Example: Fallout From a Hypothetical 1200 kt RNEP

In this MathCad file, the fallout model is tested using the 1200 kt RNEP as an example. It is assumed that the scaled depth of burst is small, so the fallout can be effectively modeled as a surface burst.

Radioactive Release

Fraction of Total Activity Released: $f_{rel} := 0.58$

Fission Fraction: $f_{fis} := 0.5$

Reference Time (hours): $t_0 := 1$

Yield (kt): $yield := 1200$

Total Gamma-Ray Activity (Ci) released for a yield (w), referenced to time t_0. $A_{rel}(w) := 530 \cdot 10^6 \cdot w \cdot f_{fis} \cdot f_{rel}$

Total Activity (Ci) at an arbirtrary time t: $A_{tot}(w,t) := A_{rel}(w) \cdot \left(\frac{t}{t_0}\right)^{-1.2}$

One hour after the detonation of a 1200 kt RNEP, the activity released into the atmospher is $A_{rel}(yield) = 1.844 \times 10^{11}$ Ci.

Cloud Dimensions

The cloud dimensions as a function of yield can be found in Glasstone Figs. 9.96 and 2.16. Instead of having to read the data aff the figures, a power function was fit to the data.

Form of the function used to fit the cloud dimension data:

$$cloud\_fit(w,a) := a_0 \cdot w^{a_1} + a_2$$

Parameters which best fit the cloud dimensions (top, bottom, radius), with the yield in kt and the dimensions in km.

$$a_{top} := \begin{pmatrix} 9.079 \\ 0.1523 \\ -6.6964 \end{pmatrix} \qquad a_{bot} := \begin{pmatrix} 1.6087 \\ 0.2705 \\ 0.1302 \end{pmatrix} \qquad a_{rad} := \begin{pmatrix} 0.0168 \\ 0.8308 \\ 2.0271 \end{pmatrix}$$

The cloud dimensions for a 1200 kt weapon:

Height of Cloud Top (km): $h\_top := cloud\_fit(yield, a_{top})$ $\quad h\_top = 20.033$

Height of Cloud bottom (km): $h\_bot := cloud\_fit(yield, a_{bot})$ $\quad h\_bot = 11.08$

Radius of Cloud (km): $R\_cloud := cloud\_fit(yield, a_{rad})$ $\quad R\_cloud = 8.101$

The stem radius will be assumed to be one-tenth of the cloud radius (Glasstone Sect. 2.17).

Stem Radius (km): $R\_stem := 0.1 \cdot R\_cloud$ $R\_stem = 0.81$

Activity Distribution vs Particle Size

The activity is distributed among the dust particles according to a log-normal distribution based on the particle radius. This example uses the parameters derived for a surface burst in Nevada-type soils (Izrael p. 8).

Mean Particle Radius (microns): $r_0 := 0.5 \cdot 10^{2.053}$ $r_0 = 56.49$

Standard Deviation: $\sigma_{part} := 0.732$

The activity distribution fuction gives the fraction of the total activity which lies on particles from radius r_1 to r_2.

$$f_{dist}(\beta_1, \beta_2) := \frac{1}{\sqrt{2\pi}\,\sigma_{part}} \cdot \int_{\beta_1}^{\beta_2} \exp\left(\frac{-\beta^2}{2 \cdot \sigma_{part}^2}\right) d\beta$$

Where $\beta_n = \log(r_n/r_0)$ is used to simplify the notation.

Particle Fallout

Atmospheric Model: The U.S. Standard Atmosphere, 1976 (NOAA, NASA, USAF) is used. The altitude h is expressed in km. The three regions in this model are h <11 km, 11 km < h < 20 km, and 20 km < h < 32 km.

Temperature (K):

$$temp(h) := \begin{cases} 288.15 - 6.5 \cdot h & \text{if } h \le 11 \\ 216.65 & \text{if } 11 < h \le 20 \\ 216.65 + (h - 20) & \text{otherwise} \end{cases}$$

Air Density (kg/m^3):

$$\rho_{air}(h) := \begin{cases} 1.225\left(1 - \frac{6.5}{288.15} \cdot h\right)^{4.25595} & \text{if } h \le 11 \\ 0.363915 \exp\left(-\frac{h - 11}{6.3415}\right) & \text{if } 11 < h \le 20 \\ 0.088032\left(1 + \frac{h - 20}{216.65}\right)^{-35.1637} & \text{otherwise} \end{cases}$$

The viscocity is calculated using Sutherland's formula (kg/m*s):

$$\eta(h) := 1.458 \cdot 10^{-6} \cdot \frac{temp(h)^{1.5}}{110.4 + temp(h)}$$

The **terminal velocity** is calculated under the assumption that the particles are spherical. I included the effects of gravity, buoyancy, and drag. The drag coefficient is from an emperical fit (Hinds, p. 44), and is valid for Reynolds number (Re) below 1000. For Re <800 the fit is within 4% of experimental values, and for Re <1000 it is within 7%.

Dust Particle Density (kg/m^3): $\rho_{obj} := 250($

Gravitational Constant (m/s^2): $grav := 9.8066\!:$

Reynolds Number
(r_{part} in microns, h in km, v in m/s): $\text{Reynolds}(v, h, r_{part}) := \dfrac{2 \cdot \rho_{air}(h) \cdot v \cdot \left(r_{part} \cdot 10^{-6}\right)}{\eta(h)}$

The following equations are used for calculating the terminal velocity:

$$v_0(h, r_{part}) := \frac{2}{9}\left(\rho_{obj} - \rho_{air}(h)\right) \cdot grav \cdot \frac{\left(r_{part} \cdot 10^{-6}\right)^2}{\eta(h)}$$

$$f1(h, v, r_{part}) := v \cdot \left(1 + 0.15 \cdot \text{Reynolds}(v, h, r_{part})^{.687}\right) - v_0(h, r_{part})$$

$$v\_guess := 5$$

Terminal Velocity (m/s): $v_{term}(h, r_{part}) := \text{root}\left(f1(h, v\_guess, r_{part}), v\_guess\right)$

The **fall time** for a particle with radius r_{part} microns starting at a height h_0 km is:

Fall Time (hrs): $t_f(h_0, r_{part}) := \dfrac{1}{3600} \cdot \displaystyle\int_0^{h_0} \frac{1000}{v_{term}(h, r_{part})}\, dh$

A 100 micron radius particle at the bottom of the cloud takes $t_f(h\_bot, 100) = 1.788$ hours to fall to the ground.

Horizontal Transport

In order to compare the results from this model with Glasstone, a constant "effective" windspeed of 15 miles per hour (6.7056 m/s) will be used. However, this can easily be changed in this file to accomidate a more complicated wind profile.

Horizontal Wind Speed (m/s): $v_x(h) := 6.705($

A particle with radius r_{part} microns starting at a height of h_0 km will travel:

Down Wind Distance (km): $D_x(h_0, r_{part}) := \displaystyle\int_0^{h_0} \frac{v_x(h)}{v_{term}(h, r_{part})}\, dh$

So a 100 micron radius particle at the bottom of the cloud travels $D_x(h\_bot, 100) = 43.163$ km before it reaches the ground.

Computational Simplifications

Before proceeding any further, it is necessary to implement some simplifications so that MathCad can readily perform the desired calculations. The particle distribution will be partitioned into bins of equal activity fraction for both the stem and the cloud.

The calculation will also be restricted to particles above a minimum size. This will of course leave some fraction of the particles in the air. However, this allows for smaller bin sizes for those particles which contribute most to the radioactive dose received.

What is the minimum size for a particle to fall within $t\_cut_{cl} := 24$ hrs from the bottom of the cloud?

$$r\_guess := 15$$

$$r\_min_{cl} := root\left(t_f(h\_bot, r\_guess) - t\_cut_{cl}, r\_guess\right)$$

$$r\_min_{cl} = 19.976 \quad \text{microns}$$

What is the minimum size for a particle to fall within $t\_cut_{stem} := 36$ hrs from the midpoint of the stem?

$$r\_min_{stem} := root\left(t_f(0.5h\_bot, r\_guess) - t\_cut_{stem}, r\_guess\right)$$

$$r\_min_{stem} = 11.671 \quad \text{microns}$$

If the calculation is restricted to particles larger than this, what fraction of the activity is neglected?

$$neglect_{cl} := f_{dist}\left(-1000, \log\left(\frac{r\_min_{cl}}{r_0}\right)\right) \qquad neglect_{stem} := f_{dist}\left(-1000, \log\left(\frac{r\_min_{stem}}{r_0}\right)\right)$$

Fraction left . . . in cloud: $neglect_{cl} = 0.269$ in stem: $neglect_{stem} = 0.175$

Divide the distribution into bins - starting with the minimum particle size. The center of each bin is defined such that there is an equal activity fraction on either side.

Number of Bins: $n_{bins} := 30$

Index: $i := 0 .. \left(n_{bins} - 1\right)$

Fraction of activity within the cloud (and stem) represented by each bin.

$$f\_cl_{bin} := \frac{1 - neglect_{cl}}{n_{bins}}$$

$f\_cl_{bin} = 0.024$ $f\_stem_{bin} = 0.028$

The cumulative activity fraction associated with the center of each bin:

$f\_cl_i := neglect_{cl} + (i + 0.5) \cdot f\_cl_{bin}$ $f\_stem_i := neglect_{stem} + (i + 0.5) f\_stem_{bin}$

Calculate the particle sizes for each bin.

$\beta\_guess := 0$

Cloud: $\beta\_cl_i := root\left(f_{dist}(-100, \beta\_guess) - f\_cl_i, \beta\_guess\right)$

Stem: $\beta\_stem_i := root\left(f_{dist}(-100, \beta\_guess) - f\_stem_i, \beta\_guess\right)$

The **particle sizes** (microns) at the center of each bin:

Cloud

$r\_part\_cl_i := r_0 \cdot 10^{\beta\_cl_i}$

$r\_part\_cl =$

	0
0	21.245
1	23.942
2	26.868
3	30.05
4	33.518
5	37.305
6	41.452
7	46.005
8	51.018
9	56.556
10	62.696
11	69.529
12	77.167
13	85.749
14	95.443
15	106.462

Stem

$r\_part\_stem_i := r_0 \cdot 10^{\beta\_stem_i}$

$r\_part\_stem =$

	0
0	12.743
1	15.024
2	17.506
3	20.214
4	23.174
5	26.419
6	29.985
7	33.914
8	38.256
9	43.069
10	48.423
11	54.402
12	61.109
13	68.668
14	77.236
15	87.006

Dose Rate Calculation

The initial activity-density for a single bin (referenced to 1 hour after the explosion) in the stem and the cloud is determined below. The relative fraction of the activity in the stem vs the mushroom cap is from Glasstone Section 9.61.

Fraction of released activity within the main cloud and stem:

$$f\_stem_{bin} := \frac{1 - neglect_{stem}}{n_{bins}}$$

$f_{cloud} := 0.9$ $\qquad f_{stem} := 1 - f_{cloud}$

The **horizontal diffusion** is governed by a Gaussian distribution with a time dependant standard deviation. The initial activity-density (Ci/km^3) is chosen so that roughly 86% of the activity lies within the cloud (stem) dimensions.

Estimated Time Constant (hrs): $\tau := 1$

And the Diffusion Coefficient (100m2/s):

$$\mathrm{Diff} := 100 \cdot \frac{1}{1000} \cdot \frac{1}{1000} \cdot 360($$

to change to km2/hour

Squared Standard Deviation (km^2) . . .

Cloud: $$\sigma2\_cloud\left(h_0, r_{part}\right) := \left(\frac{R\_cloud}{2}\right)^2 + 2 \cdot \mathrm{Diff} \cdot t_f\left(h_0, r_{part}\right)$$

Stem: $$\sigma2\_stem\left(h_0, r_{part}\right) := \left(\frac{R\_stem}{2}\right)^2 + 2 \cdot \mathrm{Diff} \cdot t_f\left(h_0, r_{part}\right)$$

The **two-dimensional number density** (km^{-2}) when a horizontal slice of the cloud (or stem) hits the ground is given below. This is governed by the distance (r_s in km) from the center of the slice.

$$d2\_cloud\left(h_0, r_{part}, r_s\right) := \frac{1}{2\pi \cdot \sigma2\_cloud\left(h_0, r_{part}\right)} \cdot \exp\left(\frac{-r_s^{\,2}}{2 \cdot \sigma2\_cloud\left(h_0, r_{part}\right)}\right)$$

$$d2\_stem\left(h_0, r_{part}, r_s\right) := \frac{1}{2\pi \cdot \sigma2\_stem\left(h_0, r_{part}\right)} \cdot \exp\left(\frac{-r_s^{\,2}}{2 \cdot \sigma2\_stem\left(h_0, r_{part}\right)}\right)$$

Vertically, the cloud and stem are assumed to have a uniform activity density (Ci/km). The initial vertical distribution for a single particle size is given below.

$$\alpha\_v\_stem := \frac{A_{rel}(yield) \cdot f_{stem} \cdot f\_stem_{bin}}{h\_bot}$$

$$\alpha\_v\_cloud := \frac{A_{rel}(yield) \cdot f_{cloud} \cdot f\_cl_{bin}}{h\_top - h\_bot}$$

In what follows, it is useful to know the maximum distance a particle will travel . . .

in the cloud: $d\_max\_cloud(r_{part}) := D_x(h\_top, r_{part})$

in the stem: $d\_max\_stem(r_{part}) := D_x(h\_bot, r_{part})$

It is also useful to know the height (km) as a function of down wind distance x in km.

$$hx(x, r_{part}) := if(x > d\_max\_cloud(r_{part}), h\_top, root(D_x(hx\_guess, r_{part}) - x, hx\_guess, 0, h\_top))$$

The limits of integration are more complicated than necessary due to limitations of MathCad. Normally the integrals would be performed over the entire height of the cloud and stem, but here we try an pick out the main contribution for a given down wind distance and particle size. (Distances are in km).

The goal is to restrict the integration to wihin three standard deviations of the center of a slice on the ground.

$$\sigma_s(x, r_{part}) := \sqrt{\sigma2\_stem(hx(x, r_{part}), r_{part})}$$

$$left\_stem(x, r_{part}) := x - 3\sigma_s(x, r_{part})$$

$$right\_stem(x, r_{part}) := x + 3\sigma_s(x, r_{part})$$

$$a\_stem(x, r_{part}) := \begin{cases} 0 & \text{if } left\_stem(x, r_{part}) < 0 \\ h\_bot & \text{if } left\_stem(x, r_{part}) > d\_max\_stem(r_{part}) \\ max(hx(left\_stem(x, r_{part}), r_{part}), 0) & \text{otherwise} \end{cases}$$

$$b\_stem(x, r_{part}) := \begin{cases} h\_bot & \text{if } right\_stem(x, r_{part}) > d\_max\_stem(r_{part}) \\ 0 & \text{if } right\_stem(x, r_{part}) < 0 \\ min(hx(right\_stem(x, r_{part}), r_{part}), h\_bot) & \text{otherwise} \end{cases}$$

$$\sigma_c(x, r_{part}) := \sqrt{\sigma2\_cloud(hx(x, r_{part}), r_{part})}$$

$$left\_cloud(x, r_{part}) := x - 3\sigma_c(x, r_{part})$$

$$right\_cloud(x, r_{part}) := x + 3\sigma_c(x, r_{part})$$

$$a\_cloud(x, r_{part}) := \begin{cases} h\_bot & \text{if } left\_cloud(x, r_{part}) < d\_max\_stem(r_{part}) \\ h\_top & \text{if } left\_cloud(x, r_{part}) > d\_max\_cloud(r_{part}) \\ max(hx(left\_cloud(x, r_{part}), r_{part}), h\_bot) & \text{otherwise} \end{cases}$$

$$b\_cloud(x, r_{part}) := \begin{cases} h\_top & \text{if } right\_cloud(x, r_{part}) > d\_max\_cloud(r_{part}) \\ h\_bot & \text{if } right\_cloud(x, r_{part}) < d\_max\_stem(r_{part}) \\ \min(hx(right\_cloud(x, r_{part}), r_{part}), h\_top) & \text{otherwise} \end{cases}$$

The distance from the center of a slice to the point (x,y) on the ground is:

$$r_{slice}(x, y, h, r_{part}) := \sqrt{(D_x(h, r_{part}) - x)^2 + y^2}$$

The surface (or ground) activity density (Ci/km^2) for a single particle size at a particular point is calculated by integrating over the entire cloud (this is still referenced to 1 hour after the explosion and is not the actual activity-density).

$$cp_{stem}(x, y, r_{part}) := \begin{cases} 0 & \text{if } b\_stem(x, r_{part}) \le a\_stem(x, r_{part}) \\ \displaystyle\int_{a\_stem(x, r_{part})}^{b\_stem(x, r_{part})} \alpha\_v\_stem \cdot d2\_stem(h, r_{part}, r_{slice}(x, y, h, r_{part}))\, dh & \text{otherwise} \end{cases}$$

$$cp_{cloud}(x, y, r_{part}) := \begin{cases} 0 & \text{if } b\_cloud(x, r_{part}) \le a\_cloud(x, r_{part}) \\ \displaystyle\int_{a\_cloud(x, r_{part})}^{b\_cloud(x, r_{part})} \alpha\_v\_cloud \cdot d2\_cloud(h, r_{part}, r_{slice}(x, y, h, r_{part}))\, dh & \text{otherwise} \end{cases}$$

The conversion from a surface activity concentration to a dose rate depends upon the average photon energy. Here it is assumed that the average photon energy is 0.7 MeV and the dose rate is determined at 1 meter above the ground. At this energy, a uniform activity concentration of 1 MCi/km^2 is equivalent to 2.05 rad/hr. This and other conversion factores can be found in Glasstone Fig. 9.155.

Dose Conversion Factor: $\gamma := 2.05 \cdot 10^{-6}$

Reference Dose Rates (rads/hr at time t_0):

$$dose\_rate_{stem}(x, y, r_{part}) := \gamma \cdot cp_{stem}(x, y, r_{part})$$

$$dose\_rate_{cloud}(x, y, r_{part}) := \gamma \cdot cp_{cloud}(x, y, r_{part})$$

The overall **reference dose rate** (rads/hr) at a point (x,y), which can be compared with Glasstone, is then:

$$dose\_rate(x,y) := \sum_i \left(dose\_rate_{stem}(x,y,r\_part\_stem_i) + dose\_rate_{cloud}(x,y,r\_part\_cl_i)\right)$$

Glasstone Dose Rate Comparison

Glasstone (p. 430) provides scaling relations for the reference dose rate contours as a function of the yield using a 15 mph effective wind speed. Below are the values along the centerline, adjusted for a 50% fission yield weapon.

Dose Rate (rads/hr) | Conversion Coefficient ($miles/kt^{0.45}$)

$$rate\_gl := \begin{pmatrix} 1500 \\ 500 \\ 150 \\ 50 \\ 15 \\ 5 \\ 1.5 \\ 0.5 \end{pmatrix} \qquad coeff := \begin{pmatrix} 0.96 \\ 1.8 \\ 4.5 \\ 8.9 \\ 16 \\ 24 \\ 30 \\ 40 \end{pmatrix}$$

The corresponding down wind distance (km):

$$dist\_gl := 1.609 \cdot coeff\ yield^{0.45}$$

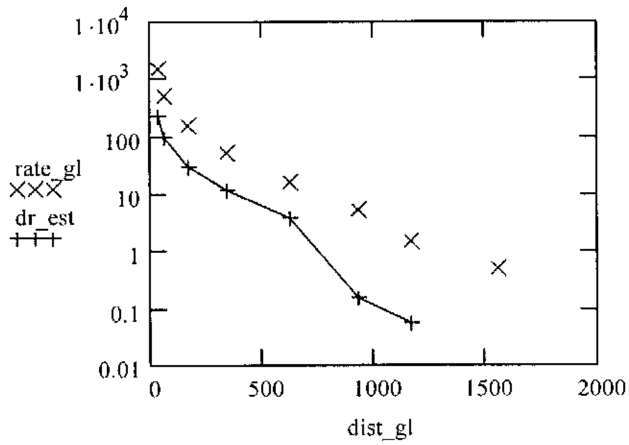
Index: $j := 0 .. 7$

$$dist\_gl = \begin{pmatrix} 37.537 \\ 70.382 \\ 175.954 \\ 347.999 \\ 625.616 \\ 938.423 \\ 1.173\times 10^{3} \\ 1.564\times 10^{3} \end{pmatrix}$$

At these distances, we estimate a dose rate (rads/hr):

$$dr\_est_j := dose\_rate\left(dist\_gl_j, 0\right)$$

$$dr\_est = \begin{pmatrix} 213.684 \\ 96.448 \\ 28.86 \\ 11.508 \\ 3.838 \\ 0.146 \\ 0.055 \\ 0 \end{pmatrix}$$



Accumulated Dose Calculation

Tp simplify the accumulated dose calculations, the integration of the dose rate at a particular point begins at the time of arrival at that point. The total dose will then be integrated out to 4 days after the explosion.

$t\_4day := 96 \qquad t_{min} := .01$

$$t_{arrive}(x, r_{part}) := \begin{cases} t_{min} & \text{if } x < 0 \\ \max\left(t_{min}, t_f\left(hx(x, r_{part}), r_{part}\right)\right) & \text{otherwise} \end{cases}$$

The decay factor (hours) depends upon the down wind distance x and the particle size r_{part}.

$$decay(x, r_{part}) := 5 \cdot t_0 \cdot \left[\left(\frac{t_0}{t_{arrive}(x, r_{part})}\right)^{0.2} - \left(\frac{t_0}{t\_4day}\right)^{0.2}\right]$$

The accumulated dose from the stem and the cloud due to a single particle bin is determined below. (Adjustments are made to overcome MathCad limitations).

$$dose_{stem}(x, y, r_{part}) := \begin{cases} 0 & \text{if } x > \left(d\_max\_stem(r_{part}) + 3 \cdot \sigma_s\left(d\_max\_stem(r_{part}), r_{part}\right)\right) \\ dose\_rate_{stem}(x, y, r_{part}) \cdot decay(x, r_{part}) & \text{otherwise} \end{cases}$$

$$dose_{cloud}(x, y, r_{part}) := \begin{cases} 0 & \text{if } x > \left(d\_max\_cloud(r_{part}) + 3 \cdot \sigma_s\left(d\_max\_cloud(r_{part}), r_{part}\right)\right) \\ 0 & \text{if } x < d\_max\_stem(r_{part}) - 3 \cdot \sigma_s\left(d\_max\_stem(r_{part}), r_{part}\right) \\ dose\_rate_{cloud}(x, y, r_{part}) \cdot decay(x, r_{part}) & \text{otherwise} \end{cases}$$

The **total dose accumulated** after 4 days at a particular point on the ground is:

$$dose_{tot}(x,y) := \sum_i \left(dose_{stem}(x,y,r\_part\_stem_i) + dose_{cloud}(x,y,r\_part\_cl_i)\right)$$

The **dose contour dimensions** can now be computed:

$n_x := 1($ $\quad i_x := 0..n_x$ $\quad n_y := 1$ $\quad i_y := 0..n_y$

$$x_{inc} := \frac{1000}{n_x} \qquad y_{inc} := 16.20$$

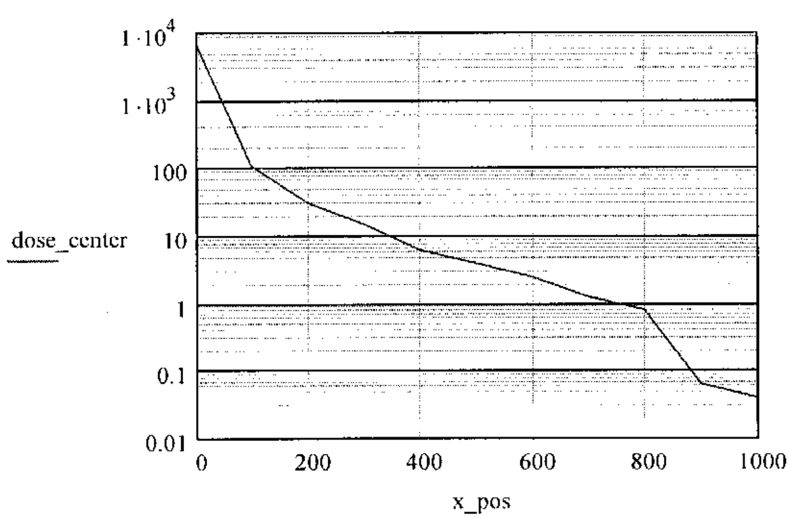
$x_{inc} = 100$

$y\_pos_{i_y} := -R\_cloud + i_y \cdot y_{inc}$

$x\_pos_{i_x} := i_x \cdot x_{inc}$

$$dose\_center_{i_x} := dose_{tot}\left(x\_pos_{i_x}, 0\right)$$

Here is the total accumulated dose (REM) at a distance along the center line.



Now for the **specific dose contours** (300, 25, and 1 REM):

This Function takes a starting x-value, the range that we will check the value in, and the total Accumulated dosage amount that we are checking for. It then returns either the input x-value or the input x value plus half of the input range.

$$\mathrm{fxn}(\mathrm{xval},\mathrm{range},\mathrm{rems}) := \begin{cases} \mathrm{xval} & \text{if } \mathrm{dose}_{\mathrm{tot}}\left(\mathrm{xval}+\frac{\mathrm{range}}{2},0\right) < \mathrm{rems} \\ \mathrm{xval}+\frac{\mathrm{range}}{2} & \text{if } \mathrm{dose}_{\mathrm{tot}}\left(\mathrm{xval}+\frac{\mathrm{range}}{2},0\right) > \mathrm{rems} \\ \mathrm{xval} & \text{otherwise} \end{cases}$$

This next function only takes, as an argument, the total dosage amount that we are looking for. It uses the previous function to telescope down to a value closer to the input dosage. It returns the maximum value along the x-axis that has the given total accumulated dosage.

$i_x := 18$ $\qquad$ $n_x := 0..i_x$

$$r_{n_x} := \left(\frac{1}{2}\right)^{n_x} 2000($$

$$\mathrm{telescopex}(\mathrm{rm}) := \mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(\mathrm{fxn}(0,r_0,\mathrm{rm}),r_1,\mathrm{rm}),r_2,\mathrm{rm}),r_3,\mathrm{rm})$$

This function takes a y-value, an x-value, the range, and total accumulated dose that we are looking for. It returns either the input y-value or the input y-value plus half of the range.

$$\mathrm{fyn}(\mathrm{yval},\mathrm{xinput},\mathrm{rangey},\mathrm{rems}) := \begin{cases} \mathrm{yval} & \text{if } \mathrm{dose}_{\mathrm{tot}}\left(\mathrm{xinput},\mathrm{yval}+\frac{\mathrm{rangey}}{2}\right) < \mathrm{rems} \\ \mathrm{yval}+\frac{\mathrm{rangey}}{2} & \text{if } \mathrm{dose}_{\mathrm{tot}}\left(\mathrm{xinput},\mathrm{yval}+\frac{\mathrm{rangey}}{2}\right) > \mathrm{rems} \\ \mathrm{yval} & \text{otherwise} \end{cases}$$

This next function takes, as an argument, the x-value that we are checking and the total accumulated dosage that we are looking for. It then returns a y-value at that x-value that corresponds to the requested total accumulated dose.

$i_y := 13$ $\qquad$ $n_y := 0..i_y$

$$q_{n_y} := \left(\frac{1}{2}\right)^{n_y} 100($$

$$\mathrm{telescopey}(\mathrm{inputx},\mathrm{qm}) := \mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(\mathrm{fyn}(0,\mathrm{inputx},q_0,\mathrm{qm}),\mathrm{inputx},q_1,\mathrm{qm}),\mathrm{inp}$$

First we find the maximum centerline values where the total accumulated dosages are 300, 25, and 1 REM respectively.

$x300 := telescopex(300)$

$x25 := telescopex(25)$

$x1 := telescopex(1)$

Now we split up the centerline values into 10 increments and find the maximum y-value that corresponds to a given total dosage. Then, we graph the y and x positions of those dosage contours. All distances are in km.

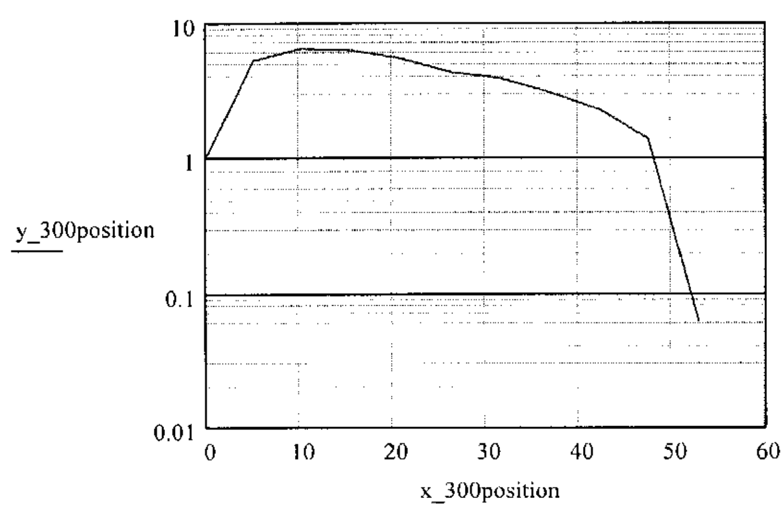
For the 300 REM Contour:

$n_s := 10 \qquad i_s := 0..n_s$

$$xstep300 := \frac{x300}{n_s}$$

$$x\_300position_{i_s} := i_s \cdot xstep300 + .000000$$

$$y\_300position_{i_s} := telescopey\left(x\_300position_{i_s}, 300\right)$$



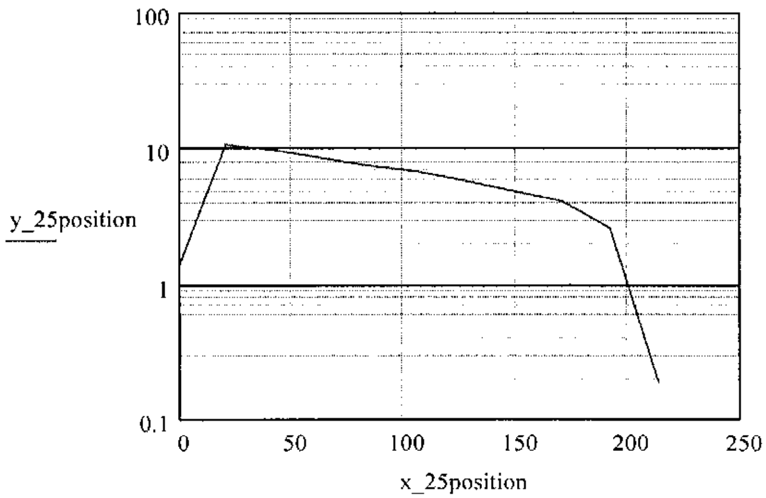
For the 25 REM Contour:

$n_t := 10 \qquad i_t := 0..n_t$

$$xstep25 := \frac{x25}{n_t}$$

$$x\_25position_{i_t} := i_t \cdot xstep25 + .000000$$

$$y\_25position_{i_t} := telescopey\left(x\_25position_{i_t}, 25\right)$$



For the 1 REM Contour:

$n_u := 10$ $\qquad$ $i_u := 0 .. n_u$

$$xstep1 := \frac{x1}{n_u}$$

$$x\_1position_{i_u} := i_u \cdot xstep1 + .000000$$

$$y\_1position_{i_u} := telescopey\left(x\_1position_{i_u}, 1\right)$$