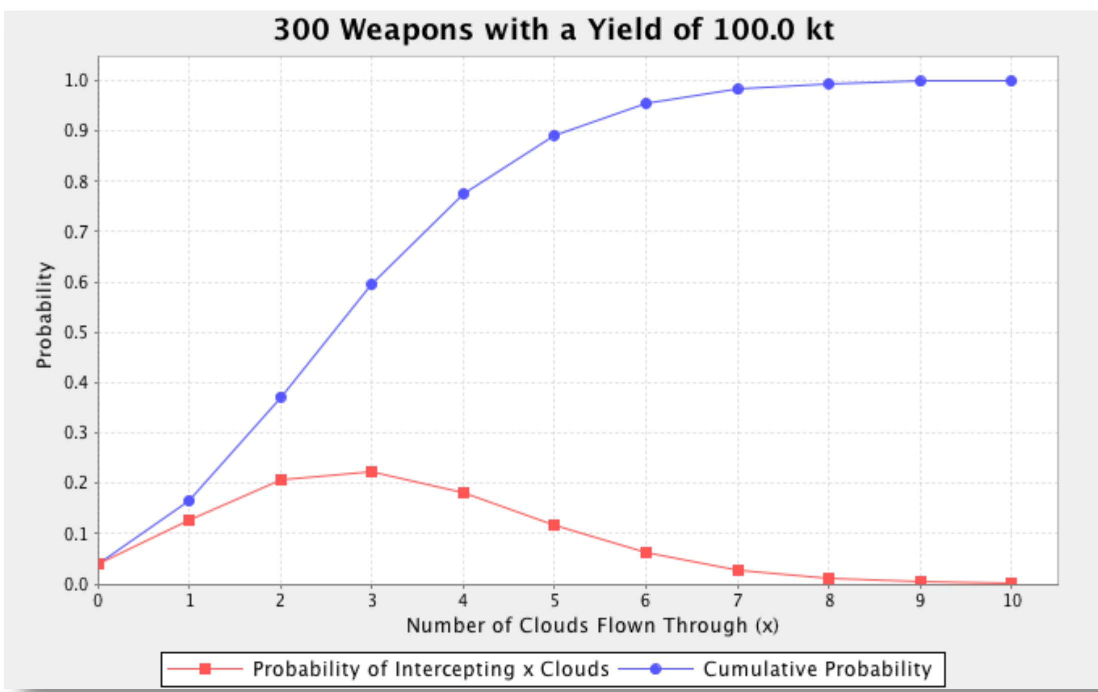

Figure 32—Probability of Flying Through 100 kt Clouds

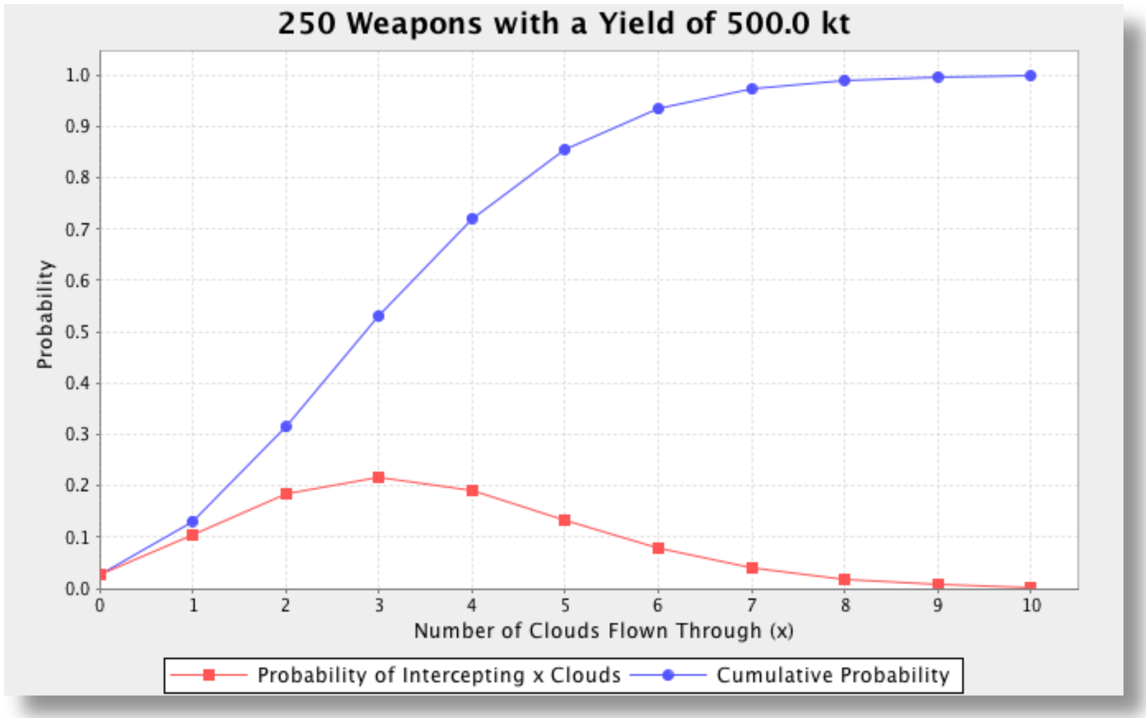

Figure 33—Probability of Flying Through 500 kt Clouds

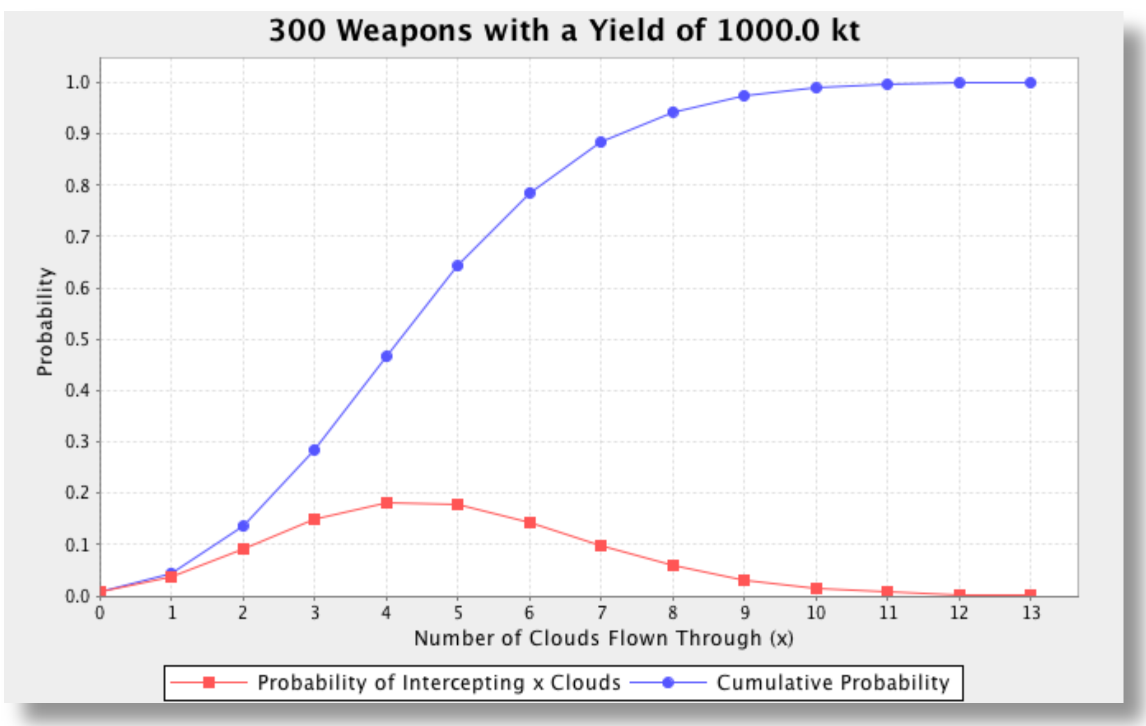

Figure 34—Probability of Flying Through 1,000 kt Clouds

Table 3—Worst Case Dust Mass Calculation for 1 and 10 Percent Risk Levels

Yield (kt)	1 % Risk Cloud Encounters	10 Percent Risk Cloud Encounters	Dust Mass for One Cloud (kg/m^2)	1 % Risk Dust Mass (kg/m^2)	10 % Risk Dust Mass (kg/m^2)
1,000	10	8	1.546	15.46	12.36
500	8	6	1.121	8.968	6.726
100	8	6	0.579	4.632	3.474
Total Mass				29.06	22.56

The dust masses in Table 3 assume that each cloud encounter results in the aircraft flying through the center of the cloud. The "Dust Masses for One Cloud" were calculated using the "Fly Through Mass Tab". A less conservative approach is to use the average dust mass for a cloud encounter. Using a cloud diameter of 4 standard deviations, the average dust mass is:

$$Ave = \frac{MassFT\sqrt{2\pi}}{4} \qquad (5)$$

where:
Ave is the average dust mass intercepted when a large number of random paths are flown through the cloud at one altitude, and
MassFT is the horizontal fly through mass calculated at the desired altitude using the "Fly Through Mass" tab.

The value of the square root of 2 Pi divided by 4, is called the average fly-through factor. See Appendix A for a derivation of Equation (5). The factor is about equal to 0.63.

Table 4 shows the accumulated dust mass for the same 1% risk, and 10% risk calculation as in Table 3, but now the average fly through mass for a cloud encounter is used.

Table 4—Average Dust Mass Calculation for 1 and 10 Percent Risk Levels

Yield (kt)	1 % Risk Cloud Encounters	10 Percent Risk Cloud Encounters	Average Mass for One Cloud (kg/m^2)	1 % Risk Dust Mass (kg/m^2)	10 % Risk Dust Mass (kg/m^2)
1,000	10	8	0.974	9.740	7.792
500	8	6	0.706	5.650	4.237
100	8	6	0.365	2.918	2.189
Total Mass				18.30	14.21

Summary

The AFNWC Dust Cloud Calculator can display particle size distributions, calculate the areal dust mass and dose for an aircraft flying through a nuclear dust cloud, calculate the vertical distribution of the dust mass, and the probability of flying through a number of dust clouds. It assumes that the wind shear is a constant 1 per hour. The cloud is stationary, and it is not transported by the wind. The stabilized cloud dimensions are derived from fits to DELFIC cloud rise calculations. The cloud model has been validated, and accepted for use in Air Force studies to set dust and radiation requirements for systems that could encounter a dust cloud.

Appendix A—Derivation of the Average Fly-Through Factor

To calculate the average dust mass when a dust cloud is flown through at a random distance from the cloud center, first assume that the cloud is 4 standard deviations in diameter. The probability calculations for the cloud diameter in the "Probability of Cloud Fly-Through" tab use this assumption, because the cloud standard deviation in Conners was calculated assuming that the DELFIC cloud diameter was 4 standard deviations. Assume that the aircraft is flying parallel to the x axis, and the y axis is perpendicular to the flight path. Then at any distance y, from the cloud center, the dust mass flown through in kg/m^2 is:

$$Mass(y) = \frac{MassTot}{\sqrt{2\pi}\sigma_y} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \qquad \text{(A-1)}$$

where:
Mass(y) is the fly through mass at any distance y offset from the cloud center, in kg/m^2
MassTot is the total dust mass at the desired cloud altitude in kg/m, and
σ_y is the cloud standard deviation in the y direction, in m.

The average value for the fly-through dust mass is:

$$Ave = \frac{\int_{ymin}^{ymax} Mass(y)dy}{ymax - ymin} \qquad \text{(A-2)}$$

where:
Ave is the average value of many fly throughs at random offsets of y from the cloud center, in kg/m^2
Mass(y) is the Mass(y) in Equation (A-1), and
ymax is $+2\sigma_y$, in m and
ymin is $-2\sigma_y$, in m, since the cloud diameter is assumed to be 4 sigma.

Completing the integral in Equation (A-2), and assuming it is about equal to 1, we have:

$$Ave \approx \frac{MassFT}{4\sigma_y} \qquad \text{(A-3)}$$

From Equation (A-1), the maximum possible fly-through dust mass is at the cloud center where y = 0, so from Equation (A-1) the maximum fly-through mass is:

$$MassFT = \frac{MassTot}{\sqrt{2\pi}\sigma_y} \qquad \text{(A-4)}$$

or,

$$MassTot = MassFT\sqrt{2\pi}\sigma_y \qquad \text{(A-5)}$$

Substituting this into Equation (A-3), gives the average mass as:

$$Ave = \frac{MassFT\sqrt{2\pi}}{4} \quad \text{(A-6)}$$

The MassFT can be calculated using the “Fly-Through Mass” tab.

As a check of the derivation of Equation (A-6), use the “Fly-Through Mass” tab to calculate the horizontal fly through mass for a 1 Mt surface burst, with the fly-through at 0 hours, at a height of 12 km, and a dust mass fraction of 0.33. Use a Baker PSD. The horizontal dust mass is 6.962 kg. This is the MassFT.

Now in the “Vertical Distribution” tab, calculate the vertical distribution for a 1 Mt surface burst, at 0 hours, with a 0.33 surface burst dust fraction, and a Baker PSD. Get the vertical dust mass at 12 km altitude. This value is 4.83E04 kg/m. This is the MassTot.

The cloud standard deviation at this time is 2768 m. You can’t see this value, but it is calculated internally in the code.

Using Equation (A-3), the MassTot, and the sigma, the average dust mass is 4.36 kg/m^2. Using Equation (A-6), and the MassFT, the average dust mass is 4.36 kg/m^2.

In Equation (A-6) the 4 in the denominator comes from the assumption that the cloud is 4 standard deviations in width. The 4 standard deviations is used to calculate the probability of flying through a cloud in the “Probability of Cloud Fly-Through” tab. If we assume that the cloud is 6 standard deviations in width, then Equation (A-6) would have a 6 in the denominator. The average dust mass would be lower by a factor of 50%, but the probability of flying through a given cloud size would by higher by a factor of 50%. The end result for the total dust mass for a given risk percentage would be about the same.

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Glossary of Terms

AFNWC	Air Force Nuclear Weapons Center
AGL	Above Ground Level
DOE	Department of Energy
DTRIAC	Defense Threat Reduction Information Analysis Center
DVD	Digital Video Disk
ft	feet
HOB	Height of Burst
Java™	A programming language and trademark of Oracle Corporation
JRE	Java Runtime Environment
KCAS	Knots Calibrated Airspeed
km	kilometers
kt	kilotons
KTAS	Knots True Airspeed
LANL	Los Alamos National Laboratory
m	meters
MORE	Moving Object Receiver Environments
MSL	Mean Sea Level
nm	nautical miles
NOAA	National Oceanic and Atmospheric Administration
psi	pounds per square inch

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