MILDOS-AREA

Version 4

Fall RAMP Users Group Meeting

North Bethesda, Maryland

10/16/17 to 10/17/17

Overview

- **What is MILDOS-AREA?**
  - Program scope
  - Uranium reserves and mining / milling
  - MILDOS-AREA development
  - Documentation & guidance / regulations
  - New features and demo
- **Models and Methodology**
  - User Interface
    - Example case development follows model discussion
    - Receptor options
  - Radionuclides, source types, and source terms
  - Air dispersion, ground concentrations, and resuspension
  - Media concentrations
  - Exposure calculations
  - Interactive results
  - Sensitivity analysis
- **Topic Specific Problem Sets**

What is MILDOS-AREA?

Computer code

- Based on U.S. Nuclear Regulatory Commission (NRC) guidance

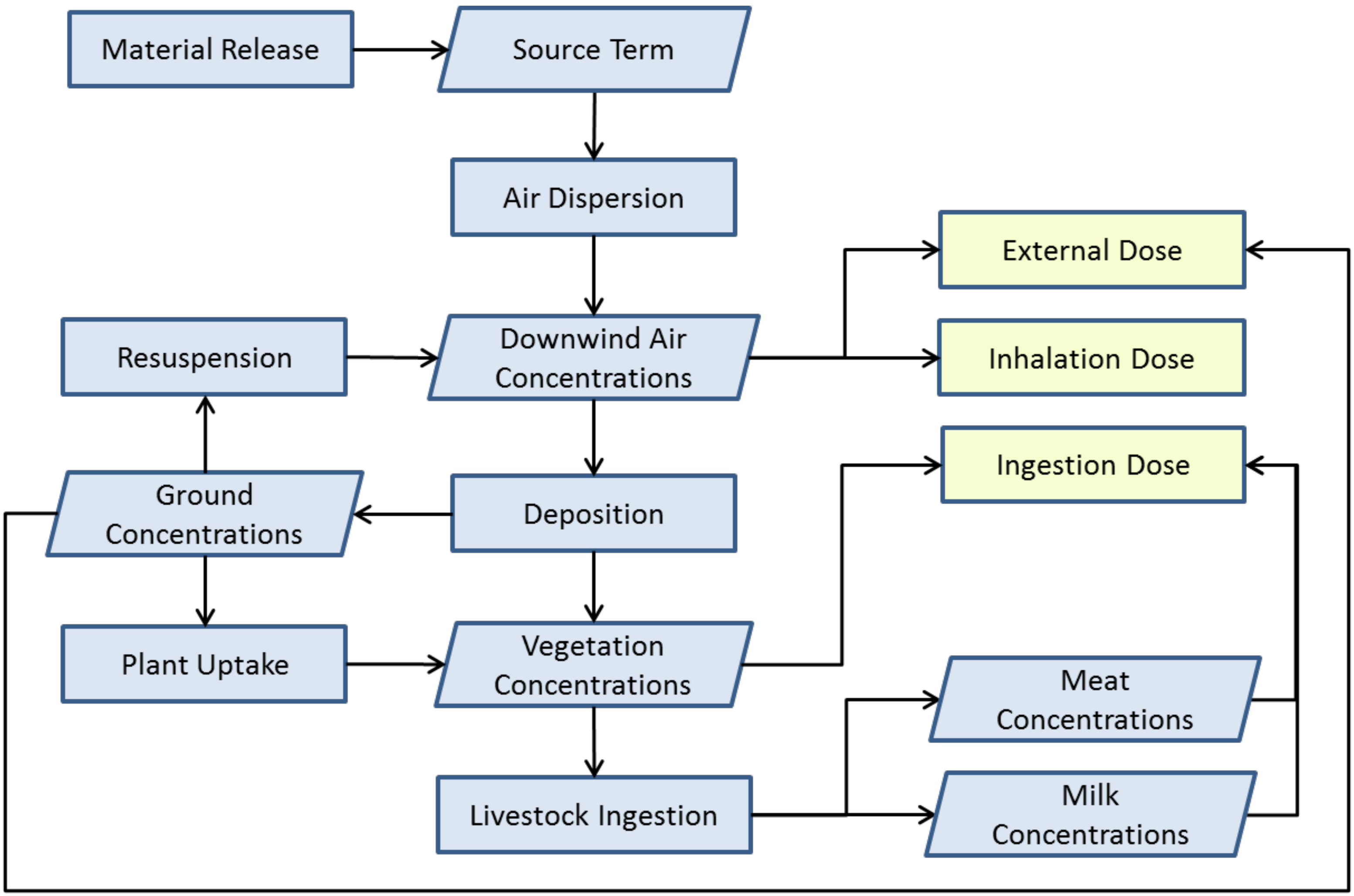
Licensing tool

- Applicants and licensees
- NRC staff

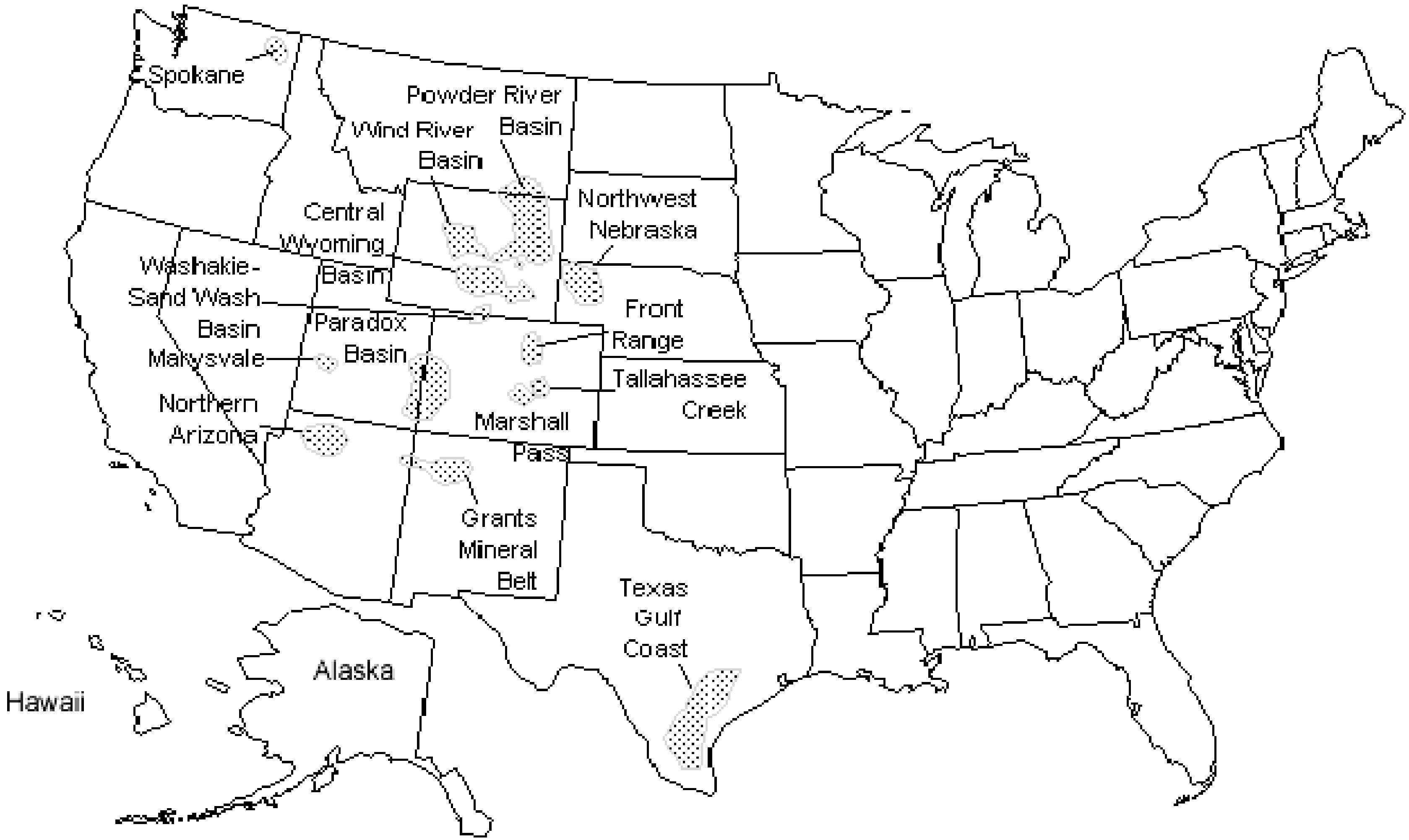
Program Scope

- **Impact estimation from radioactive emissions from uranium milling facilities (traditional ore and in-situ recovery)**
  - Dose commitments to individuals and regional population
  - Air, ground, and food concentrations
  - Different processes occur at different times in the facility's operational lifetime
    - For example: well drilling, operations, storage, restoration
- **Only radioactive emissions from airborne release**
  - Uses sector averaged plume model
  - Includes deposition, resuspension, accumulation, weathering, decay & ingrowth
  - No release to surface water or groundwater
- **Exposure pathways include**
  - External from groundshine and cloudshine
  - Inhalation
  - Ingestion of meat, milk, and vegetables

Exposure Pathways

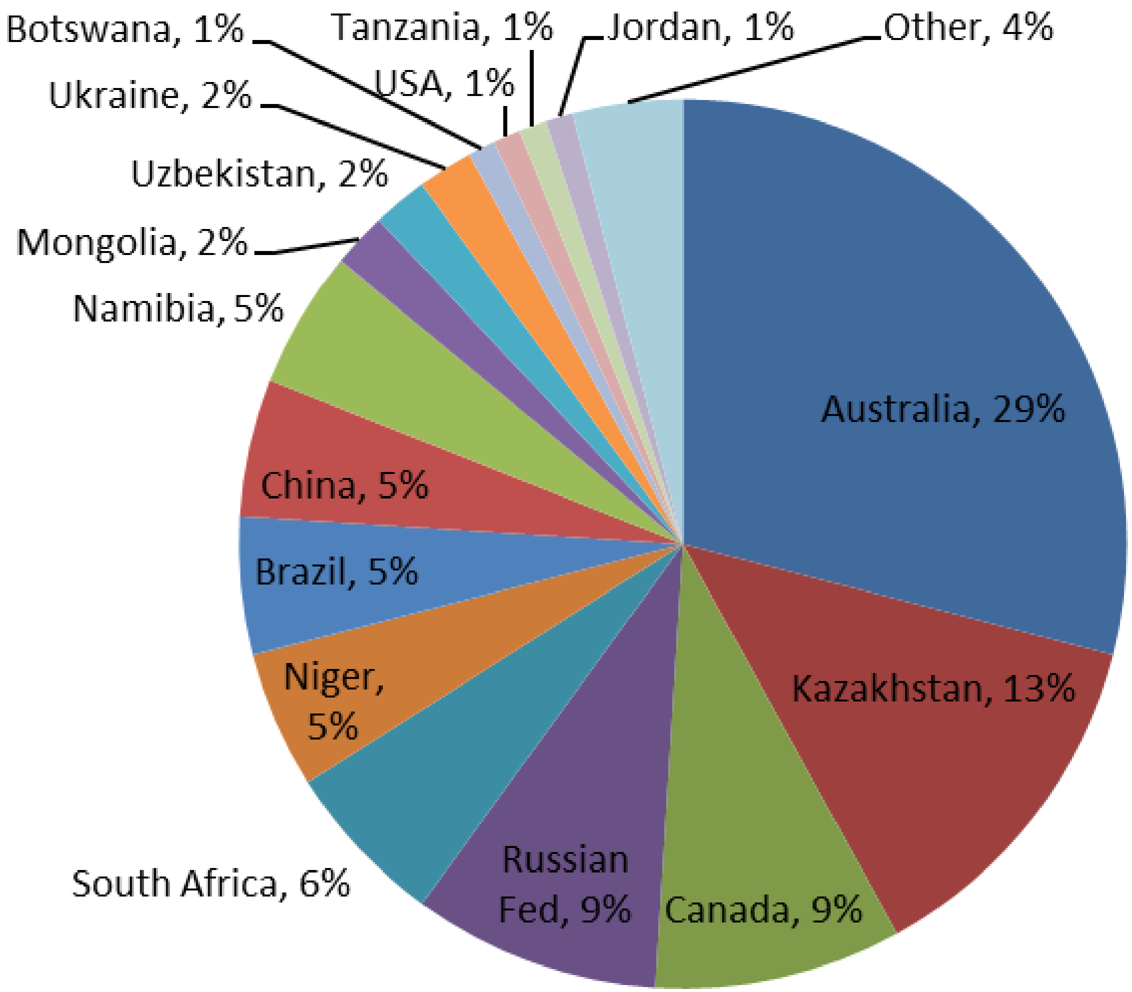


Major U.S. Uranium Reserves



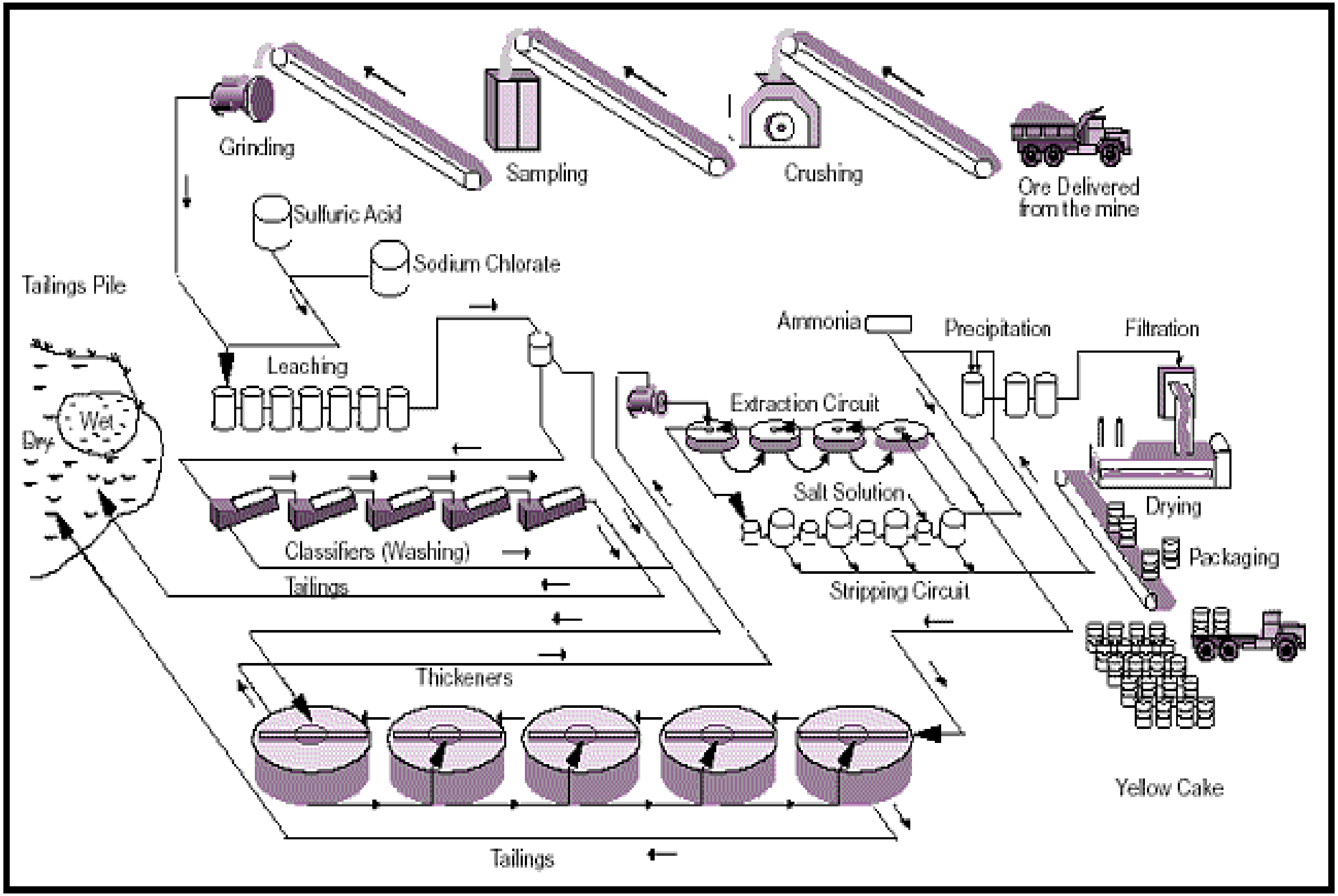
Sources: Based on U.S. Department of Energy, Grand Junction Project Office (GJPO), National Uranium Resources Evaluation, Interim Report (June 1979) Figure 3.2; and GJPO data files.

Known Recoverable Sources of Uranium, 2015



http://www.world-nuclear.org/information-library/nuclear-fuel-cycle/uranium-resources/supply-of-uranium.aspx

Conventional Uranium Ore Milling Process



U.S. Uranium Mills

Table 4. U.S. uranium mills and heap leach facilities by owner, location, capacity, and operating status at end of the year, 2011-16

Owner	Mill and *Heap Leach*[1] *Facility* Name	County, State (existing and *planned* locations)	Capacity (short tons of ore per day)	Operating Status at End of the Year					
				2011	2012	2013	2014	2015	2016
Anfield Resources	Shootaring Canyon Uranium Mill	Garfield, Utah	750	Standby	Standby	Standby	Standby	Standby	Standby
EFR White Mesa LLC	White Mesa Mill	San Juan, Utah	2,000	Operating	Operating	Operating-Processing Alternate Feed	Operating-Processing Alternate Feed	Operating-Processing Alternate Feed	Operating-Processing Alternate Feed
Energy Fuels Wyoming Inc	*Sheep Mountain*	*Fremont, Wyoming*	725	-	-	Undeveloped	Undeveloped	Undeveloped	Undeveloped
Kennecott Uranium Company/Wyoming Coal Resource Company	Sweetwater Uranium Project	Sweetwater, Wyoming	3,000	Standby	Standby	Standby	Standby	Standby	Standby
Pinon Ridge Resources Corporation	Pinon Ridge Mill	*Montrose, Colorado*	500	Permitted And Licensed	Partially Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed
Total Capacity:			**6,975**						

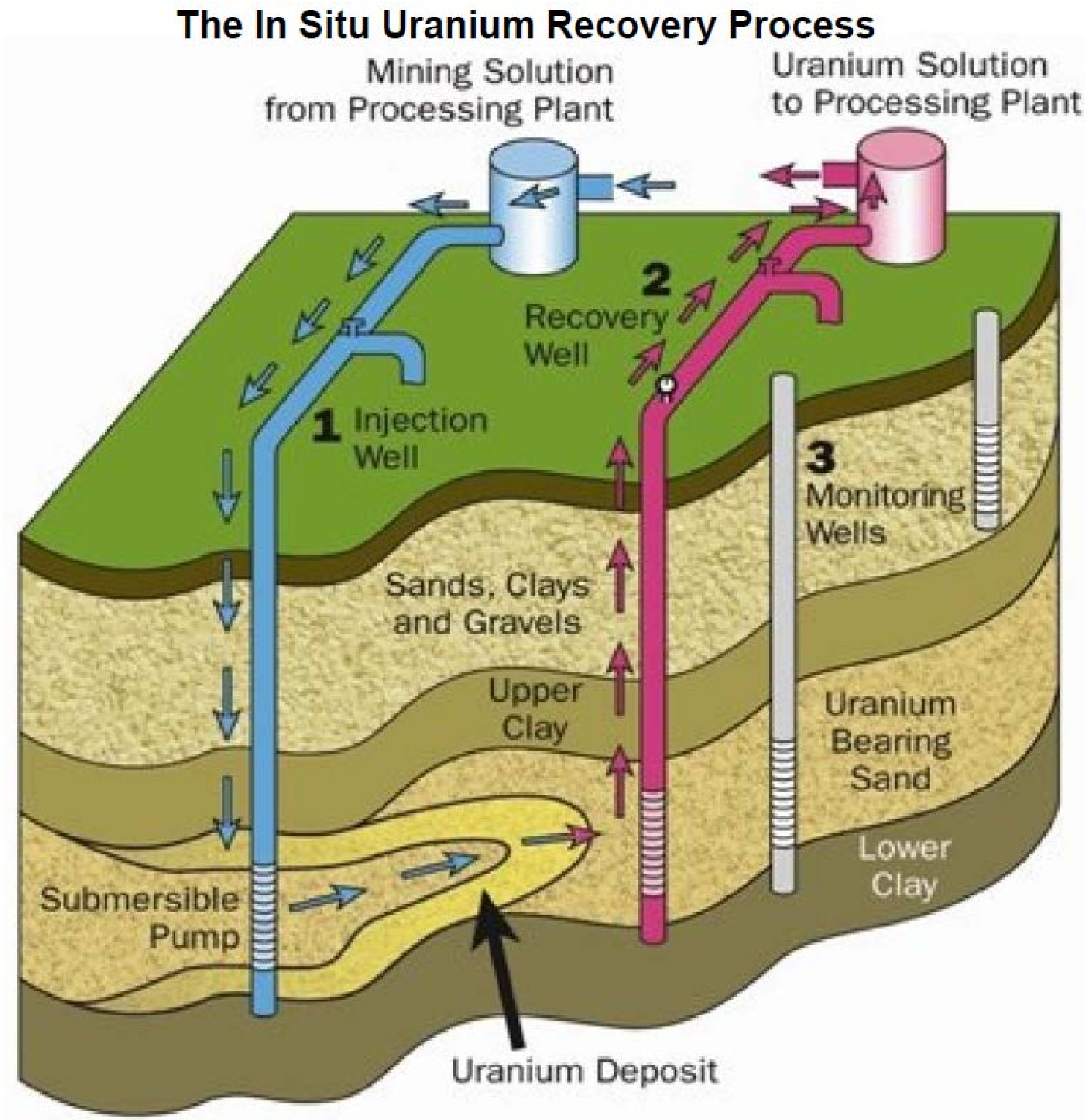
- = No data reported.

[1] Heap leach solutions: The separation, or dissolving-out from mined rock, of the soluble uranium constituents by the natural action of percolating a prepared chemical solution through mounded (heaped) rock material. The mounded material usually contains low grade mineralized material and/or waste rock produced from open pit or underground mines. The solutions are collected after percolation is completed and processed to recover the valued components.

Notes: Capacity for 2015. An operating status of "Operating" indicates the mill usually was producing uranium concentrate at the end of the period.

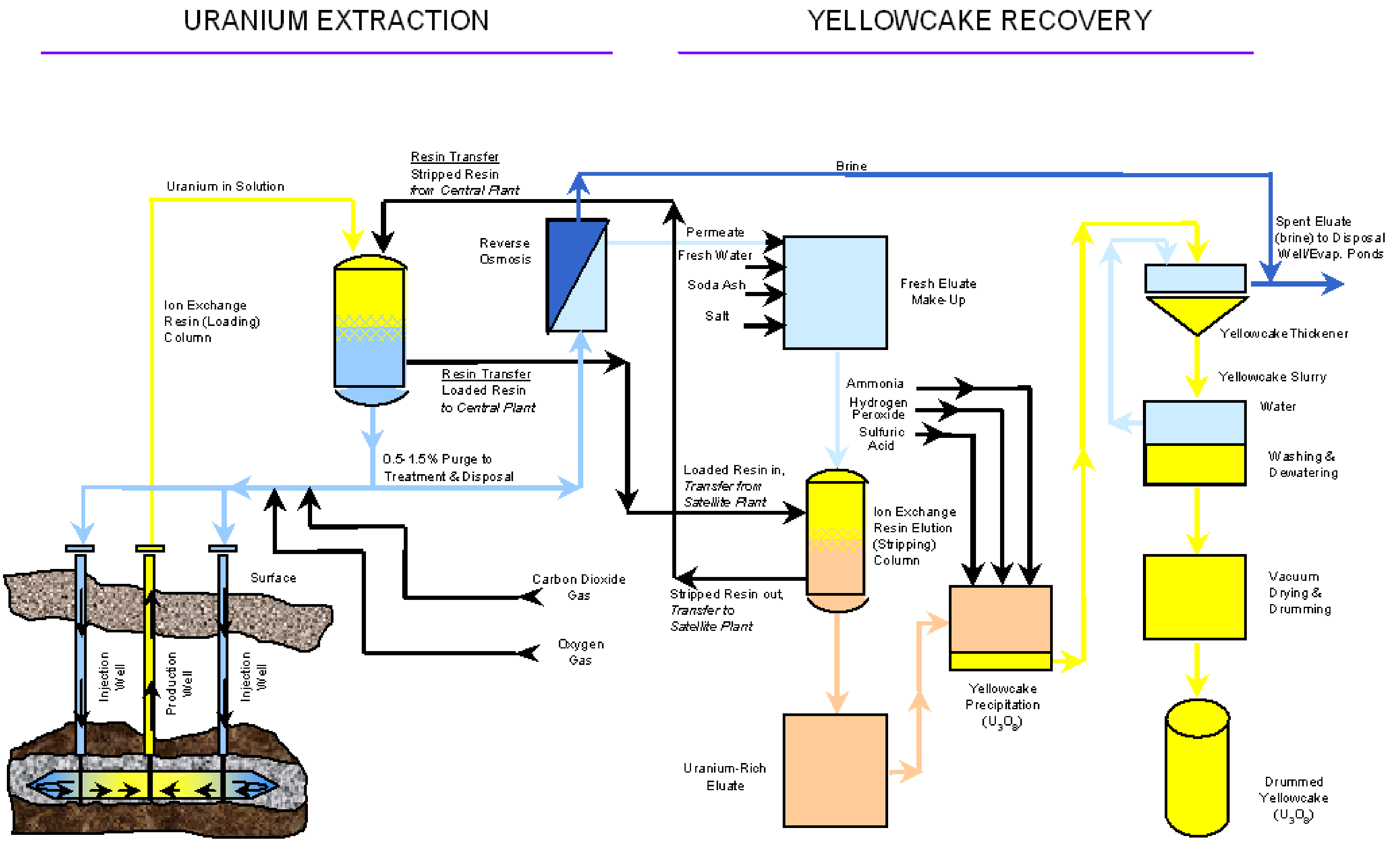
Source: U.S. Energy Information Administration: Form EIA-851A, "Domestic Uranium Production Report" (2011-16).

In Situ Recovery



Source: U.S. Nuclear Regulatory Commision.

In Situ Recovery (cont.)



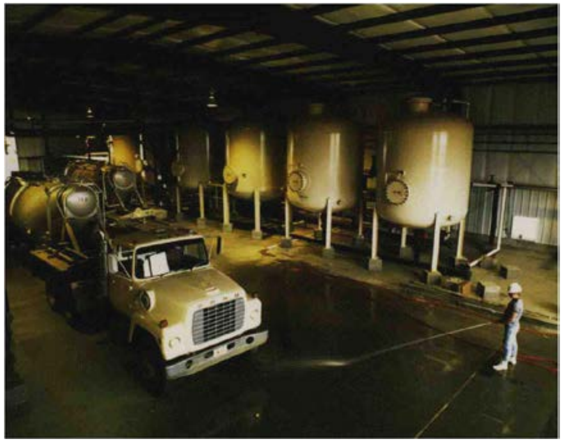
In Situ Recovery

New Well Field Development

Production Well Fields

Drying and Packaging of Yellow Cake

Restoration Well Fields and Land Application



U.S. Uranium In Situ Leach Plants

Table 5. U.S. uranium in-situ-leach plants by owner, location, capacity, and operating status at end of the year, 2011-16

In-Situ-Leach Plant Owner	In-Situ-Leach Plant Name	County, State (existing and *planned* locations)	Production Capacity (pounds U_3O_8 per year)	Operating Status at End of the Year					
				2011	2012	2013	2014	2015	2016
AUC LLC	Reno Creek	*Campbell, Wyoming*	2,000,000	-	-	Developing	Developing	Partially Permitted and Licensed	Partially Permitted and Licensed
Azarga Uranium Corp	Dewey Burdock Project	*Fall River and Custer, South Dakota*	1,000,000	Undeveloped	Developing	Developing	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed
Cameco	Crow Butte Operation	Dawes, Nebraska	1,000,000	Operating	Operating	Operating	Operating	Operating	Operating
Hydro Resources, Inc.	Church Rock	*McKinley, New Mexico*	1,000,000	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed
Hydro Resources, Inc.	Crownpoint	*McKinley, New Mexico*	1,000,000	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed	Partially Permitted And Licensed
Lost Creek ISR LLC	Lost Creek Project	Sweetwater, Wyoming	2,000,000	Partially Permitted And Licensed	Under Construction	Operating	Operating	Operating	Operating
Mestena Uranium LLC	Alta Mesa Project	Brooks, Texas	1,500,000	Producing	Producing	Producing	Producing	Standby	Standby
Power Resources Inc., dba Cameco Resources	Smith Ranch-Highland Operation	Converse, Wyoming	5,500,000	Operating	Operating	Operating	Operating	Operating	Operating
South Texas Mining Venture	Hobson ISR Plant	Karnes, Texas	1,000,000	Operating	Operating	Operating	Operating	Operating	Standby
South Texas Mining Venture	La Palangana	Duval, Texas	1,000,000	Operating	Operating	Operating	Operating	Operating	Standby

U.S. Uranium In Situ Leach Plants (cont.)

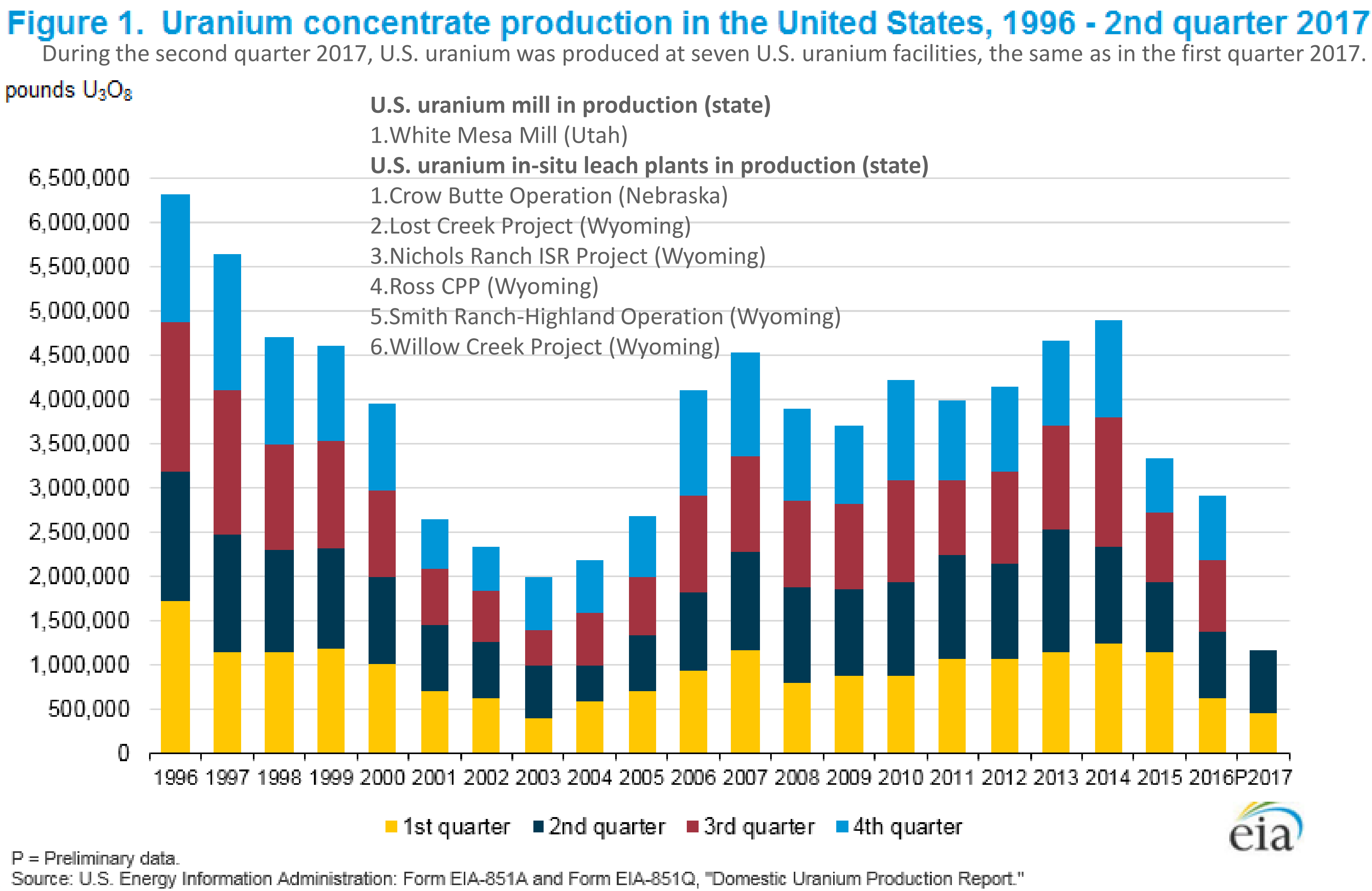
Strata Energy Inc	Ross CPP	Crook, Wyoming	375,000	Developing	Partially Permitted And Licensed	Partially Permitted And Licensed	Under Construction	Changing License to Operational	Operating
URI, Inc.	Kingsville Dome	Kleberg, Texas	1,000,000	Standby	Standby	Restoration	Restoration	Restoration	Restoration
URI, Inc.	Rosita	Duval, Texas	1,000,000	Standby	Standby	Restoration	Restoration	Reclamation	Reclamation
URI, Inc.	Vasquez	Duval, Texas	800,000	Restoration	Restoration	Restoration	Restoration	Restoration	Restoration
Uranerz Energy Corporation	Nichols Ranch ISR Project	Johnson and Campbell, Wyoming	2,000,000	Under Construction	Under Construction	Under Construction	Producing	Operating	Operating
Uranium Energy Corp.	Goliad ISR Uranium Project	*Goliad, Texas*	1,000,000	Partially Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Standby
Uranium One Americas, Inc.	Jab and Antelope	*Sweetwater, Wyoming*	2,000,000	Developing	Developing	Developing	Developing	Developing	Developing
Uranium One Americas, Inc.	Moore Ranch	*Campbell, Wyoming*	500,000	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed	Permitted And Licensed
Uranium One USA, Inc.	Willow Creek Project (Christensen Ranch and Irigaray)	Campbell and Johnson, Wyoming	1,300,000	Producing	Producing	Producing	Operating	Operating	Operating
Total Production Capacity:			**26,975,000**						

- = No data reported.

Notes: Production capacity for 2016. An operating status of "Operating" indicates the in-situ-leach plant usually was producing uranium concentrate at the end of the period. Hobson ISR Plant processes uranium concentrate that came from La Palangana. Hobson and La Palangana are part of the same project. ISR stands for in-situ recovery. Christensen Ranch and Irigaray are part of the Willow Creek Project. Uranerz Energy has a tolling arrangement with Cameco Resources. Uranium is first processed at the Nichols Ranch plant and then transported to the Smith Ranch-Highland Operation plant for final processing into Uranerz's uranium concentrate. CPP stands for central processing plant.

Source: U.S. Energy Information Administration: Form EIA-851A, "Domestic Uranium Production Report" (2011-16).

U.S. Uranium Production



http://www.eia.gov/uranium/production/quarterly/

MILDOS-AREA Development

- 1979: UDAD (Uranium Dispersion and Dosimetry)
- 1981: MILDOS
- 1989: MILDOS-AREA to include large-area sources and changes in dosimetry methodologies
- 1997/8: MILDOS-AREA 3.0X to include ISL specific sources, update interface to Windows, and update results for regulations
- 2012: MILDOS-AREA 3.10 – refinement of interface, bug fixes, update interface to work with new Windows operating systems
- 2016 : MILDOS-AREA 4.0 – Windows 7 to 10, rewrite of code with integration of conventional and ISR mining/milling, Th-232 series nuclides added
- 2016 (September): MILDOS-AREA 4.01 – Maintenance release: GUI upgrades, GIS module update, runtime speed improvements, bug fixes

NRC Reference Materials

- **Regulatory Guides**
  - 3.46 – Standard Format and Content of License Applications, including Environmental Reports, for In Situ Uranium Solution Mining (1982)
  - 3.51 – Calculational Models for Estimating Radiation Doses to Man from Airborne Radioactive Materials Resulting from Uranium Milling Operations (1982)
  - 3.59 – Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations (1987)
  - 4.14 – Radiological Effluent and Environmental Monitoring at Uranium Mills (1980)

- **Interim Staff Guidance**
  - FSME-ISG-001, Evaluations of Uranium Recovery Facility Surveys of Radon and Radon Progeny in Air and Demonstrations of Compliance with 10 CFR 20.1301 (2014)

NRC Reference Materials (cont.)

- **Reports**
  - *Final Generic Environmental Impact Statement on Uranium Milling* [NUREG-0706 (1980)]
  - Standard Review Plan for In Situ Leach Uranium Extraction License Applications [NUREG-1569 (2003)]
  - *Compliance Determination Procedures for Environmental Radiation Protection Standards for Uranium Recovery Facilities 40 CFR Part 190* [NUREG-0859 (1982)]
  - *Consolidated Guidance: 10 CFR Part 20 – Standards for Protection Against Radiation* [NUREG-1736 (2001)]

Regulatory Guide 3.59

Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations (1987)

- **Particle process emissions**
  - Ore handling and storage
  - Grinding and crushing
  - Yellowcake drying and packaging
- **Particle wind blown emissions**
  - Dusting (erosion) rate calculation
- **Radon emissions**
  - Ore storage
  - Crushing and grinding
  - Tailings
  - In situ leaching

Regulatory Guide 3.51

Calculational Models for Estimating Radiation Doses to Man from Airborne Radioactive Materials Resulting from Uranium Milling Operations (1982)

- **Recommended Dose Models**
  - Individual / Population
  - Inhalation, External (Ground / Air), Ingestion (Vegetables, Meat, Milk)

- **10 CFR 20 compliance (Standards for Protection Against Radiation)**
  - 10 CFR 20.1101(b): concept of as low as reasonably achievable (ALARA)
  - 10 CFR 20 1101(d): annual maximum of 10 mrem to member of the public from airborne releases (excluding Rn-222 and its daughters)
  - 10 CFR 20 1301(a)(1): annual maximum of 100 mrem to member of the public
  - 10 CFR 20 1302(b)(2)(i): compliance with above can be shown if effluent air and ground releases do not exceed the values specified in Table 2 of Appendix B to part 20 at the boundary of the unrestricted area and the external dose rate is less than 2 mrem per hour

Regulatory Guide 3.51(cont.)

- **40 CFR 190 compliance (Environmental Radiation Protection Standards for Nuclear Power Operations)**
  - Annual dose equivalent of 25 mrem to whole body, 75 mrem to thyroid, 25 mrem to any other organ
  - Excludes emission of radon and daughters

Documentation

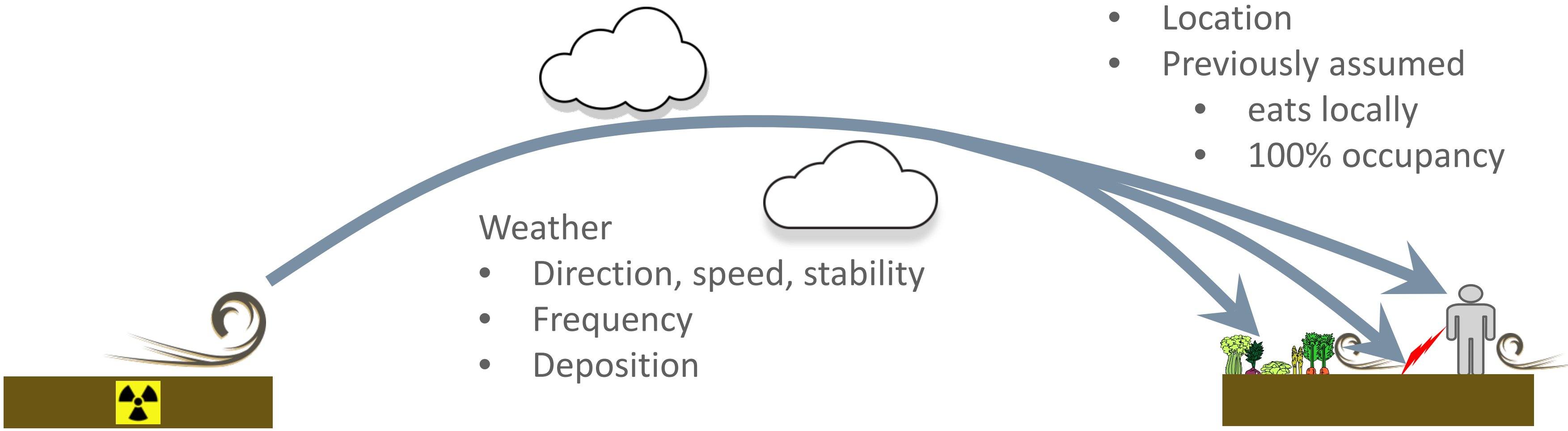
- 1979 – *Uranium Dispersion and Dosimetry (UDAD) Code* [NUREG/CR-0553]
- 1981 – *MILDOS – A Computer Program for Calculating Environmental Radiation Doses From Uranium Recovery Operations* [NUREG/CR-2011]
- *1984 - Methods for Estimating Radioactive and Toxic Airborne Source Terms for Uranium Milling Operations* [NUREG/CR-4088]
- 1989 – *MILDOS-AREA: An Enhanced Version of MILDOS for Large-Area Sources* [ANL/ES-161]
- 1997 – *MILDOS-AREA: An Update with Incorporation of In Situ Leach Uranium Recovery Technology* [NRC letter report; App. D in NUREG-1569]
- 2016 – *Technical Manual and User's Guide for MILDOS-AREA Version 4* [NUREG/CR-7212]
- 2016 – *MILDOS-AREA Version 4 Computational Verification Report* [NUREG/CR-7213]

What's New (Version 4)

- **Code re-write**
  - Integrate conventional ore and ISR analyses
  - Run natively as a Windows 7 application
  - Improved user interface
- **More user accessible model parameters**
- **Support for ores containing thorium-232 and its daughters**
- **Updated area source model**
- **Sensitivity analysis for specific input parameters**
- **Meteorological data input processor**
- **Upgraded map graphics**

Input Components

Receptor
- Location
- Previously assumed
  - eats locally
  - 100% occupancy

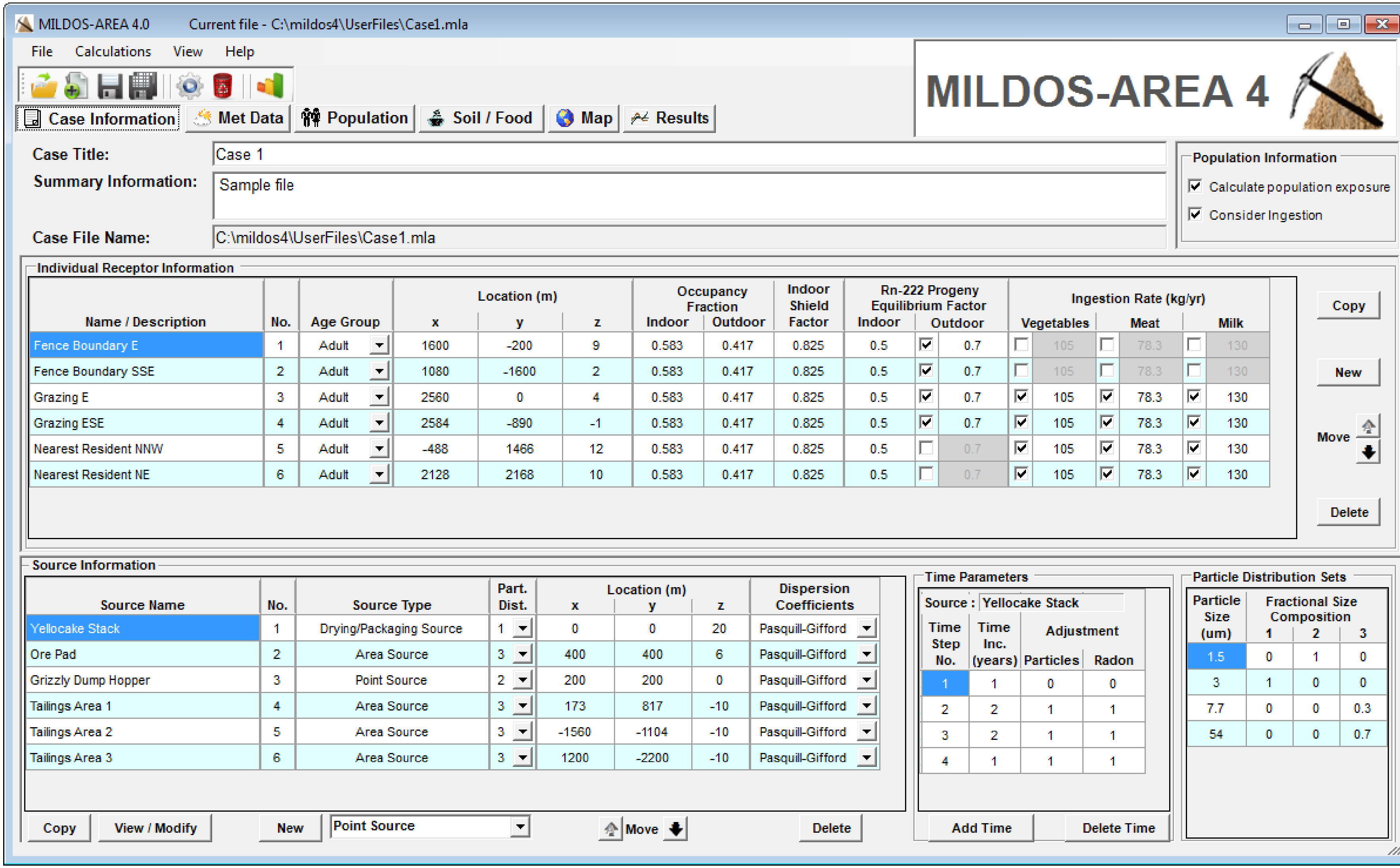


Weather
- Direction, speed, stability
- Frequency
- Deposition

Source release
- Types
- Radon / Particulates Releases
- Particulate characterization
- Source time dependence

Land
- Food yield
- Weathering
- Resuspension

MILDOS-AREA Demo



MILDOS-AREA 4.0 Current file - C:\mildos4\UserFiles\Case1.mla

File Calculations View Help

Case Information | Met Data | Population | Soil / Food | Map | Results

MILDOS-AREA 4

Case Title: Case 1

Summary Information: Sample file

Case File Name: C:\mildos4\UserFiles\Case1.mla

Population Information

- [x] Calculate population exposure
- [x] Consider Ingestion

Individual Receptor Information

Name / Description	No.	Age Group	Location (m) x	y	z	Occupancy Fraction Indoor	Outdoor	Indoor Shield Factor	Rn-222 Progeny Equilibrium Factor Indoor	Outdoor	Ingestion Rate (kg/yr) Vegetables	Meat	Milk
Fence Boundary E	1	Adult	1600	-200	9	0.583	0.417	0.825	0.5	[x] 0.7	[ ] 105	[ ] 78.3	[ ] 130
Fence Boundary SSE	2	Adult	1080	-1600	2	0.583	0.417	0.825	0.5	[x] 0.7	[ ] 105	[ ] 78.3	[ ] 130
Grazing E	3	Adult	2560	0	4	0.583	0.417	0.825	0.5	[x] 0.7	[x] 105	[x] 78.3	[x] 130
Grazing ESE	4	Adult	2584	-890	-1	0.583	0.417	0.825	0.5	[x] 0.7	[x] 105	[x] 78.3	[x] 130
Nearest Resident NNW	5	Adult	-488	1466	12	0.583	0.417	0.825	0.5	[ ] 0.7	[x] 105	[x] 78.3	[x] 130
Nearest Resident NE	6	Adult	2128	2168	10	0.583	0.417	0.825	0.5	[ ] 0.7	[x] 105	[x] 78.3	[x] 130

Copy New Move Delete

Source Information

Source Name	No.	Source Type	Part. Dist.	Location (m) x	y	z	Dispersion Coefficients
Yellocake Stack	1	Drying/Packaging Source	1	0	0	20	Pasquill-Gifford
Ore Pad	2	Area Source	3	400	400	6	Pasquill-Gifford
Grizzly Dump Hopper	3	Point Source	2	200	200	0	Pasquill-Gifford
Tailings Area 1	4	Area Source	3	173	817	-10	Pasquill-Gifford
Tailings Area 2	5	Area Source	3	-1560	-1104	-10	Pasquill-Gifford
Tailings Area 3	6	Area Source	3	1200	-2200	-10	Pasquill-Gifford

Copy View / Modify New Point Source Move Delete

Time Parameters

Source : Yellocake Stack

Time Step No.	Time Inc. (years)	Adjustment Particles	Radon
1	1	0	0
2	2	1	1
3	2	1	1
4	1	1	1

Add Time Delete Time

Particle Distribution Sets

Particle Size (um)	Fractional Size Composition 1	2	3
1.5	0	1	0
3	1	0	0
7.7	0	0	0.3
54	0	0	0.7

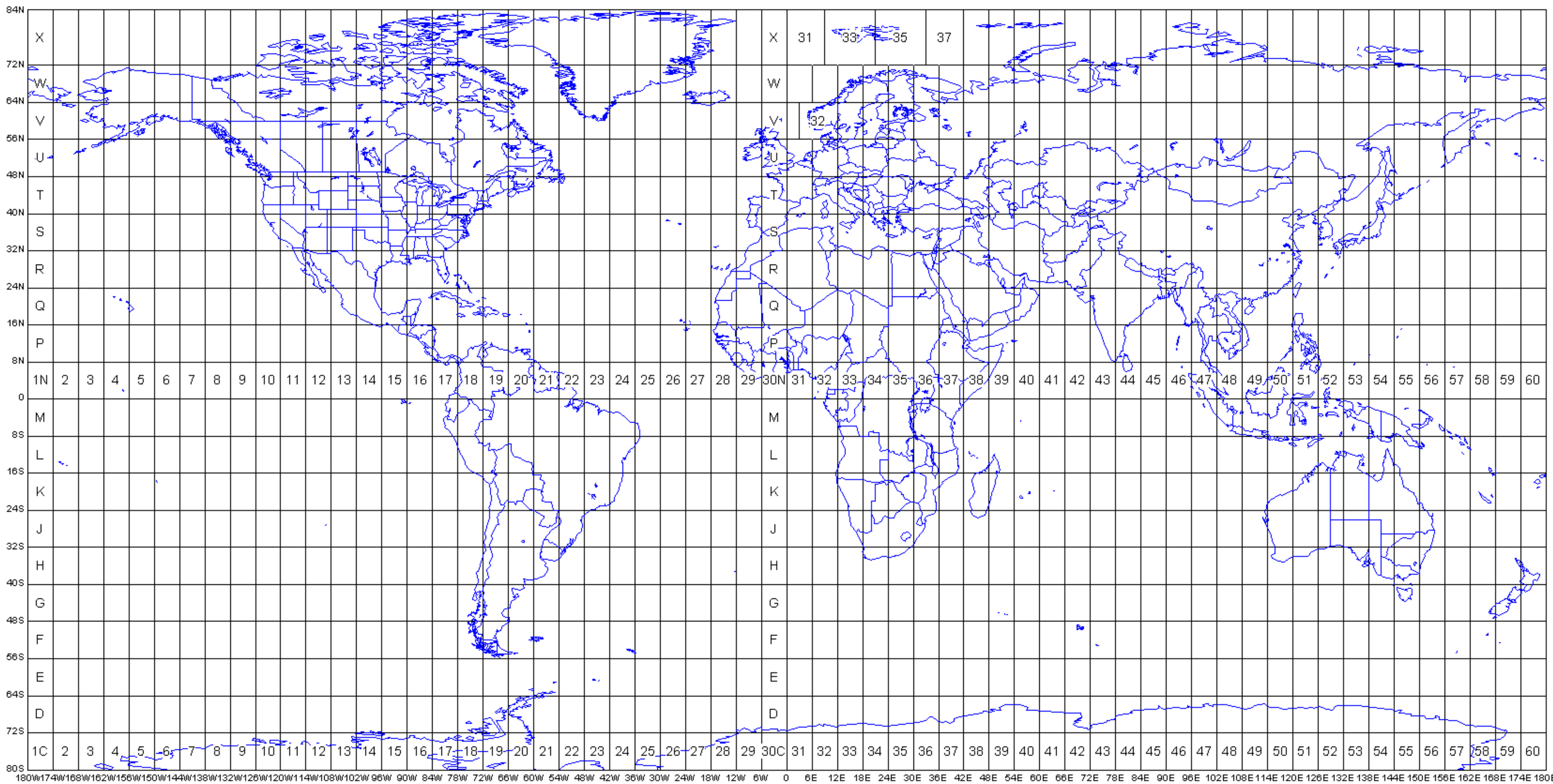
Map Interface

- **Cartesian coordinate system (x,y) with distance units in meters**
- **Local coordinates**
  - 1st emission source located at origin (0,0)
- **Universal Transverse Mercator (UTM) coordinates**
  - Projection with 60 northern zones and 60 southern zones
  - Zones widths are 6° in longitude
  - Zones are numbered 1 through 60 starting at 180°W longitude
  - Continental United States lies in northern zones 10 through 19 (10N through 19N)
  - Easting – east-west direction (x) coordinate
  - Northing – north-south direction (y) coordinate

Datum – mathematical model that describes the shape of the earth (WGS84 and NAD83 are the most recent) WGS84 is a global representation

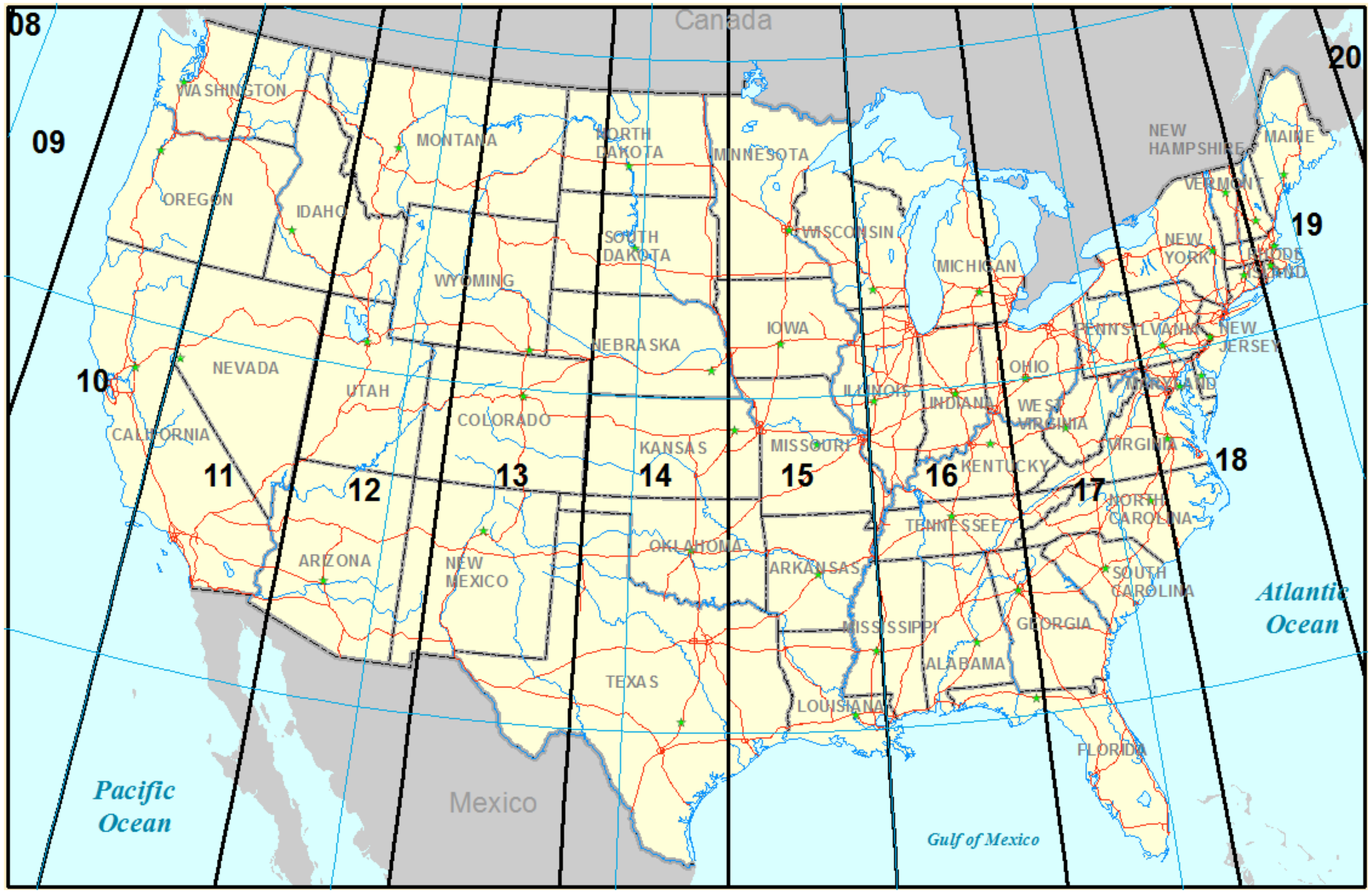
Projection – representation of a curved surface on a flat plan (datum is integral to projection)

Universal Transverse Mercator (UTM) Projection



http://www.dmap.co.uk/utmworld.htm

UTM Zones in the Contiguous United States



Map Data

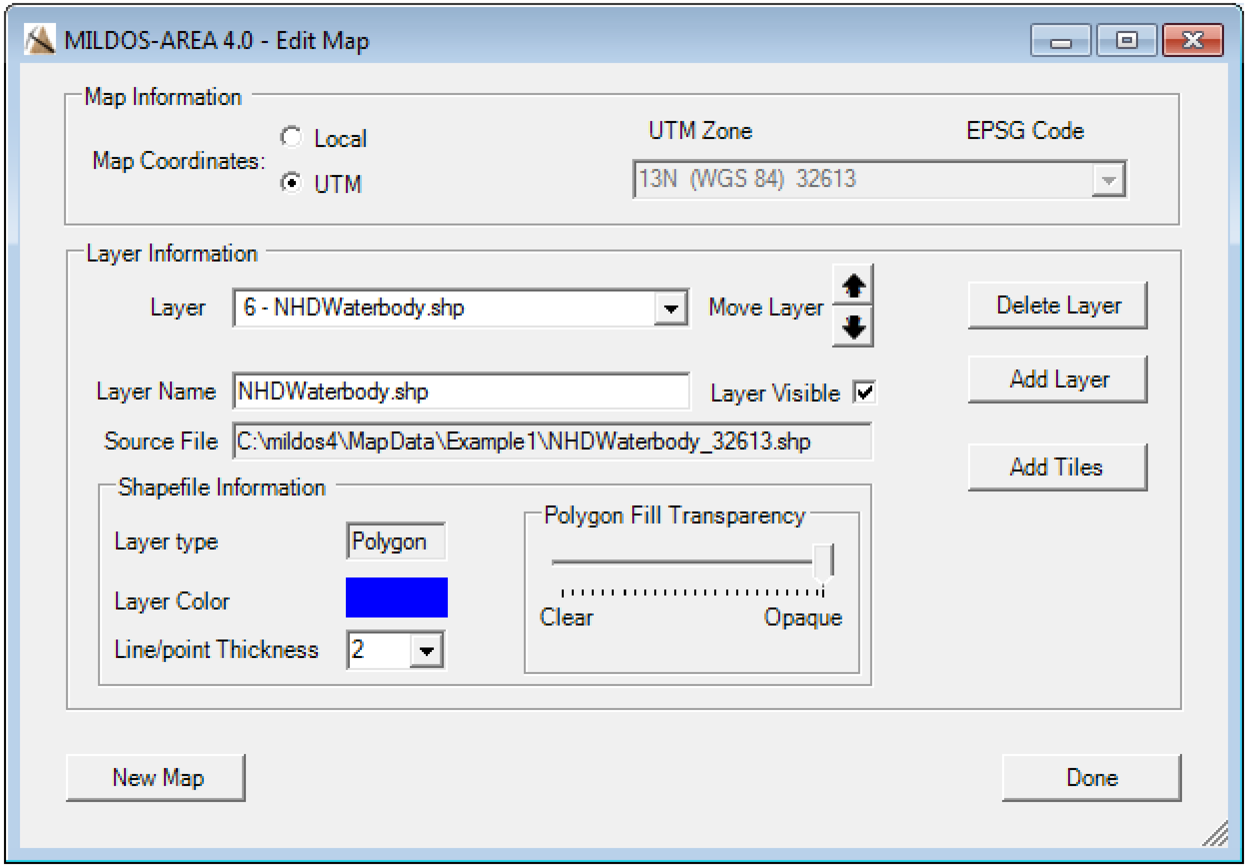
- **Geographic Information System (GIS) module [MapWinGIS]**
  - Limited subset of capabilities

- **Data is geo-referenced**
  - Vector: stored as points, lines, or polygons (collection of coordinated points)
  - Raster: image stored as matrix of cells (e.g., digital pictures or a scanned map)

- **Managed as layers - one vector or image file per layer**
  - May be re-ordered, displayed in order (highest index drawn on top)
  - May be set to invisible

- **All layers must be in the same projection to display properly**
  - Image layers must have the same projection as used by the map control
  - Capability exists to re-project shapefiles (vector) into the proper UTM format
    - Many shapefiles use the decimal degree format

Map Management



Supported Raster Data

File Type	File Extension
Bitmap	.bmp
Graphics Interchange Format (GIF)	.gif
Joint Photographic Experts Group (JPEG) & JPEG2000	.jpg, jp2
Portable Network Graphics (PNG)	.png
Multiresolution Seamless Image Database (MrSID)	.sid
Tagged Image File Format (TIFF)	.tif
Geodata Data Abstraction Library (GDAL) Virtual TIFF	.vrt

Sources of Free Map Data

- **The National Map**
  - nationalmap.gov
  - http://viewer.nationalmap.gov/basic/
    (jpeg2000 image files now in WGS 1984 Web Mercator Auxiliary Sphere projection; needs re-projection before use in MILDOS 4)

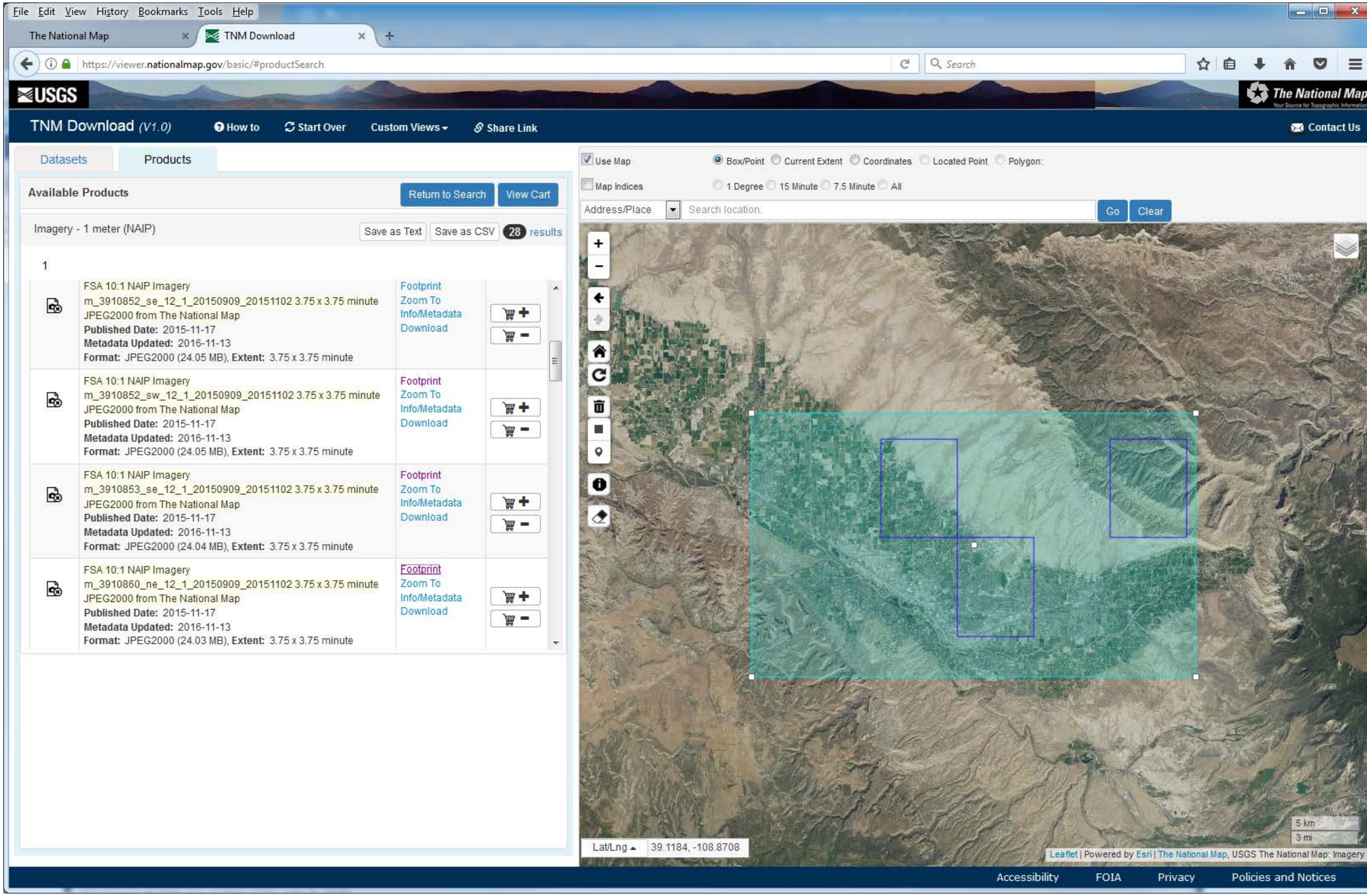
- **State / County / Local GIS Portal Examples**
  - New Mexico (http://rgis.unm.edu/getdata)
  - Utah (http://gis.utah.gov/)

- **U.S. Census Bureau**
  - Comprehensive shapefile collection (Tiger/Line data)
  - http://www.census.gov/geo/maps-data/data/tiger.html

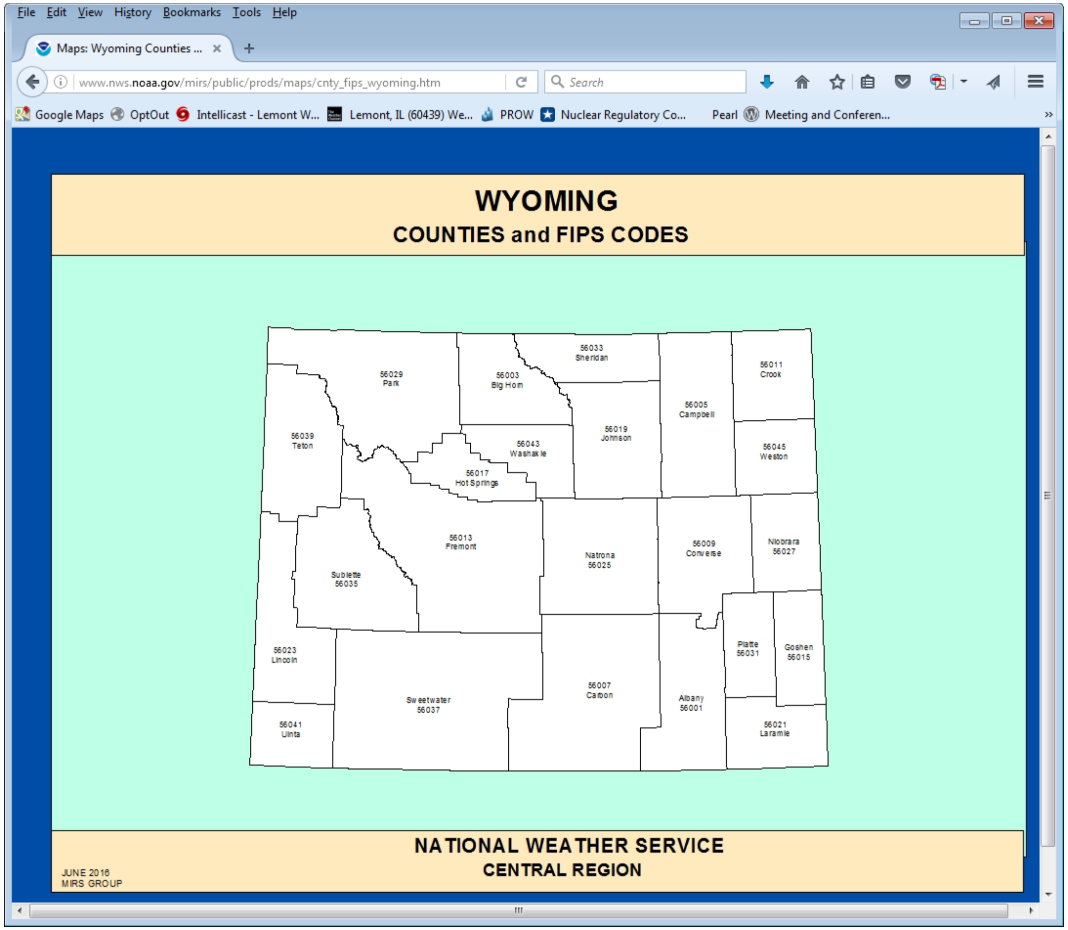
- **U.S. Department of Transportation**
  - National Transportation Atlas DB
  - http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_atlas_database/index.html

National Map Themes
US Topo
Historical Topo Maps
Structures
Transportation
Boundaries
Geographic Names
USGS Map Indicies
Hydrography
Contours
Land Cover
Elevation
Orthoimagery

The National Map (provided through the USGS)



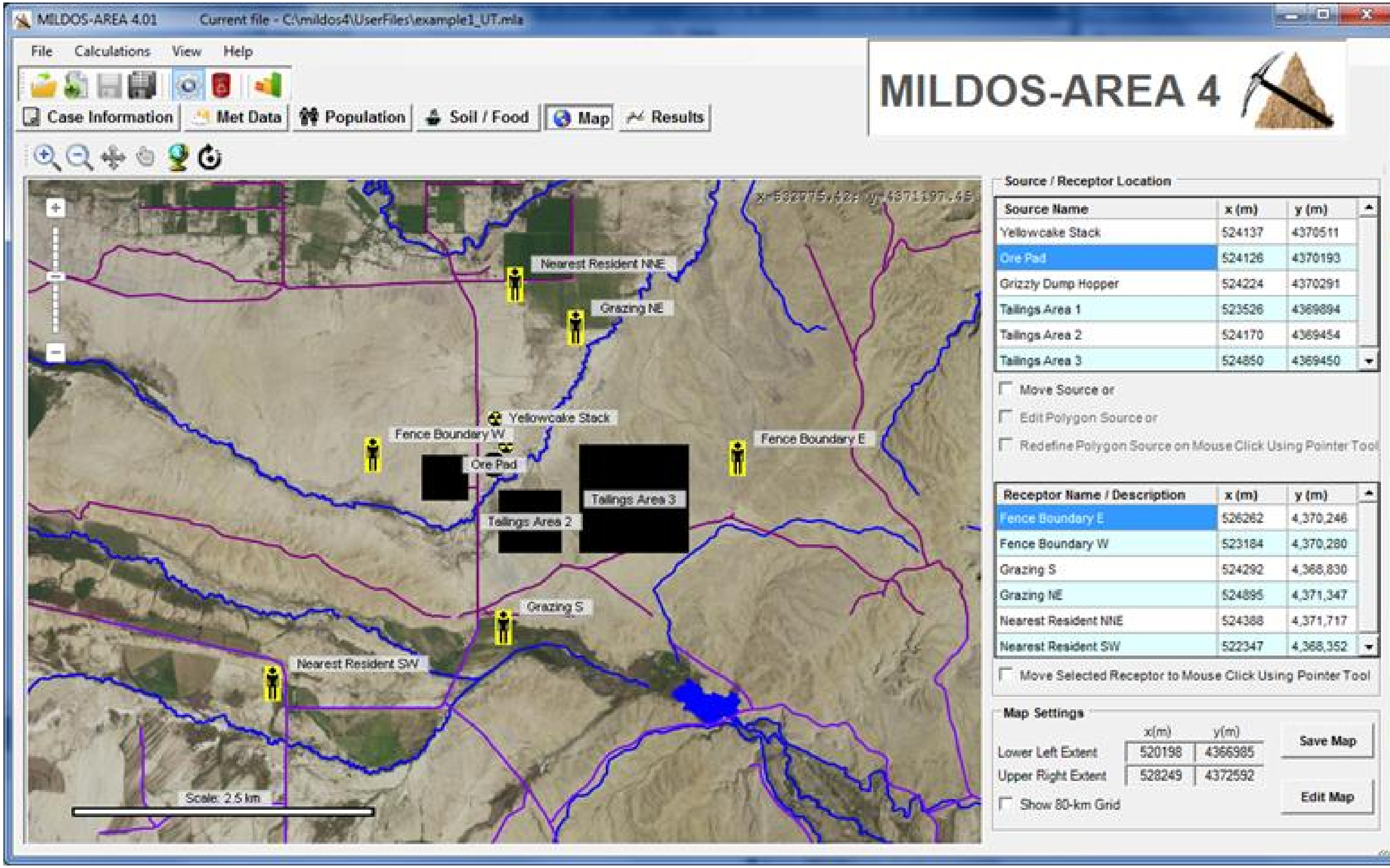
Tiger File Downloads –
File Names Based on County FIPS Codes



http://nws.noaa.gov/mirs/public/prods/maps/cnty_fips_list.htm

https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/home/?cid=nrcs143_013697
https://www.census.gov/geo/reference/codes/cou.html

Example Case – Setup Location in New Input File

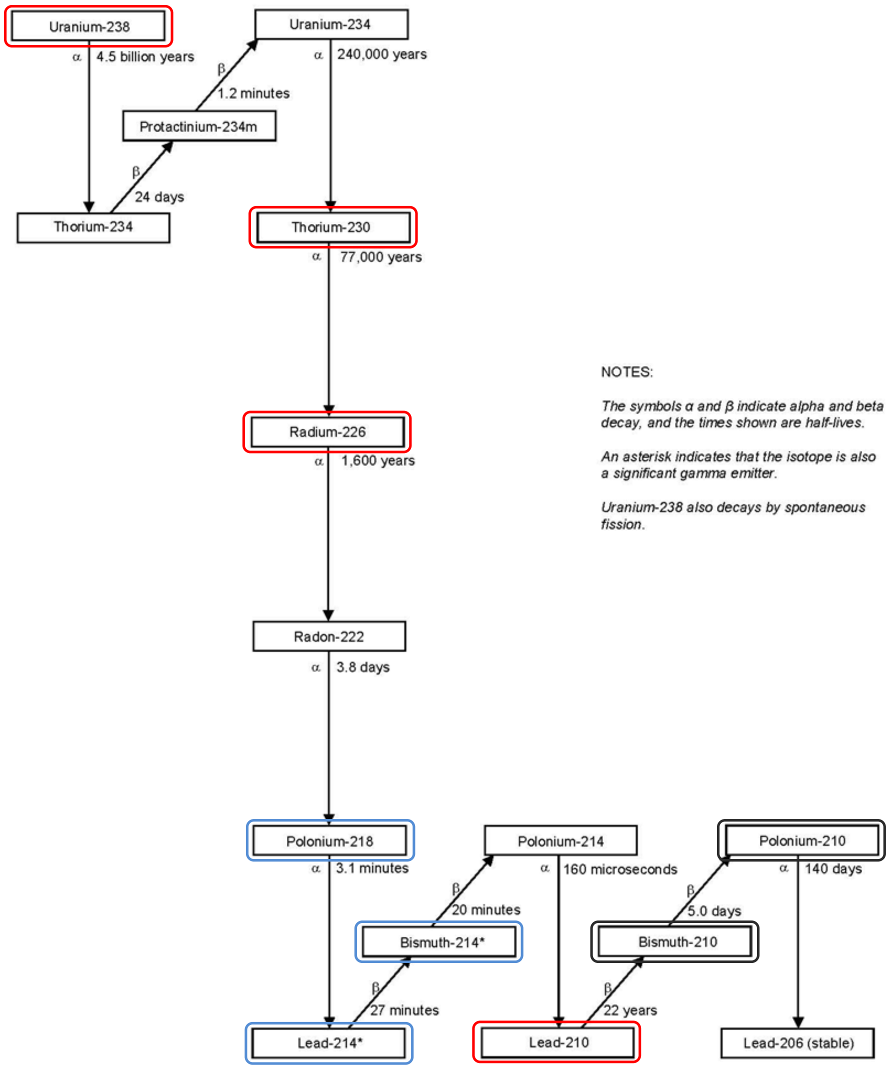


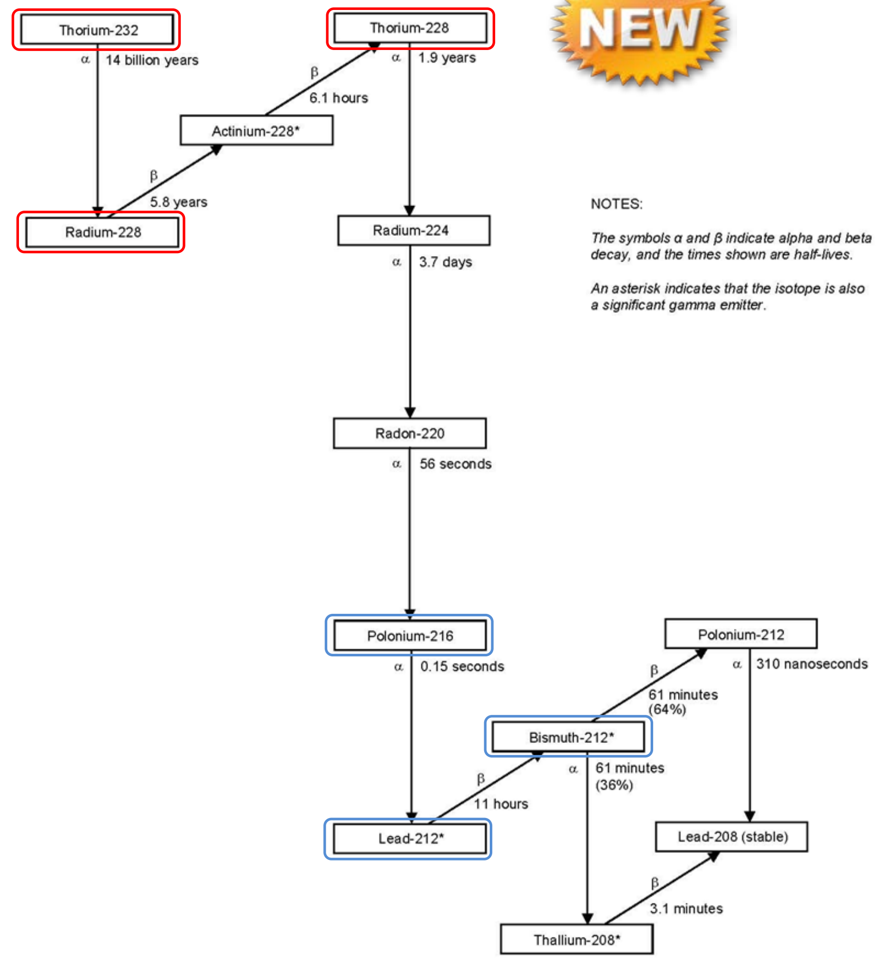
Receptor Options

- **Individual receptors**
  - Number of receptors not limited (constrained by available computer memory)
  - Age group (infant, child, teenager, adult)
  - Indoor and outdoor occupancy fractions (previously fixed)
  - Vegetable, meat, and milk ingestion rates (previously fixed)

- **Local Population (optional)**
  - 80-km grid / 16 directions / centered on 1st emission source
  - 12 segments each direction between 1, 2, 3, 4, 5, 10, 20, 30, 40, 50, 60, 70, and 80 km
  - Fraction of population in each age group (for ingestion) no longer fixed

Radionuclides





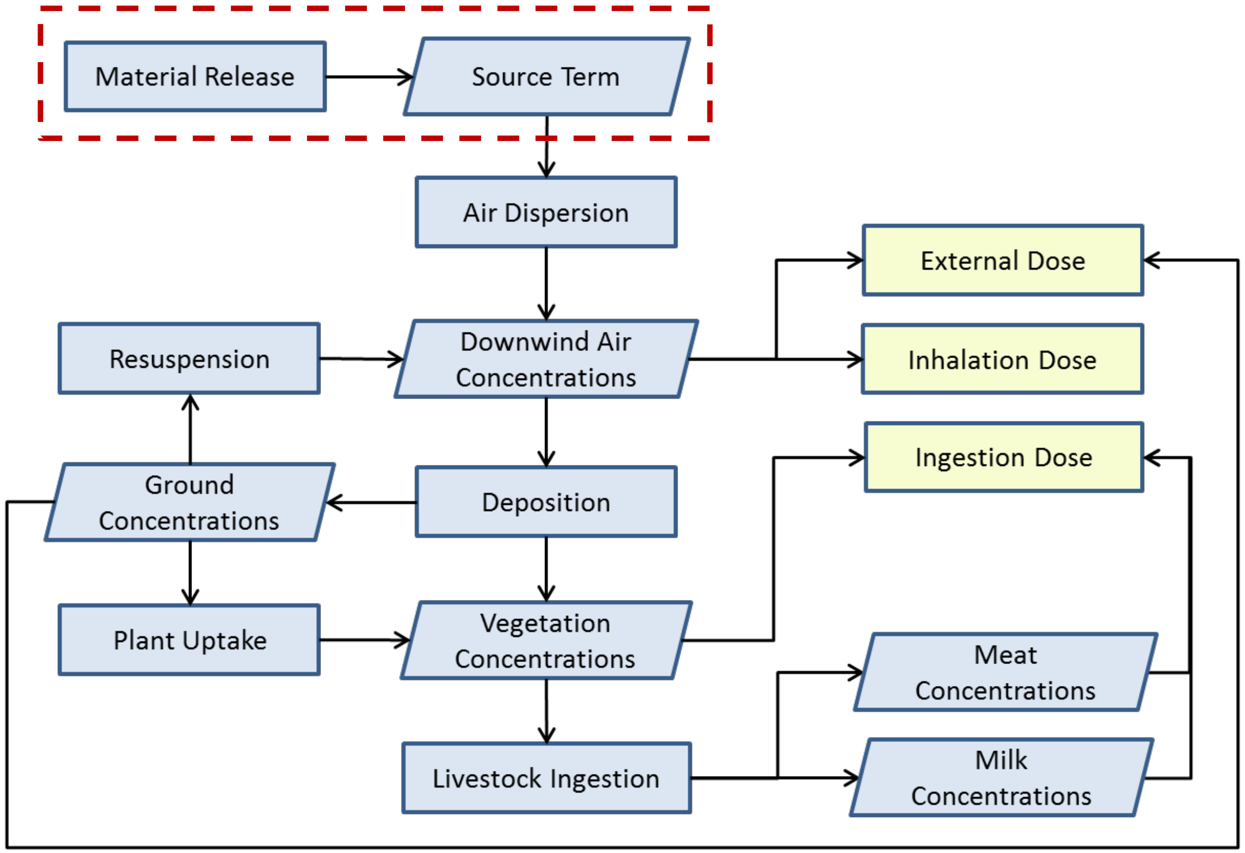
NEW

particulate source term; downwind air and ground concentrations

downwind air and ground concentrations

downwind air concentrations

Sources



Material Release
Source Term
Air Dispersion
External Dose
Resuspension
Downwind Air Concentrations
Inhalation Dose
Ingestion Dose
Ground Concentrations
Deposition
Plant Uptake
Vegetation Concentrations
Meat Concentrations
Livestock Ingestion
Milk Concentrations

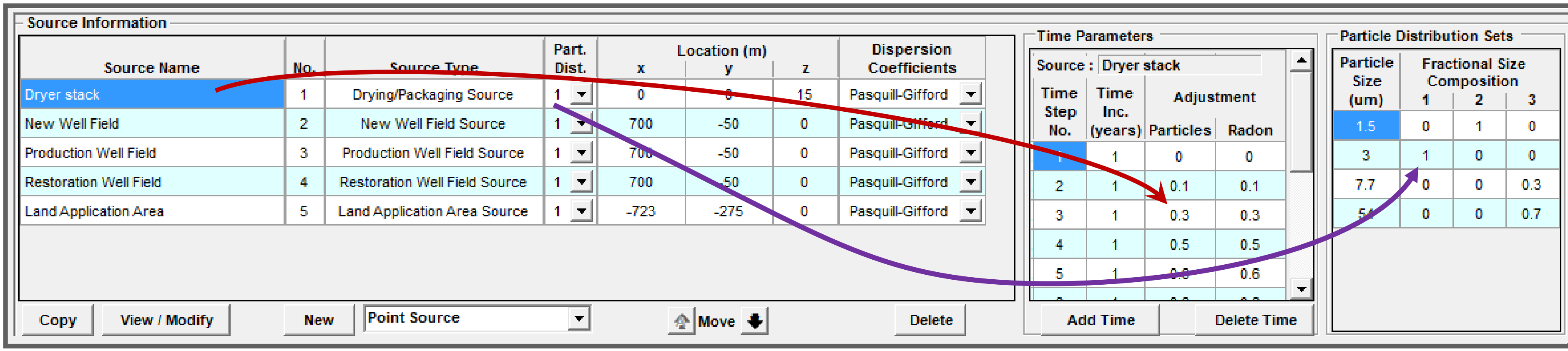
7 Named Source Types

- **Point source (1)**
  - Plume rise (momentum driven or buoyancy-induced)
- **Area source (2)**
  - Erosion model or user-specified release rates
  - Circle, rectangle, and polygon shape options
- **Drying and packaging source (3)**
  - Plume rise (momentum driven or buoyancy-induced)
- **In situ recovery (4 – 7)**
  - New well field source
  - Production well field source
  - Restoration well field source
  - Land application source

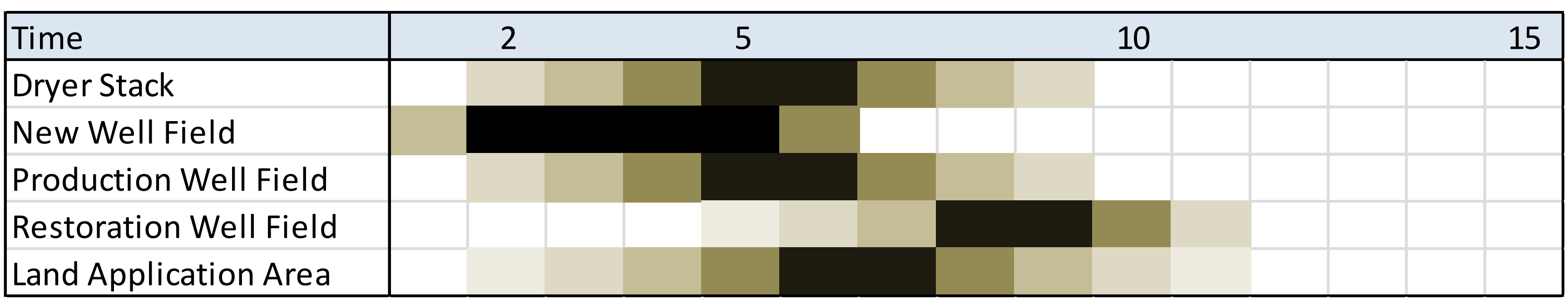
Source Characteristics – All Sources
(Main Program Window)

- Type, location, particulate size

Only 0.3 micron particles in Set 1

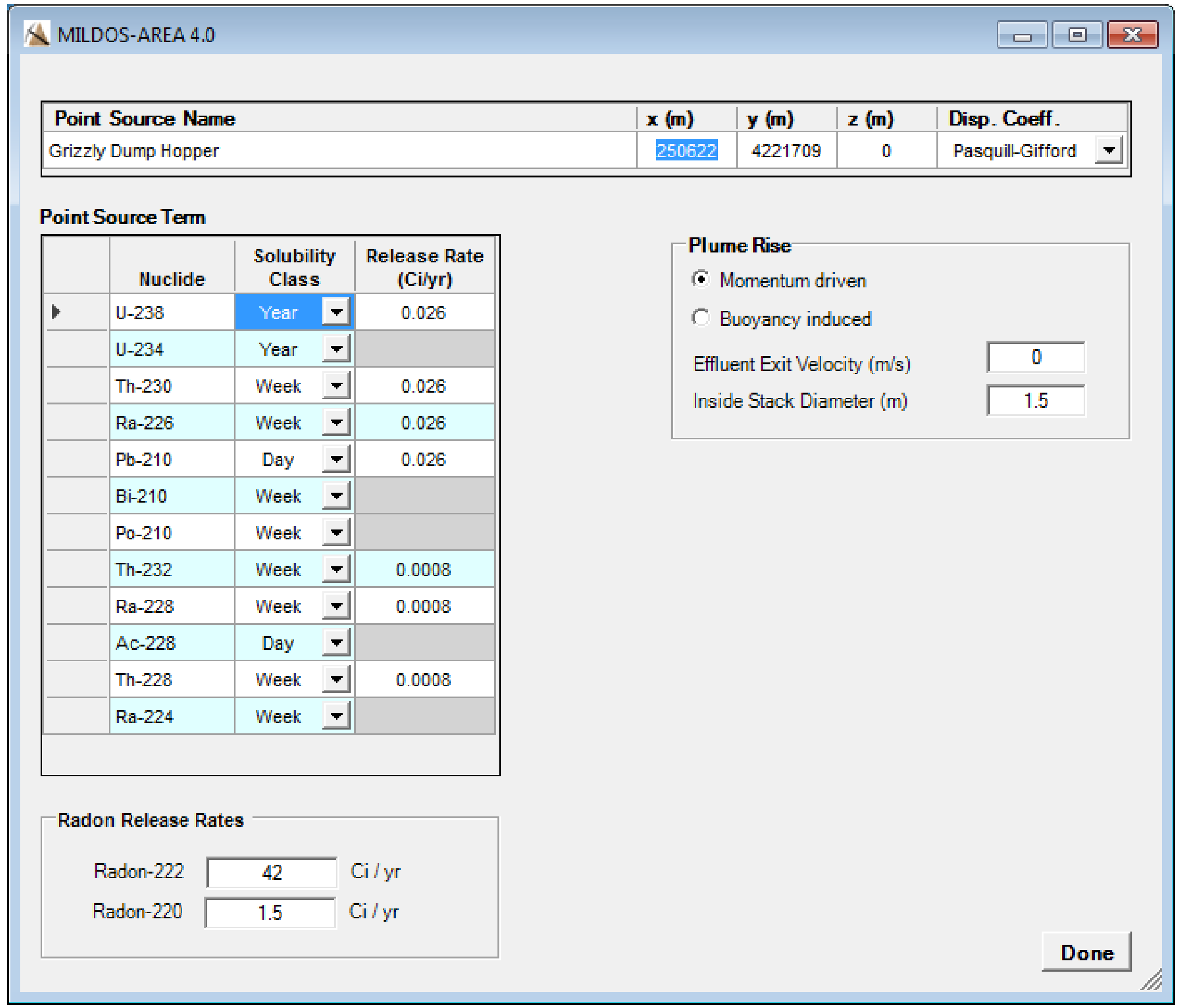


- And time dependence



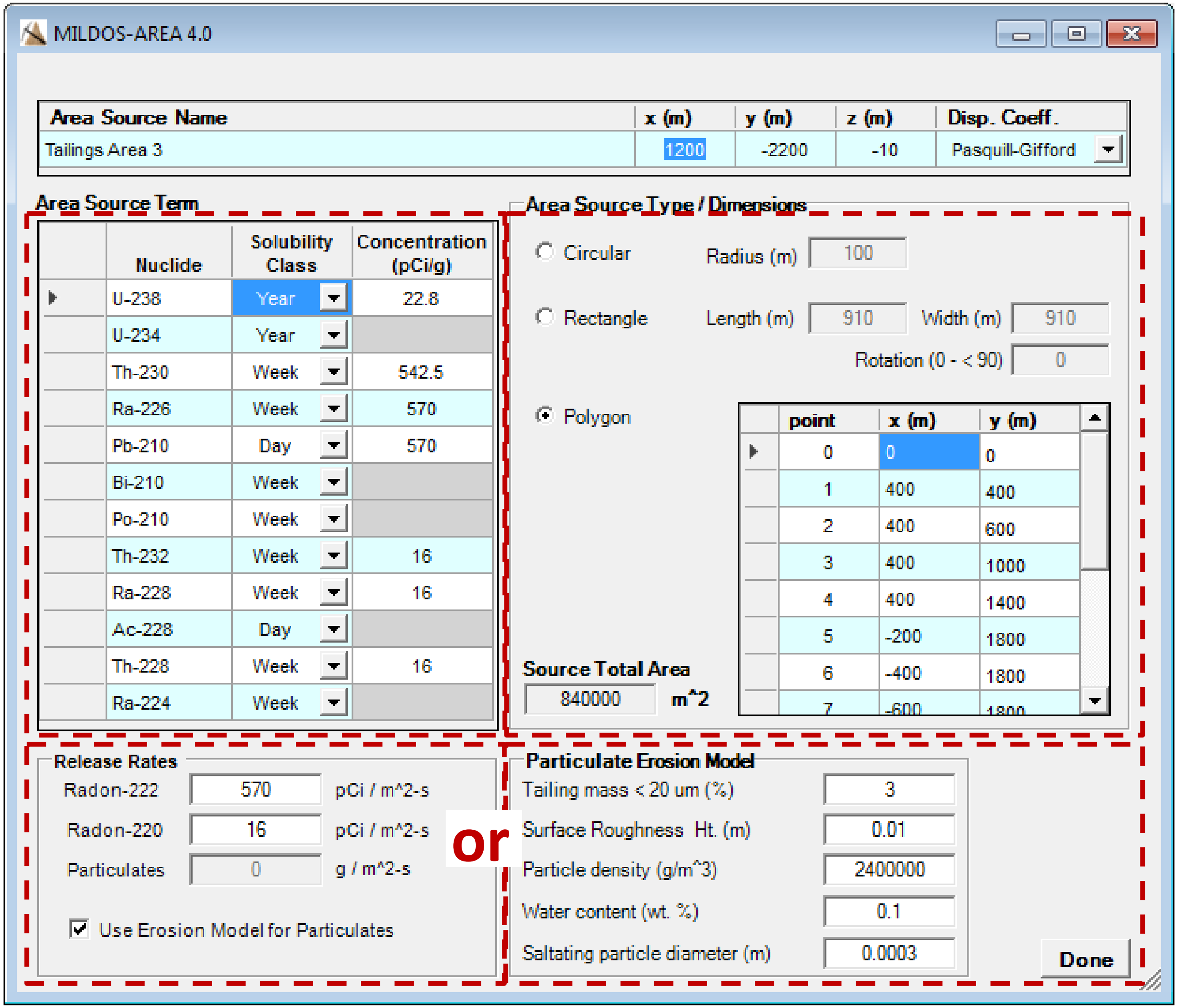
Point Source

- **Release rates**
- **Lung clearance classes**
- **Plume rise model**
  - Momentum-driven
  - Buoyancy-induced



Area Source

Inventory

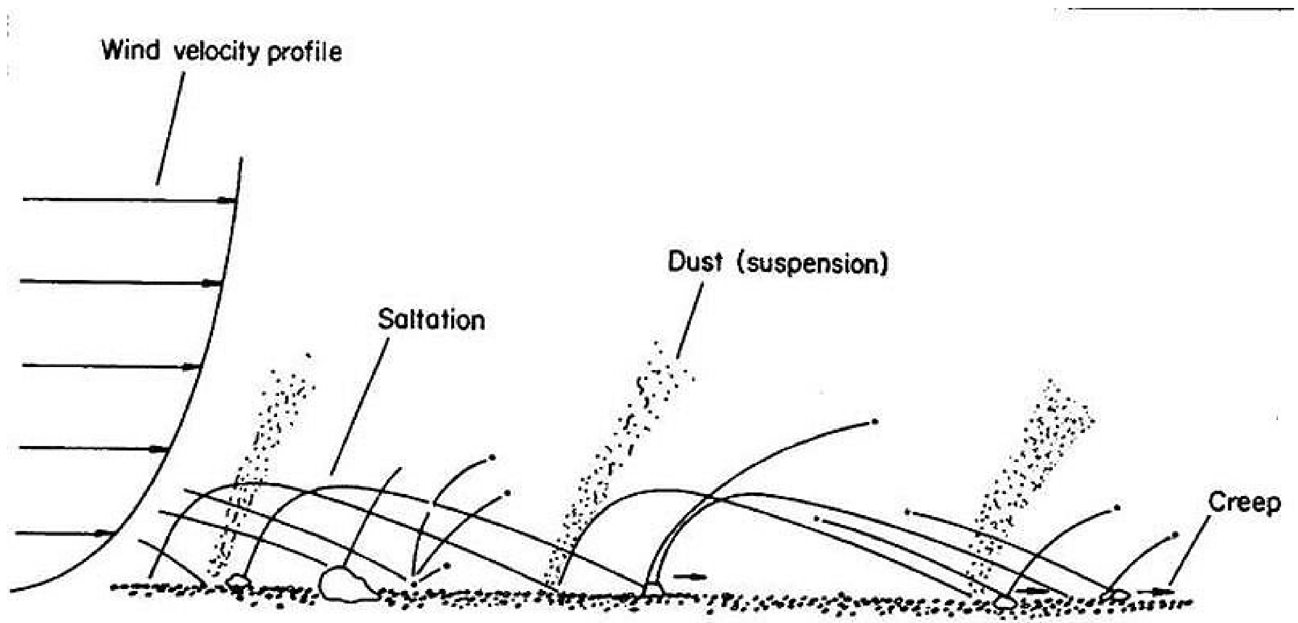


Shape & Size

Release

Erosion Model -- Particulate Release Rate

- Available for area sources only
- Based on saltation process
- Empirical (derivation in NUREG-0706, App. G)



Erosion Model -- Particulate Release Rate (cont.)

- **Calculates vertical flux (release)**

$$q_v = q_h \left(\frac{c_v}{c_h} \right) \frac{1}{u_{*t}^3} \left[\left(\frac{u_*}{u_{*t}} \right)^{\left(p_{tm} / 3 \right)} - 1 \right]$$

q_h = horizontal flux of particulate material (g/m-s),
c_v = coefficient of proportionality for vertical flux (2×10^{-6} g/m^2-s),
c_h = empirical constant to relate shear velocity to horizontal flux (1×10^2 g-s^2/m^4),
u_* = shear velocity (m/s),
u_{*t} = threshold shear velocity (m/s), and
p_{tm} = percent of tailing mass that has a diameter smaller than 20 μm (unitless)

- **Shear velocity (friction velocity)**

$$u_* = \frac{u_z}{2.5 \ln \left(z / z_o \right)}$$

u_z = wind velocity at height z (m/s),
z = wind measurement height (m), and
z_o = characteristic surface roughness height (m)

Erosion Model -- Particulate Release Rate (cont.)

- **Threshold shear velocity**

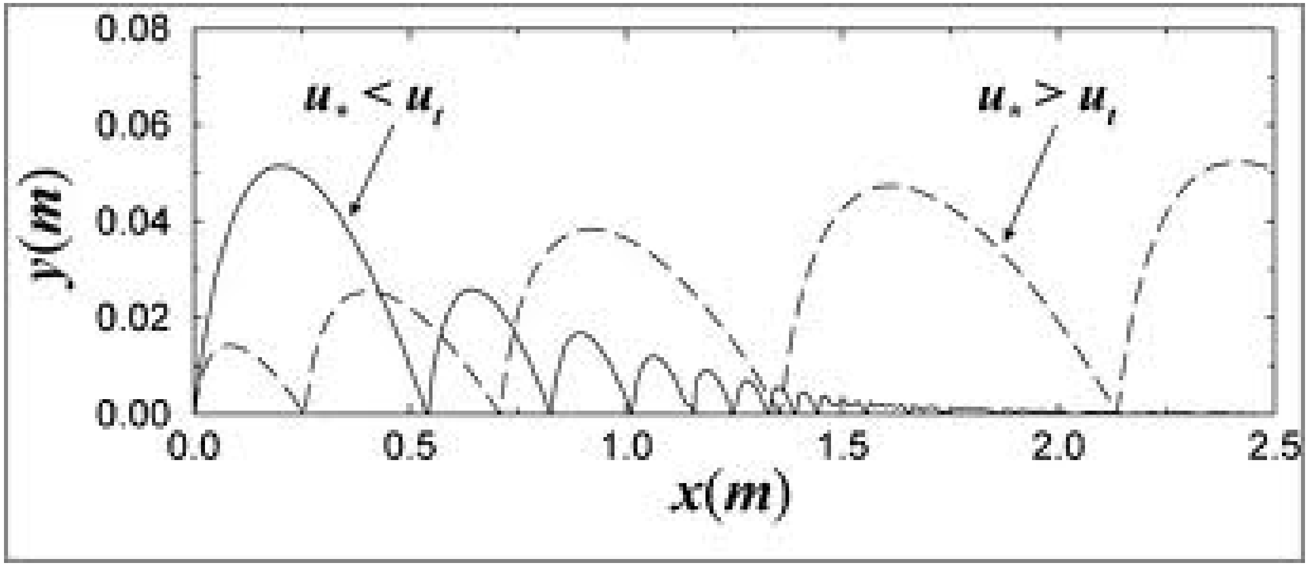
$$u_{*t} = c_t \sqrt{\frac{\rho_p - \rho_a}{\rho_a} g\, d \left(1.8 + 0.6 \log_{10} W\right)}$$

c_t = dimensionless coefficient equal to 0.1,
ρ_p = particle density (g/m^3),
ρ_a = density of air (g/m^3),
g = gravitational acceleration (m/s^2),
d = average diameter of saltating particle (m), and
W = water content expressed in weight percent

- **Shear velocity vs. threshold shear velocity to get horizontal flux**

$$q_h = c_h u_*^2 \left(u_* - u_{*t}\right)$$

$q_h = 0$ when $u_* < u_t$



In Situ Recovery

New Well Field Development

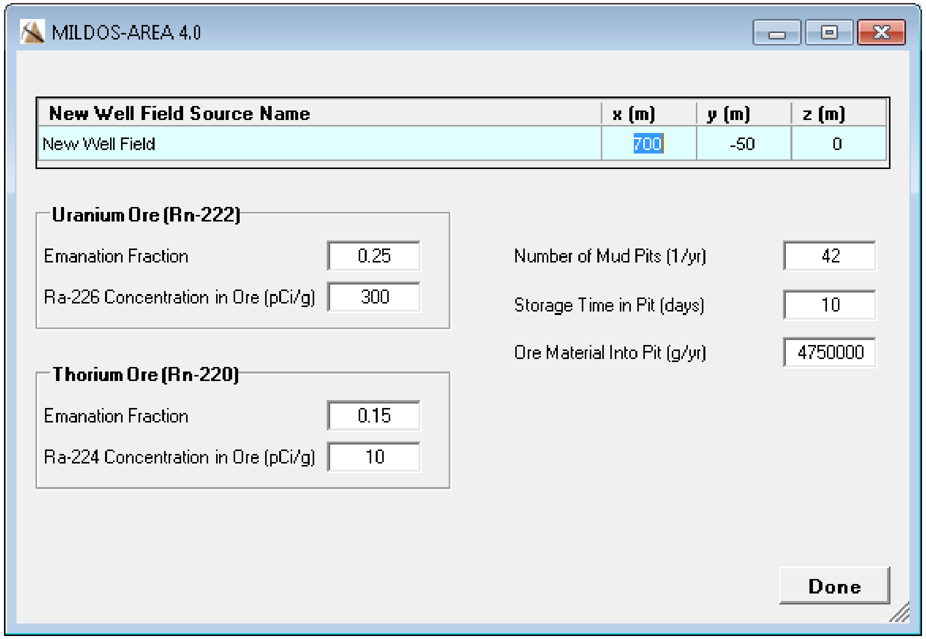
Production Well Fields

Drying and Packaging of Yellowcake

Restoration Well Fields and Land Application

New Well Field - Conceptualization

- **Particulates: No release**
  - During drilling, a bentonite slurry flows out of the drill head and through the borehole
- **Radon: released from the cuttings that are temporarily stored in the "mud" pits**
  - average mass of cutting that are temporarily stored in the slurry pits
    - Number of mud pits generated per year
    - Average mass of cutting in a mud pit
    - Storage time of cuttings in mud pit



New Well Field

- **Annual radon emission**

$$Rn\text{-}222_{nw} = 10^{-12} E_{Rn222}\, \lambda_{Rn222}\, [\mathrm{Ra}\text{-}226]\, t_{pit} M_{ore} N_{pit}$$

$$Rn\text{-}220_{nw} = 10^{-12} E_{Rn220}\, \lambda_{Rn220}\, [\mathrm{Ra}\text{-}224]\, t_{pit} M_{ore} N_{pit},$$

$Rn\text{-}222_{nw}$ = Rn-222 release rate from a new well field (Ci/yr),

$Rn\text{-}220_{nw}$ = Rn-220 release rate from a new well field (Ci/yr),

10^{-12} = unit conversion factor (Ci/pCi),

E_{Rn222}, E_{Rn220} = emanating power for Rn-222 or Rn-220 (unitless),

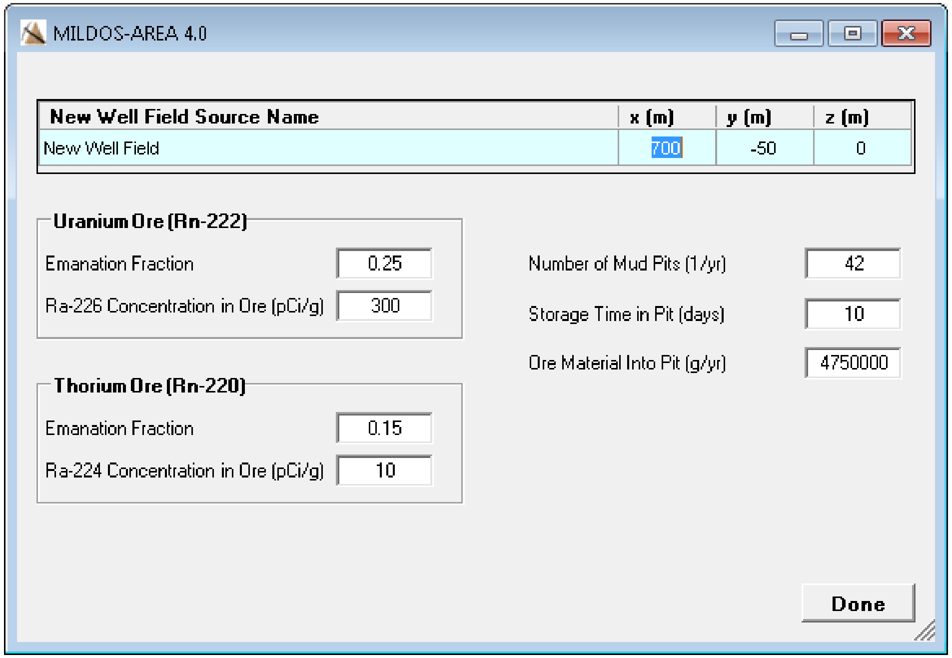
λ_{Rn222}, λ_{Rn220} = Rn-222 or Rn-220 decay constant (1/d),

[Ra-226], [Ra-224] = concentration of Ra-226 or Ra-224 in the ore (pCi/g),

t_{pit} = storage time in a mud pit (d),

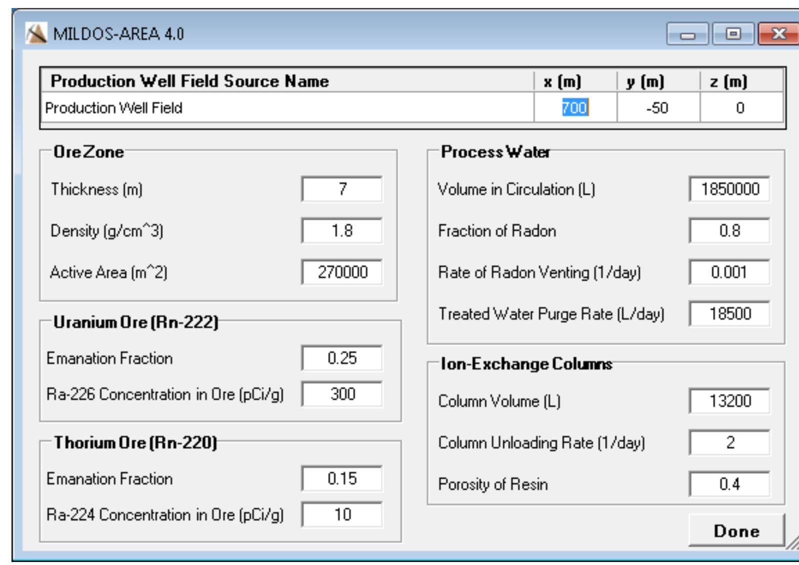
M_{ore} = average mass of ore material in a mud pit (g), and

N_{pit} = number of mud pits generated per year.



Production Well Field - Conceptualization

- **Particulates: No release**
  - Closed loop from the production well through the ion exchange column to the injection well
- **Radon: Released from the ore body into the process water**
  - Radon circulates and builds up in the process water – released in 3 ways:
    - Purge: From process water that is purged
      - » Production well extracts more fluid than is pumped in through the injection well to maintain a cone of depression to prevent migration of mining solutions out of the ore in the production area
    - Resin Unloading: From the process water that is discharged during resin unloading from the ion exchange columns
    - Venting: From pipes and valves



Production Well Field

- **Change in Rn-222 and Rn-220 concentrations over time**

$$V\frac{dC_{Rn222}}{dt} = f_{Rn}S_{Rn222} - \left(\lambda_{\mathrm{Rn222}} + v_{Rn}\right)VC_{Rn222} - \left(F_p + F_{ix}\right)C_{Rn222}$$

$$V\frac{dC_{Rn220}}{dt} = f_{Rn}S_{Rn220} - \left(\lambda_{\mathrm{Rn220}} + v_{Rn}\right)VC_{Rn220} - \left(F_p + F_{ix}\right)C_{Rn220} \text{ ,}$$

V = volume of water in circulation (L),

C_{Rn222}, C_{Rn220} = Rn-222 or Rn-220 concentration in process water (pCi/L),

f_{Rn} = fraction of radon source carried by circulating water (unitless),

S_{Rn222}, S_{Rn220} = Rn-222 or Rn-220 source (pCi/d),

λ_{Rn222}, λ_{Rn220} = Rn-222 or Rn-220 decay constant (1/d),

v_{Rn} = rate of radon venting from piping and valves during circulation (1/d),

F_p = “purge” rate of treated water (L/d), and

F_{ix} = water discharge rate from resin unloading of IX columns (L/d).

Production Well Field (cont.)

- **Radon source terms**

$$S_{Rn222} = 10^6 E_{Rn222}\ \lambda_{\mathrm{Rn222}}\ [\mathrm{Ra-226}]\ AD\rho$$

$$S_{Rn220} = 10^6 E_{Rn220}\ \lambda_{\mathrm{Rn220}}\ [\mathrm{Ra-224}]\ AD\rho$$

10^6 = unit conversion factor (cm^3/m^3),
E_{Rn222}, E_{Rn220} = emanating power for Rn-222 or Rn-220 (unitless),
[Ra-226], [Ra-224] = concentration of Ra-226 or Ra-224 in the ore (pCi/g),
A = active area of the ore zone (m^2),
D = average thickness of the ore zone (m), and
ρ = bulk density of the ore material (g/cm^3).

- **Radon discharge from resin unloading**

$$F_{ix} = N_{ix} V_{ix} P_{ix}$$

N_{ix} = number of IX unloadings per day,
V_{ix} = volume content of the IX column (L), and
P_{ix} = porosity of the IX resin (unitless).

Production Well Field (cont.)

- **Radon steady-state process water concentrations**

$$C_{Rn222} = \frac{f_{Rn} 10^6 E_{Rn222}\ \lambda_{\mathrm{Rn222}}\ [\mathrm{Ra\text{-}226}]\ AD\rho}{(\lambda_{\mathrm{Rn222}} + v_{Rn})V + F_p + F_{ix}} \qquad C_{Rn220} = \frac{f_{Rn} 10^6 E_{Rn220}\ \lambda_{\mathrm{Rn220}}\ [\mathrm{Ra\text{-}224}]\ AD\rho}{(\lambda_{\mathrm{Rn220}} + v_{Rn})V + F_p + F_{ix}}$$

- **Radon from purge water**

$$Rn222_w = 3.65 \times 10^{-10} C_{Rn222}\ F_p$$

$$Rn220_w = 3.65 \times 10^{-10} C_{Rn220}\ F_p$$

- **Radon from venting**

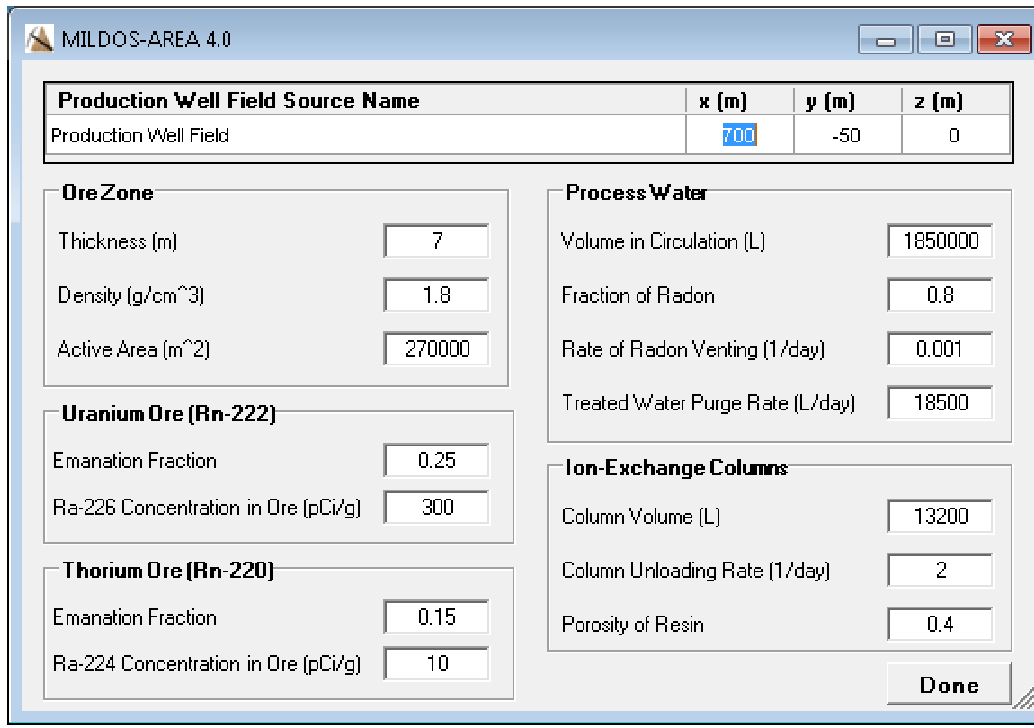
$$Rn222_v = 3.65 \times 10^{-10} v_{Rn} C_{Rn222}\ V$$

$$Rn220_v = 3.65 \times 10^{-10} v_{Rn} C_{Rn220}\ V$$

- **Radon IX resin unloading**

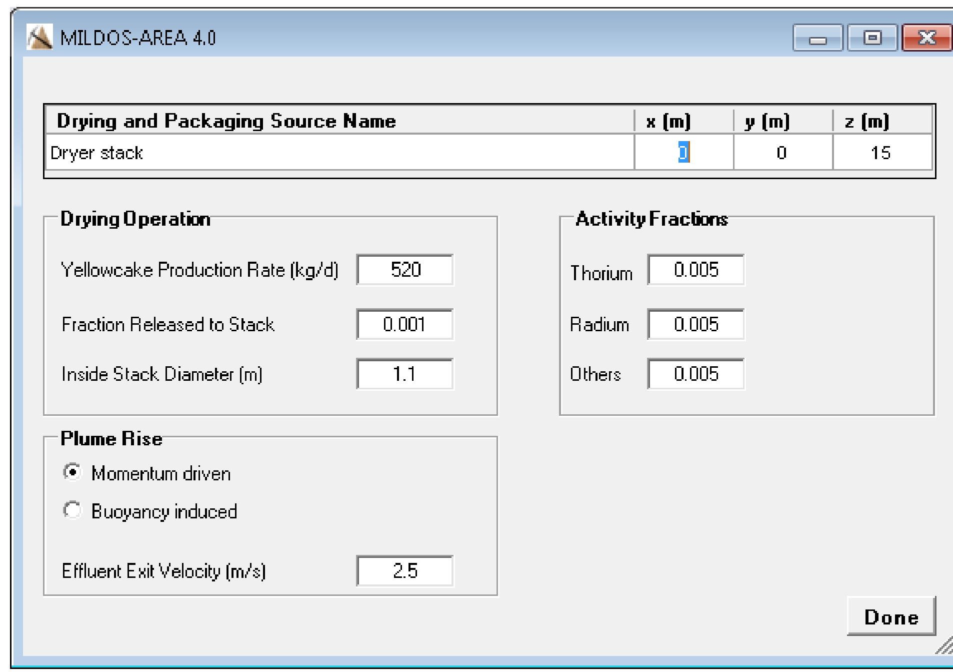
$$Rn222_{ix} = 3.65 \times 10^{-10} C_{Rn222} F_{ix}$$

$$Rn220_{ix} = 3.65 \times 10^{-10} C_{Rn220} F_{ix}$$



Drying and Packaging – Conceptualization

- **Particulates:**
  - Stack release from thermal dryers
    - Use a fraction of the production based on information from facilities that are operational
    - Progeny releases are a fraction of the uranium releases
  - No release from vacuum dryers under normal operating conditions
- **U-238 series only**
  - Purified yellowcake (no Rn or Th-series)



Yellowcake Drying and Packaging

- **U-238 release rate**

$$U238_{dp} = 3.0973 \times 10^{5} R_{yc} f_s U238_{sa},$$

$U238_{dp}$ = U-238 release rate from the facility stack (Ci/yr),
R_{yc} = daily production rate of yellowcake at the facility (kg U_3O_8/d),
f_s = fraction of production released through the facility stack (unitless),
$U238_{sa}$ = specific activity of U-238 (3.3×10^{-7} Ci/g), and
3.097×10^{5} = conversion factor, 0.8480 g of U/g of U_3O_8 × 1,000 g/kg × 365.25 d/yr (g-d/kg-yr)

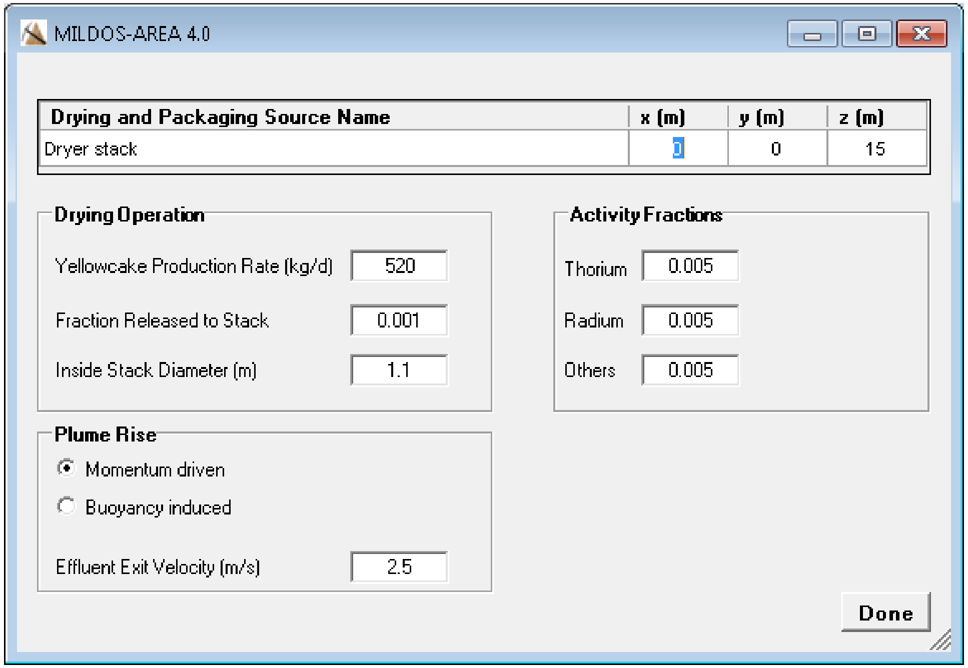
- **U-238 progeny release rates**

$$TH230_{dp} = f_{Th} U238_{dp}$$

$$RA226_{dp} = f_{Ra} U238_{dp}$$

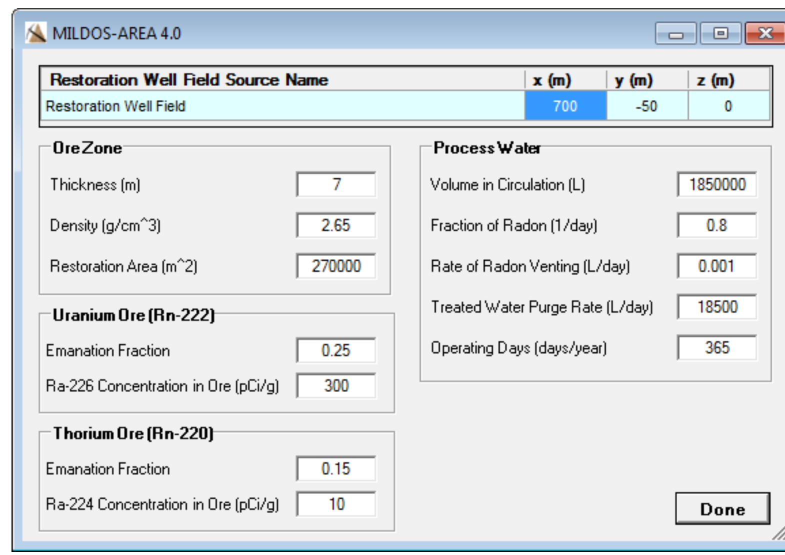
$$PB210_{dp} = f_{others} U238_{dp}$$

f_{Th}, f_{Ra}, f_{others} = Th-230, Ra-226, and Pb-210 release fractions relative to the release amount for U-238 (unitless)



Restoration Well Field – Conceptualization

- **Pump and treat with fresh water injection. Similar to production well.**
- **Particulates: No release**
  - There is a closed loop from the well through to the injection well
- **Radon: Released from the ore body into the process water**
  - Radon circulates and builds up in the process water – released in 2 ways:
    - Purge: From process water that is purged
      - » Well extracts more fluid than is pumped in through the injection well to maintain a cone of depression to prevent migration of mining solutions out of the ore in the production area
    - Venting: From pipes and valves



Restoration Well Field

- Similar to production well calculation, but no loss of radon from the IX resin

- Radon steady-state process water concentrations

$$C_{Rn222} = \frac{f_{Rn} 10^6 E_{Rn222}\ \lambda_{\mathrm{Rn222}}\ [\mathrm{Ra\text{-}226}]\ AD\rho}{(\lambda_{\mathrm{Rn222}} + v_{Rn})V + F_p}$$

$$C_{Rn220} = \frac{f_{Rn} 10^6 E_{Rn220}\ \lambda_{\mathrm{Rn220}}\ [\mathrm{Ra\text{-}224}]\ AD\rho}{(\lambda_{\mathrm{Rn220}} + v_{Rn})V + F_p}$$

- Radon from purge water

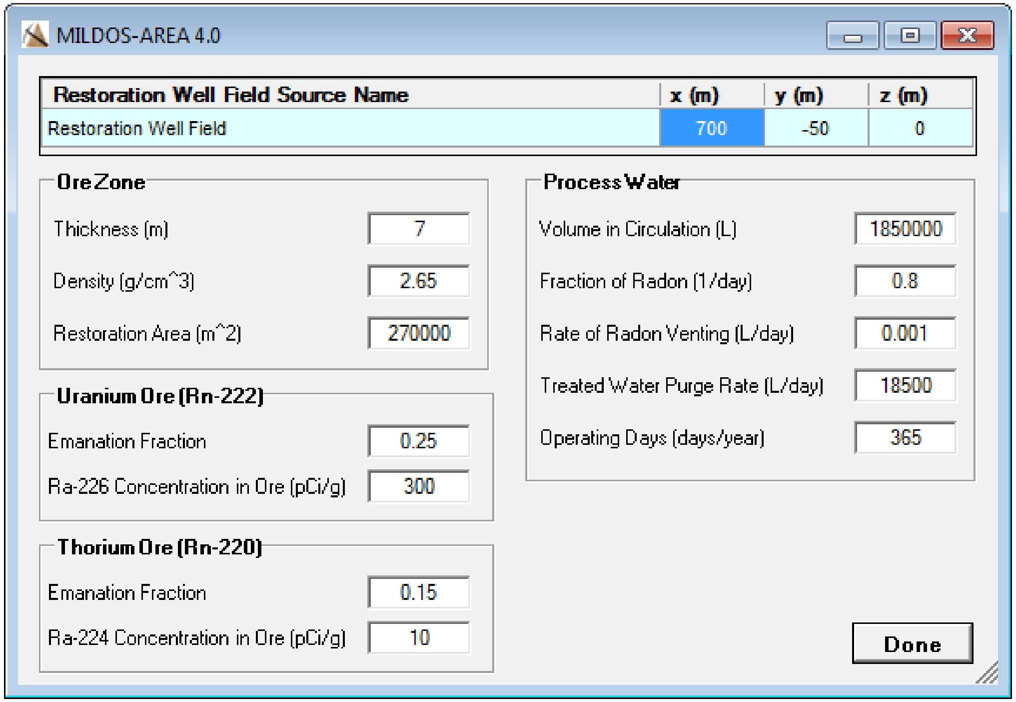
$$Rn222_w = 1 \times 10^{-12} C_{Rn222}\ F_p D_{op}$$

$$Rn220_w = 1 \times 10^{-12} C_{Rn220}\ F_p D_{op}$$

- Radon from venting

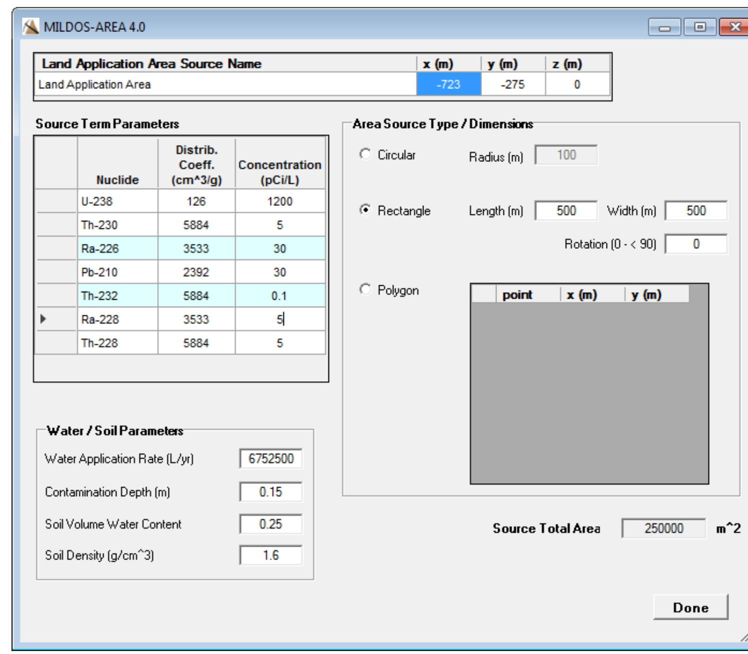
$$Rn222_v = 1 \times 10^{-12} v_{Rn} C_{Rn222}\ \mathrm{D_{op}} V$$

$$Rn220_v = 1 \times 10^{-12} v_{Rn} C_{Rn220} \mathrm{D_{op}} V$$



Land Application Area - Conceptualization

- **Release of particulates**
  - Surface soil is contaminated
    - Purge water from production wells and waste water from well field restoration are treated to unrestricted release levels and disposed of by irrigating the land
  - Uniform contamination over a specified depth
  - Equilibrium adsorption of nuclide between soil and the applied irrigation
  - Release from the area source



Land Application Area

- **Determine surface soil contamination**

$$C_{sw}(i,t_1) = \int_0^{t_1} \frac{C_{iw}(i,t_1) R_w F_s}{A_s D_s \rho_s 10^6} \exp\left(-\left(\lambda_i + \lambda_e\right)t\right) dt$$

$C_{sw}(i,t_1)$ = soil concentration of radionuclide *i* after water irrigation for time t_1 (pCi/g),
10^6 = unit conversion factor (cm^3/m^3),
$C_{iw}(i,t_1)$ = concentration of radionuclide *i* in irrigation water during time t_1 (pCi/L),
R_w = water application rate (L/yr),
t = time (yr),
F_s = fraction of radionuclides retained in the soil (unitless),
A_s = area of land application (m^2),
D_s = depth of soil penetration (m),
ρ_s = soil bulk density (g/cm^3),
λ_i = radioactive decay constant for radionuclide *i* (1/yr), and
λ_e = decay constant to account for environmental loss from soil (1/yr).

- **Fraction retained in soil**

$$F_s = 1 - \frac{1}{R_d}$$

$$R_d = 1 + \frac{\rho_s K_d}{w}$$

R_d = retardation factor (unitless),
K_d = radionuclide distribution coefficient (cm^3/g) and
w = soil volume water content (unitless)

Land Application Area (cont.)

- **Surface soil contamination after a given time and time step n**

$$C_{sw}(i,t_1) = \frac{C_{iw}(i,t_1) R_w t_1 F_s}{A_s D_s \rho_s 10^6} \left(\frac{1-\exp\left(-(\lambda_i + \lambda_e) t_1\right)}{\lambda_i + \lambda_e} \right)$$

$$C_{sw}(i,t_{s_n}) = \left(\frac{C_{iw}(i) R_w F_s}{A_s D_s \rho_s 10^6} \right) \left[\sum_{j=1}^{n-1} P_{Aj} t_{s_j} \exp\left(-(\lambda_i + \lambda_e)(t_n - t_j)\right) + P_{An} t_{s_n} \left(\frac{1-\exp\left(-(\lambda_i + \lambda_e) t_n\right)}{\lambda_i + \lambda_e} \right) \right]$$

- **Nuclide water concentration during time step j**

$$C_{iw}(i,t_{S_j}) = P_{Aj} C_{iw}(i)$$

- **Particulate emission rate**
  - 3.1×10^{-5} g/m^2-s

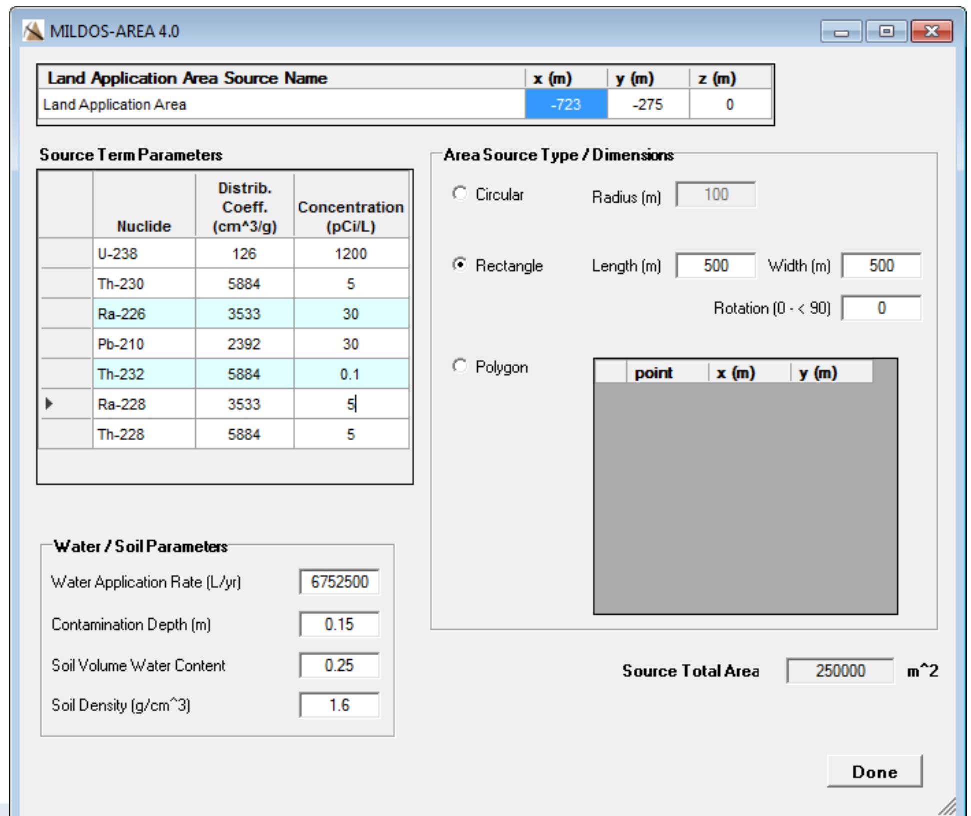
$C_{sw}(i,t_{Sn})$ = soil concentration of radionuclide *i* from water irrigation at the end of time step *n* (pCi/g),

$C_{iw}(i)$ = concentration of radionuclide *i* in irrigation water as input by the user (pCi/L),

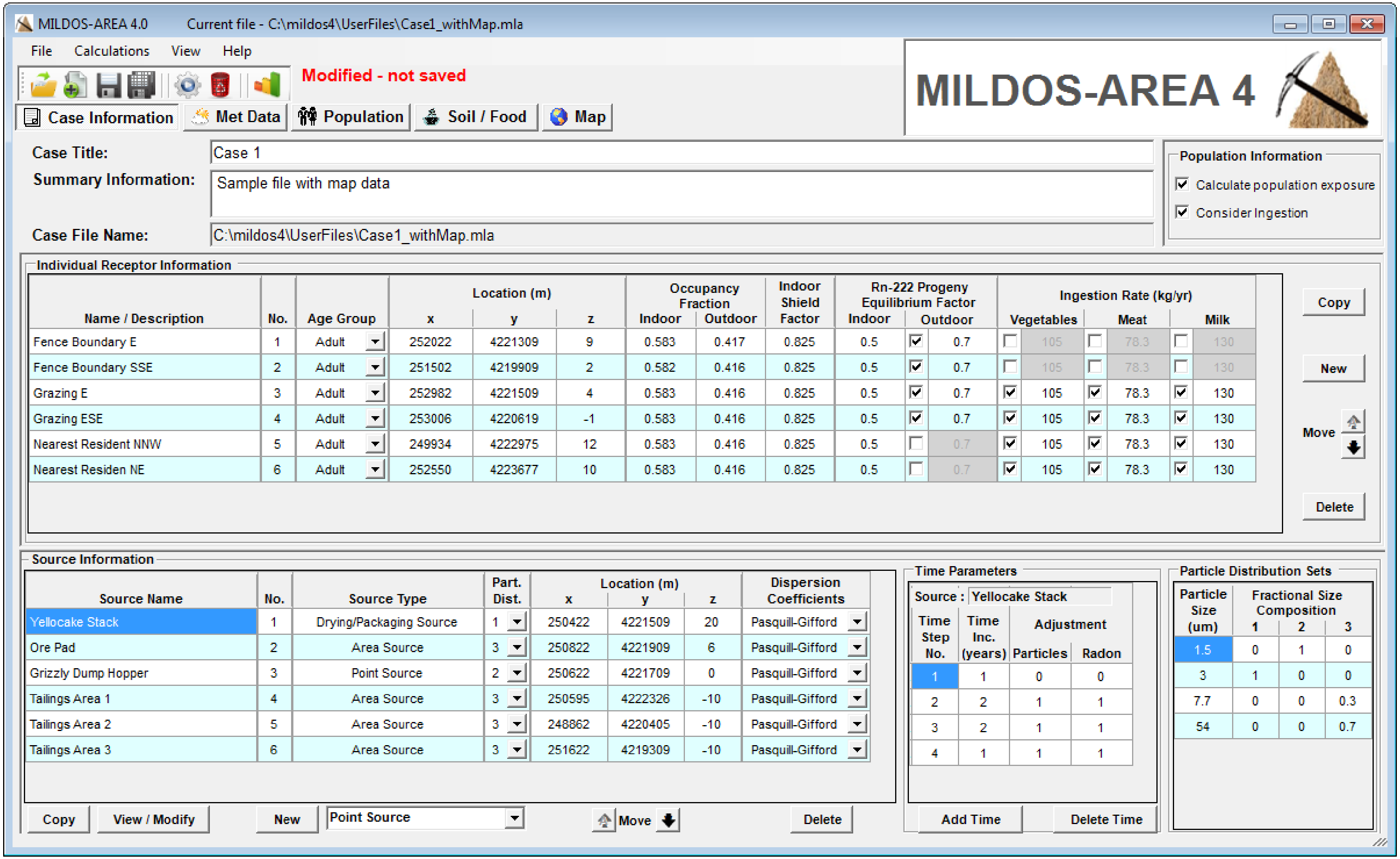
P_{Aj} = particulate adjustment factor for the source for time step *j* (unitless).

t_j = length of time from the start of the evaluation period to the end of time step *j* (yr).

t_{sj} = length of time assigned to time step j (yr)



Example Case - Receptors and Source Terms



Individual Receptor Information

Name / Description	No.	Age Group	Location (m) x	y	z	Occupancy Fraction Indoor	Outdoor	Indoor Shield Factor	Rn-222 Progeny Equilibrium Factor Indoor	Outdoor	Ingestion Rate (kg/yr) Vegetables	Meat	Milk
Fence Boundary E	1	Adult	252022	4221309	9	0.583	0.417	0.825	0.5	0.7	105	78.3	130
Fence Boundary SSE	2	Adult	251502	4219909	2	0.582	0.416	0.825	0.5	0.7	105	78.3	130
Grazing E	3	Adult	252982	4221509	4	0.583	0.416	0.825	0.5	0.7	105	78.3	130
Grazing ESE	4	Adult	253006	4220619	-1	0.583	0.416	0.825	0.5	0.7	105	78.3	130
Nearest Resident NNW	5	Adult	249934	4222975	12	0.583	0.416	0.825	0.5	0.7	105	78.3	130
Nearest Residen NE	6	Adult	252550	4223677	10	0.583	0.416	0.825	0.5	0.7	105	78.3	130

Source Information

Source Name	No.	Source Type	Part. Dist.	Location (m) x	y	z	Dispersion Coefficients
Yellocake Stack	1	Drying/Packaging Source	1	250422	4221509	20	Pasquill-Gifford
Ore Pad	2	Area Source	3	250822	4221909	6	Pasquill-Gifford
Grizzly Dump Hopper	3	Point Source	2	250622	4221709	0	Pasquill-Gifford
Tailings Area 1	4	Area Source	3	250595	4222326	-10	Pasquill-Gifford
Tailings Area 2	5	Area Source	3	248862	4220405	-10	Pasquill-Gifford
Tailings Area 3	6	Area Source	3	251622	4219309	-10	Pasquill-Gifford

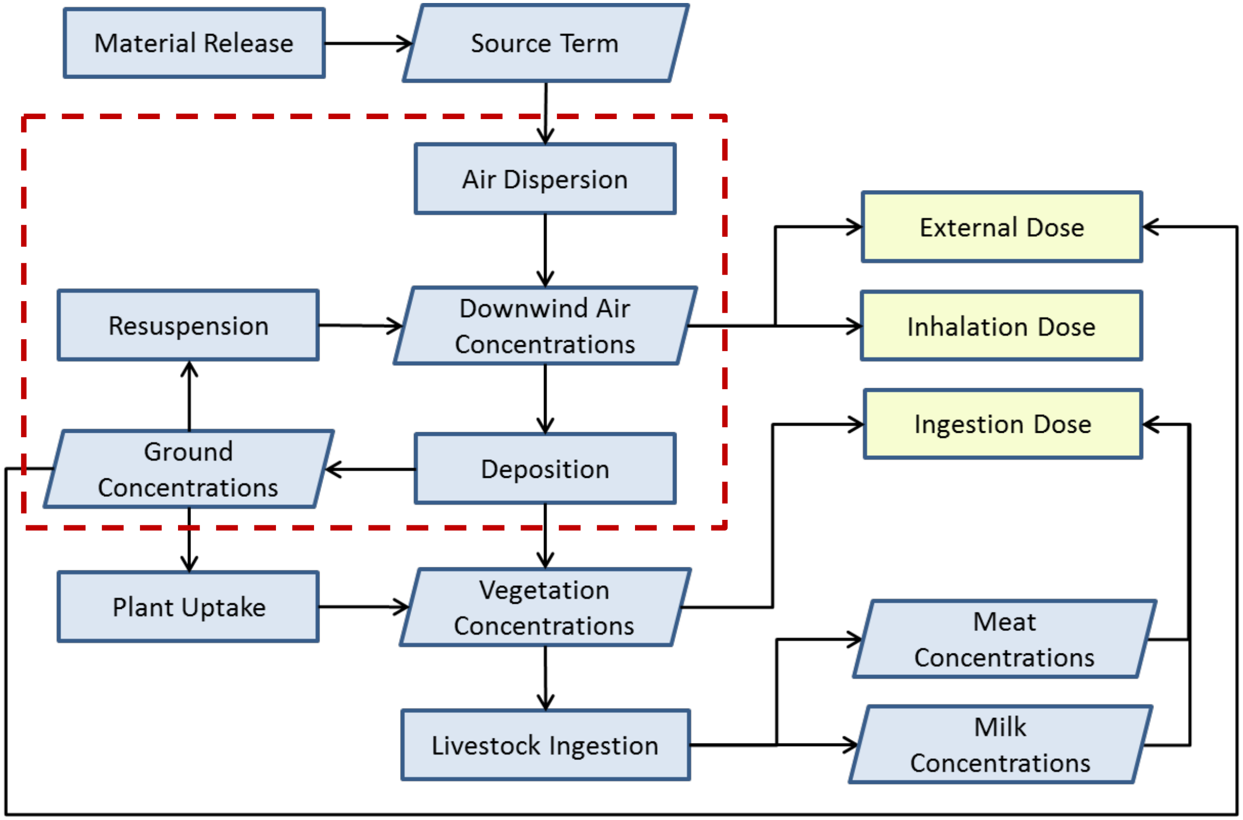
Time Parameters (Source : Yellocake Stack)

Time Step No.	Time Inc. (years)	Adjustment Particles	Radon
1	1	0	0
2	2	1	1
3	2	1	1
4	1	1	1

Particle Distribution Sets

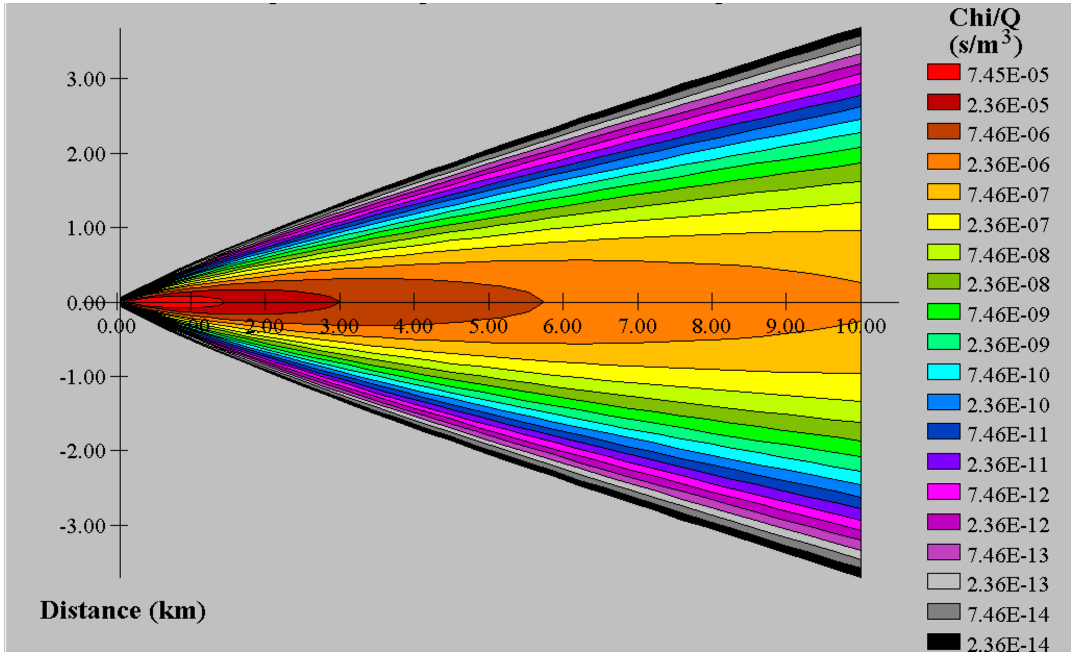
Particle Size (um)	Fractional Size Composition 1	2	3
1.5	0	1	0
3	1	0	0
7.7	0	0	0.3
54	0	0	0.7

Downwind Air and Ground Concentrations



Air Dispersion Model

- **Chronic Gaussian plume area source**
  - Based on discrete puff point source
  - Sector average time-integrated air concentrations
  - Plume reflection
  - Integrate over source area
- **Effective release height**
  - Physical release height
  - Thermal and momentum plume rise
  - Vertical settling
  - Terrain height adjustment
  - Wind speed correction
- **Plume depletion**
  - Conservation of mass
  - Dry and wet deposition
- **Buoyancy induced dispersion**



Gaussian Puff Time-Dependent Dispersion

$$C_a(i,x,y,z,t) = \frac{Q_{x_i}}{(2\pi)^{3/2}\sigma_y^2\sigma_z}\exp\left(\frac{-r^2}{2\sigma_y^2}\right)\left[\exp\left(\frac{-(z-H)^2}{2\sigma_z^2}\right)+\exp\left(\frac{-(z+H)^2}{2\sigma_z^2}\right)\right]$$

$C_a(i,x,y,z,t)$	=	air concentration of radionuclide *i* at *x,y,z* from a release at *0,0,H* at time *t* after release (Ci/m^3)
Q_{xi}	=	depleted source strength of nuclide *i* at distance *x* (Ci)
σ_y	=	horizontal dispersion coefficient (m)
σ_z	=	vertical dispersion coefficient (m)
r^2	=	$(x - u_H t)^2 + y^2$, assumes Gaussian symmetry, that is, $\sigma_x = \sigma_y$ (m^2)
x	=	downwind receptor distance from the release point (m)
y	=	crosswind distance from the plume centerline (m)
u_H	=	average wind speed at the effective release height (m/s)
t	=	time following release (s)
H	=	effective release height (m)

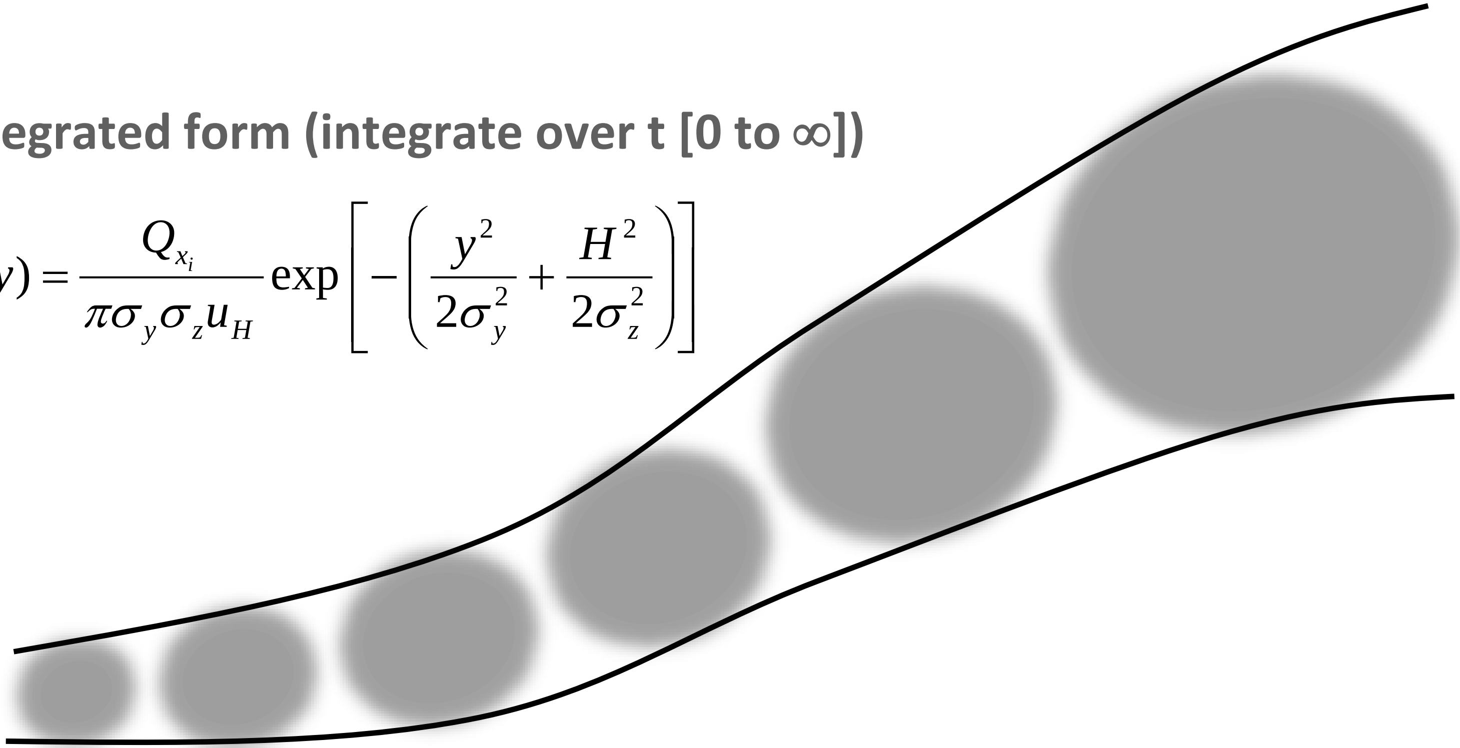
Continuous Point Source

- **Ground-level air concentrations (z = 0)**

$$C_a(i,x,y,0,t) = \frac{2Q_{x_i}}{(2\pi)^{3/2}\sigma_y^2\sigma_z}\left\{\exp-\left(\frac{r^2}{2\sigma_y^2}+\frac{H^2}{2\sigma_z^2}\right)\right\}$$

- **Time-integrated form (integrate over t [0 to ∞])**

$$\overline{C}_a(i,x,y) = \frac{Q_{x_i}}{\pi\sigma_y\sigma_z u_H}\exp\left[-\left(\frac{y^2}{2\sigma_y^2}+\frac{H^2}{2\sigma_z^2}\right)\right]$$

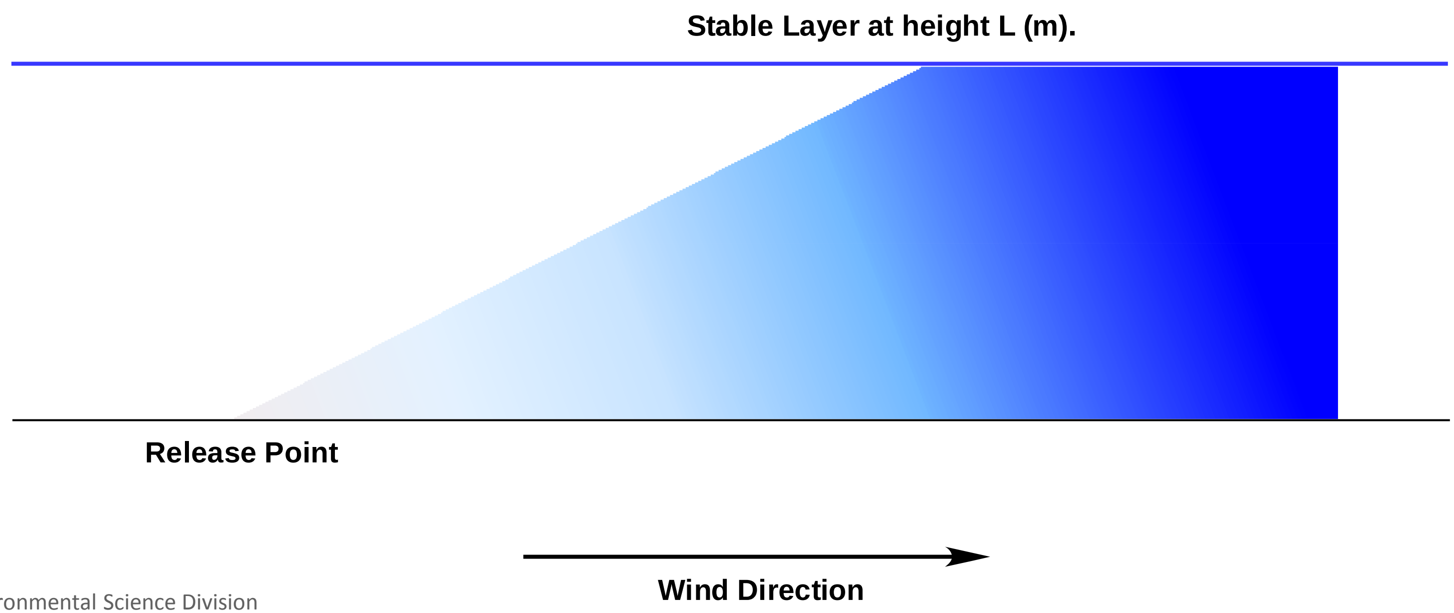


Plume Reflection

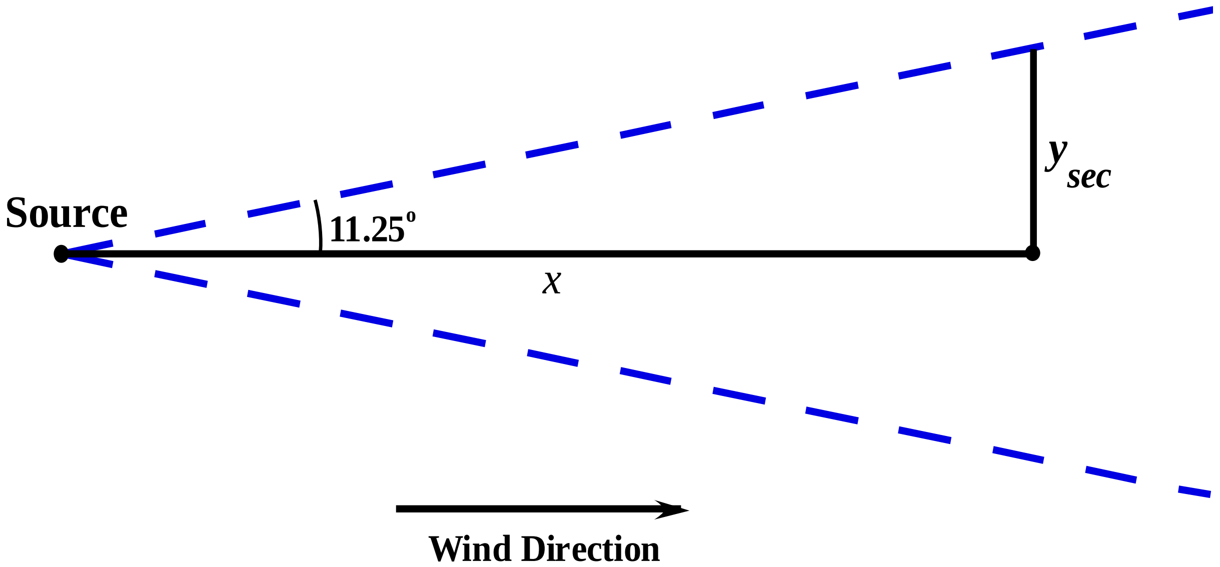
- Plume may become confined by a stable layer (lid height; mixing layer height) (integrate over z [0 to L])

$$\overline{C}_a(i,x,y) = \frac{Q_{x_i}}{\sqrt{2\pi}\sigma_y u_H L}\exp\left[-\left(\frac{y^2}{2\sigma_y^2}\right)\right]$$

- Transition between non-mixing and total mixing equations taken from NUREG/CR-0523 (MESODIF-II)



Chronic Point Source Air Concentrations (Integration over y)

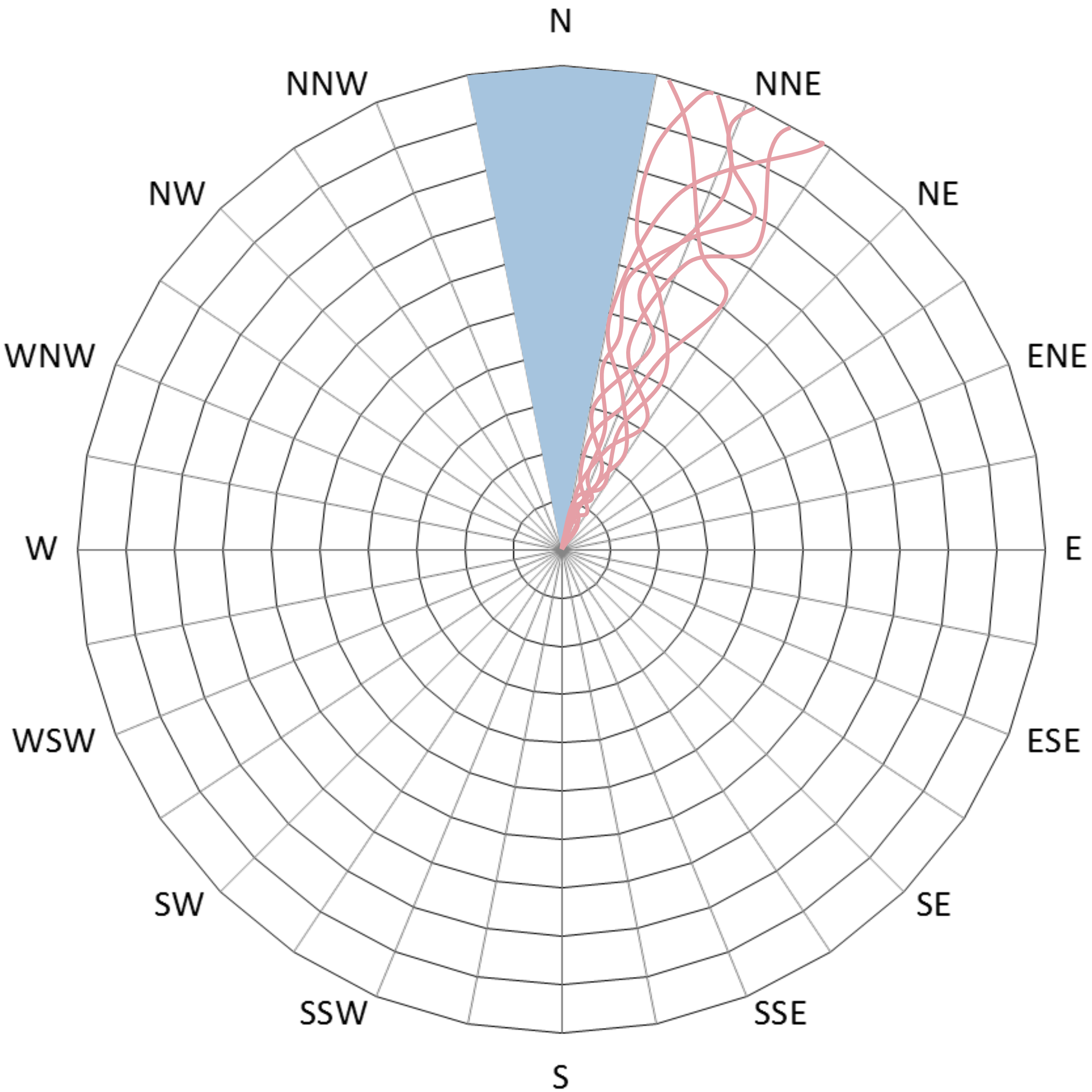


$$\overline{C_{sec}}(i,x) = \frac{Q_{x_i}}{\sqrt{2\pi}\,\sigma_z u_H y_{sec}} exp\left(\frac{-H^2}{2\sigma_z^2}\right)$$ **Non-mixing**

$$\overline{C_{sec}}(i,x) = \frac{Q_{x_i}}{2 y_{sec} u_H L}\,.$$ **Mixing**

Meteorological Data Grid

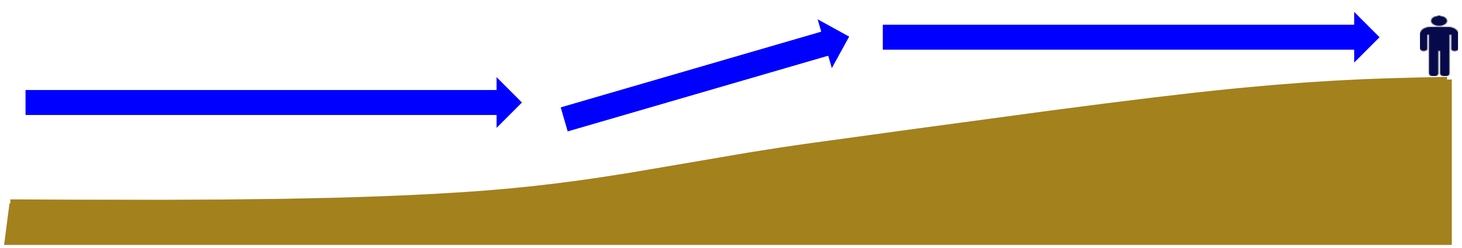
- 16 directions
- 22.5° sectors



Effective Release Height

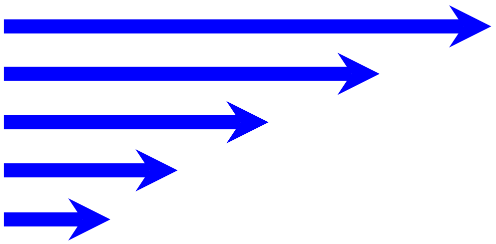
$$H = \max(h + \Delta h - h_v, 0) - (1 - P_c)[\min(\max(h + \Delta h - h_v, 0), \max(E_r - E_p, 0))]$$

- **Physical release height (h)**
- **Plume rise (*Δh*)**
  - Momentum driven : dependent on stack diameter, emission velocity, and wind speed
  - Buoyant : dependent on stability class, downwind distance, wind speed, heat flux (cal/s), ambient temperature
- **Vertical Settling (h_v)**
  - Dependent on settling velocity, downwind distance, and wind speed
- **Terrain height adjustment**
  - E_p, reference point for the release height
  - E_r, receptor elevation
  - P_c, 0.5 for PG stability categories A,B,C,D; 0.3 for E and F; 1 for non-terrain lifted plume



Wind Speed Adjustment

$$\frac{u_H}{u_a} = \left(\frac{H}{z_a}\right)^p$$



u_a = wind speed at measurement height (m/s)

z_a = height of anemometer for wind speed measurement (m)

p = power for height ratio (unitless) :

	Stability Class					
Population Zone	A	B	C	D	E	F
Rural	0.07	0.07	0.10	0.15	0.35	0.55
Suburban/urban	0.15	0.15	0.20	0.25	0.40	0.60

Pasquill Stability Classes

Meteorological Conditions Defining Pasquill Stability Classes

	Daytime insolation			Night-time conditions	
Surface wind speed (m/s)	**Strong**	**Moderate**	**Slight**	**Thin overcast or > 4/8 low cloud**	**<= 4/8 cloudiness**
< 2	A	A - B	B	E	F
2 - 3	A - B	B	C	E	F
3 - 5	B	B - C	C	D	E
5 - 6	C	C - D	D	D	D
> 6	C	D	D	D	D

A: Extremely unstable conditions

B: Moderately unstable conditions

C: Slightly unstable conditions

D: Neutral conditions

E: Slightly stable conditions

F: Moderately stable conditions

G: Extremely stable – folded into F

Notes:

1. Strong insolation corresponds to sunny midday in midsummer in England; slight insolation to similar conditions in midwinter.

2. Night refers to the period from 1 hour before sunset to 1 hour after sunrise.

3. The neutral category D should also be used, regardless of wind speed, for overcast conditions during day or night and for any sky conditions during the hour preceding or following night as defined above.

Source: https://www.ready.noaa.gov/READYpgclass.php

Plume Depletion and Deposition

- **Conservation of mass (activity)**
- **Dry deposition**

$$F(x) = \frac{\exp\left(\frac{-H^2}{2\sigma_z^2}\right)}{\sigma_z}$$

Non-mixing

$$Q_{x_i} = Q_{0_i} \exp\left[-\frac{V_{d_i}}{\sqrt{\frac{\pi}{2}} u_H} \int_0^x F(x)dx\right]$$

$$F(x) = \frac{1}{L}$$

Mixing

Q_{xi} = depleted source strength of nuclide *i* at distance *x* (Ci/s)

Q_{0i} = initial amount of radionuclide *i* released (Ci/s)

V_{di} = deposition velocity for radionuclide *i* (m/s)

Plume Depletion and Deposition (cont.)

- **Wet Deposition**
  - Washout coefficient, V_w (1/s)

$$V_w = -\frac{1}{C_a}\frac{dC_a}{dt}\,, \qquad V_w = W_C R\,, \qquad Q_{WET_{x_i}} = Q_{0_i}\, exp\left(-\frac{V_w x}{u_H}\right).$$

W_C = 1 x 10^{-3} (1/s)(mm/h)$^{-1}$ for stability classes A to D and
1.0 x 10^{-4} 1/s)(mm/h)$^{-1}$ for stability classes E and F, and

R = rainfall rate (mm/h)

- **Dry and Wet Deposition**

$$Q_{x_i} = Q_{0_i}\, exp\left\{-\left[\frac{V_w x}{u_H} + \frac{V_{d_i}}{\sqrt{\frac{\pi}{2}}u_H}\int_0^x F(x)dx\right]\right\}.$$

Dispersion Coefficients

- **Pasquill-Gifford stability classes (A through F)**
- **Pasquill coefficients (ground-level release)**

$$\sigma_z' = ax^b + c$$

- **Briggs coefficients (rural or urban)**

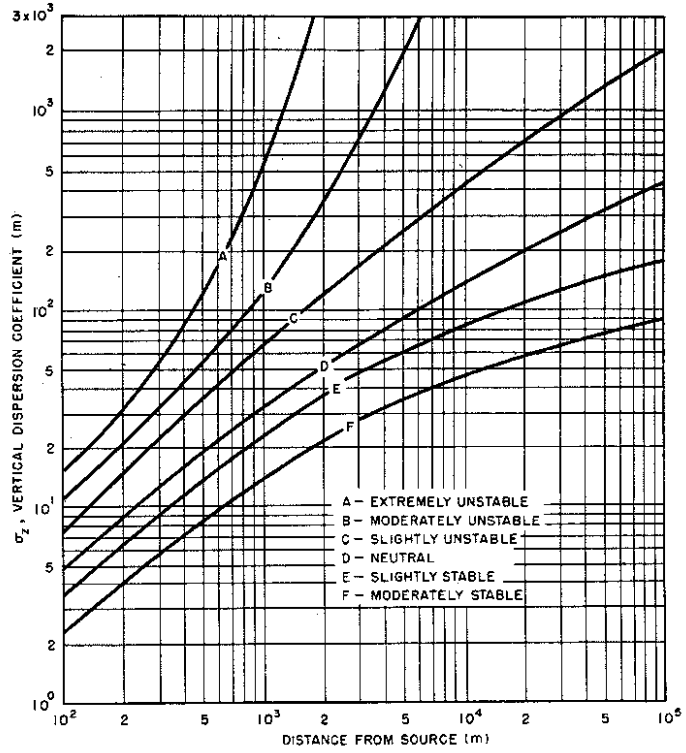
$$\sigma_z' = ax(1 + bx)^c$$

- **Buoyancy induced dispersion**

$$\sigma_{zb} = \frac{\Delta h}{3.5}$$

- **Final form**

$$\sigma_z = \left(\sigma_{zb}^2 + \sigma_z'^2\right)^{1/2}$$

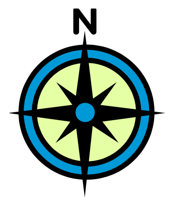


Meteorology and Atomic Energy 1968
Air Resources Laboratories
U.S. Dept. of Commerce, 1968

Account for Variation in Weather

- Chronic (long-term) model

- Variations in:
  - Wind direction
  - Wind speed
  - Atmospheric stability class



- Estimated air concentrations
  - Weighted average based on frequency of occurrence
  - For a given source / receptor pair (fixed direction):

    6 (wind speeds) x 6 (stability classes) = 36 calculations

$$C_{air,avg} = \left(\sum_{i=1\ to\ 6}^{wind} \sum_{j=1\ to\ 6}^{stability} C_{air,i,j} \right) \div 36$$

Meteorological Data

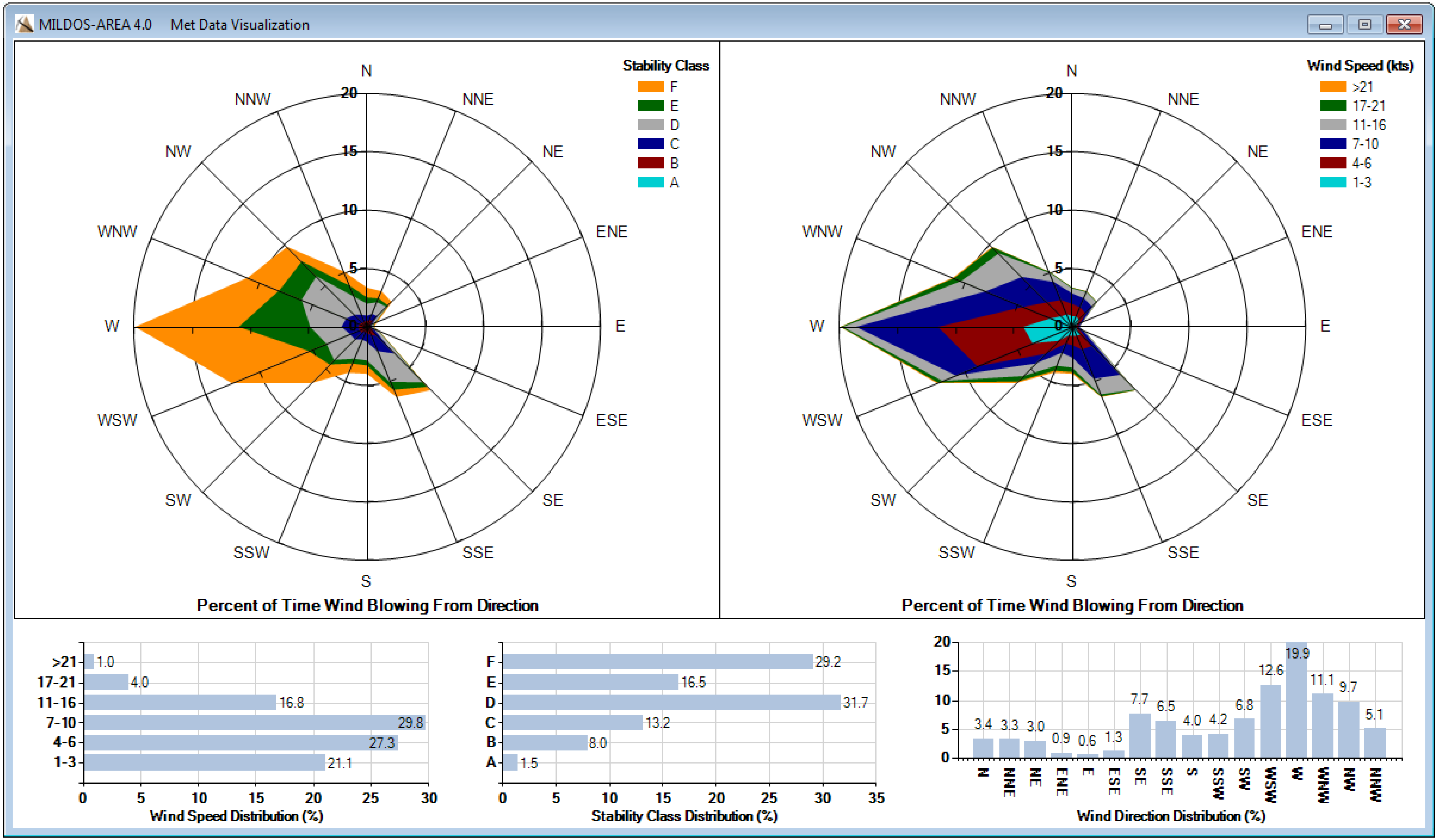
- **Joint-frequency data**
  - Fraction (frequency) of time wind is blowing:
    - Under conditions for a given stability class (A through F)
    - In a given direction (16 directions)
    - At a given wind speed (6 wind speed bins/ranges)
  - Fractions sum to 1
- **STability ARray (STAR) format**
  - Used in previous U.S. EPA regulatory models
  - Well-suited to chronic releases

Column	Value
1	Blank
2-4	Wind Direction (N, NNE, NE, ENE, E, etc.)
5	Blank
6	Stability Category (A, B, C, D, E, or F)
7	Blank
8-14	Wind speeds 1 – 3 knots (0.67 m/s)
15-21	Wind speeds 4 – 6 knots (2.46 m/s)
22-28	Wind speeds 7 – 10 knots (4.47 m/s)
29-35	Wind speeds 11 – 16 knots (6.93 m/s)
36-42	Wind speeds 17 – 21 knots (9.61 m/s)
43-49	Wind speeds > 21 knots (12.5 m/s)

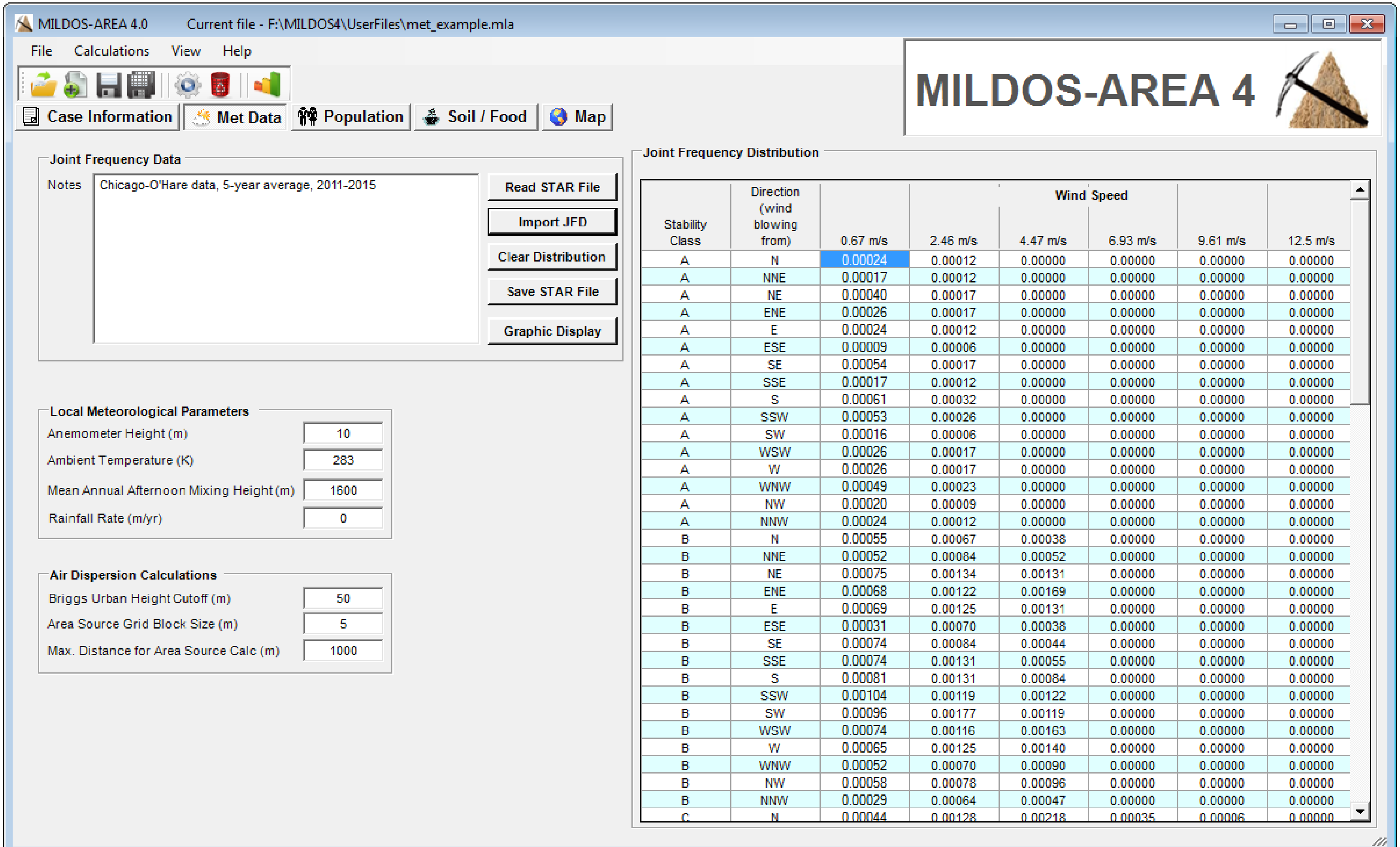
Partial STAR File Example

N	A	.00131	.00012	.00000	.00000	.00000	.00000
NNE	A	.00229	.00000	.00000	.00000	.00000	.00000
NE	A	.00165	.00036	.00000	.00000	.00000	.00000
ENE	A	.00096	.00047	.00000	.00000	.00000	.00000
E	A	.00136	.00036	.00000	.00000	.00000	.00000
ESE	A	.00160	.00012	.00000	.00000	.00000	.00000
SE	A	.00091	.00024	.00000	.00000	.00000	.00000
SSE	A	.00000	.00000	.00000	.00000	.00000	.00000
S	A	.00057	.00000	.00000	.00000	.00000	.00000
SSW	A	.00062	.00024	.00000	.00000	.00000	.00000
SW	A	.00131	.00012	.00000	.00000	.00000	.00000
WSW	A	.00177	.00024	.00000	.00000	.00000	.00000
W	A	.00266	.00107	.00000	.00000	.00000	.00000
WNW	A	.00108	.00036	.00000	.00000	.00000	.00000
NW	A	.00160	.00012	.00000	.00000	.00000	.00000
NNW	A	.00108	.00036	.00000	.00000	.00000	.00000
N	B	.00359	.00059	.00000	.00000	.00000	.00000
NNE	B	.00347	.00071	.00000	.00000	.00000	.00000
NE	B	.00444	.00131	.00000	.00000	.00000	.00000
ENE	B	.00761	.00249	.00095	.00000	.00000	.00000

Meteorological Data Visualization



Meteorological Data Options



Stability Class	Direction (wind blowing from)	Wind Speed 0.67 m/s	2.46 m/s	4.47 m/s	6.93 m/s	9.61 m/s	12.5 m/s
A	N	0.00024	0.00012	0.00000	0.00000	0.00000	0.00000
A	NNE	0.00017	0.00012	0.00000	0.00000	0.00000	0.00000
A	NE	0.00040	0.00017	0.00000	0.00000	0.00000	0.00000
A	ENE	0.00026	0.00017	0.00000	0.00000	0.00000	0.00000
A	E	0.00024	0.00012	0.00000	0.00000	0.00000	0.00000
A	ESE	0.00009	0.00006	0.00000	0.00000	0.00000	0.00000
A	SE	0.00054	0.00017	0.00000	0.00000	0.00000	0.00000
A	SSE	0.00017	0.00012	0.00000	0.00000	0.00000	0.00000
A	S	0.00061	0.00032	0.00000	0.00000	0.00000	0.00000
A	SSW	0.00053	0.00026	0.00000	0.00000	0.00000	0.00000
A	SW	0.00016	0.00006	0.00000	0.00000	0.00000	0.00000
A	WSW	0.00026	0.00017	0.00000	0.00000	0.00000	0.00000
A	W	0.00026	0.00017	0.00000	0.00000	0.00000	0.00000
A	WNW	0.00049	0.00023	0.00000	0.00000	0.00000	0.00000
A	NW	0.00020	0.00009	0.00000	0.00000	0.00000	0.00000
A	NNW	0.00024	0.00012	0.00000	0.00000	0.00000	0.00000
B	N	0.00055	0.00067	0.00038	0.00000	0.00000	0.00000
B	NNE	0.00052	0.00084	0.00052	0.00000	0.00000	0.00000
B	NE	0.00075	0.00134	0.00131	0.00000	0.00000	0.00000
B	ENE	0.00068	0.00122	0.00169	0.00000	0.00000	0.00000
B	E	0.00069	0.00125	0.00131	0.00000	0.00000	0.00000
B	ESE	0.00031	0.00070	0.00038	0.00000	0.00000	0.00000
B	SE	0.00074	0.00084	0.00044	0.00000	0.00000	0.00000
B	SSE	0.00074	0.00131	0.00055	0.00000	0.00000	0.00000
B	S	0.00081	0.00131	0.00084	0.00000	0.00000	0.00000
B	SSW	0.00104	0.00119	0.00122	0.00000	0.00000	0.00000
B	SW	0.00096	0.00177	0.00119	0.00000	0.00000	0.00000
B	WSW	0.00074	0.00116	0.00163	0.00000	0.00000	0.00000
B	W	0.00065	0.00125	0.00140	0.00000	0.00000	0.00000
B	WNW	0.00052	0.00070	0.00090	0.00000	0.00000	0.00000
B	NW	0.00058	0.00078	0.00096	0.00000	0.00000	0.00000
B	NNW	0.00029	0.00064	0.00047	0.00000	0.00000	0.00000
C	N	0.00044	0.00128	0.00218	0.00035	0.00006	0.00000

Meteorological Data Import Options

- **Standard formats**
  - Integrated surface hourly (ISH) data (DS-3505 format)
    - Available from the National Centers for Environmental Information (> 1,000 stations in U.S.) – ftp://ftp.ncdc.noaa.gov/pub/data/noaa/
  - AERMET surface file (SFC)
    - Input for current U.S. EPA regulatory model (AERMOD)
    - Often available from state air quality agencies
- **Non-standard formats**
  - Vertical temperature difference (delta-T) data (NRC-administered facilities)
  - Solar radiation (day) and delta-T (night) data (SRDT)
  - Standard deviation of wind elevation angle (σ_E)
  - Standard deviation of wind azimuth angle (σ_A)

Meteorological Data Import Options (cont.)

- **Obtaining ISH data example**
  - From ‘isd-history.csv’ file at NCEI ftp web site (text file also available)
  - Find station number

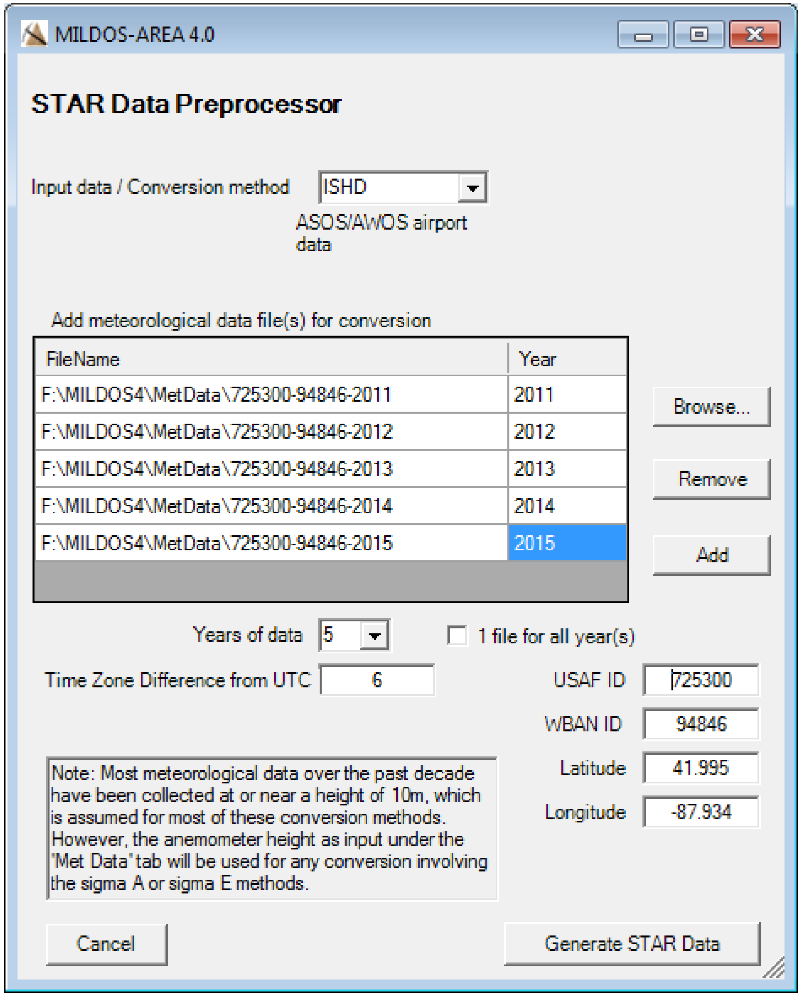
	A	B	C	D	E	F	G	H	I	J	K
1	USAF	WBAN	STATION NAME	CTRY	STATE	ICAO	LAT	LON	ELEV(M)	BEGIN	END
19981	725266	4751	BRADFORD REGIONAL AIRPORT	US	PA	KBFD	41.8	-78.633	652.9	19730101	20160510
19982	725267	94868	VENANGO REGIONAL AIRPORT	US	PA	KFKL	41.383	-79.867	469.4	19730101	20160510
19983	725267	99999	VENANGO RGNL	US	PA	KFKL	41.378	-79.86	469	20000101	20031231
19984	725270	99999	SIMCOE (MARS) &	CA			42.85	-80.267	239	19730101	19770630
19985	725280	14733	BUFFALO NIAGARA INTERNATIONAL AP	US	NY	KBUF	42.941	-78.736	218.2	19420201	20160510
19986	725283	465	CATTARAUGUS COUNTY OLEAN AIRPORT	US	NY	KOLE	42.241	-78.371	651.1	20130101	20160509
19987	725283	99999	CATTARAUGUS CO OLEAN	US	NY	KOLE	42.241	-78.371	650.7	19870813	20121231
19988	725285	99999	BUFFALO COAST GUARD STATION	US	NY		42.88	-78.88	180	19760926	19960701
19989	725287	4724	NIAGARA FALLS INTL AIRPORT	US	NY	KIAG	43.108	-78.938	178.3	19510612	20160510
19990	725287	99999	NIAGARA FALLS INTL	US	NY	KIAG	43.1	-78.933	180	20000101	20031231
19991	725288	99999	NIAGARA COAST GUARD STATION	US	NY		43.27	-79.07	82	19760926	19960701
19992	725290	14768	GREATER ROCHESTER INTERNATIONAL AP	US	NY	KROC	43.117	-77.677	164.3	19730101	20160510
19993	725291	99999	RIDGELY AIRPARK	US	MD	KRJD	38.97	-75.866	19.5	20070521	20090701
19994	725292	14976	GRINNELL REGIONAL AIRPORT	US	IA	KGGI	41.717	-92.7	307.2	20060831	20160511
19995	725293	99999	GARRETT CO	US	MD		39.58	-79.339	894	20070521	20130430
19996	725294	383	ANSON COUNTY AIRPORT JEFF CLOUD FIELD	US	NC	KAFP	35.017	-80.083	91.1	20130101	20150602
19997	725294	99999	WADESBORO ANSON CO	US	NC	KAFP	35.021	-80.077	90.8	20070521	20160509
19998	725295	99999	ROCHESTER COAST GUARD LIGHT STAT	US			43.25	-77.6	82	19760926	19960701
19999	725296	99999	BOWMAN MUNI	US	ND	KBPP	46.187	-103.428	901.6	20070521	20100603
20000	725300	94846	CHICAGO O'HARE INTERNATIONAL AIRPORT	US	IL	KORD	41.995	-87.934	201.8	19461001	20160510
20001	725305	94892	DUPAGE AIRPORT	US	IL	KDPA	41.914	-88.246	229.8	20060101	20160511
20002	725305	99999	DUPAGE	US	IL	KDPA	41.908	-88.249	231	19730101	20051231
20003	725306	14855	GLENVIEW NAS	US	IL	KNBU	42.083	-87.833	199	19730101	19950301
20004	725306	99999	GLENVIEW NAS	US	IL	KNBU	42.083	-87.817	199	20050905	20050905
20005	725307	99999	WILMETTE (MARINES)&	US	IL	K62G	42.067	-87.683	223	19760212	19960214

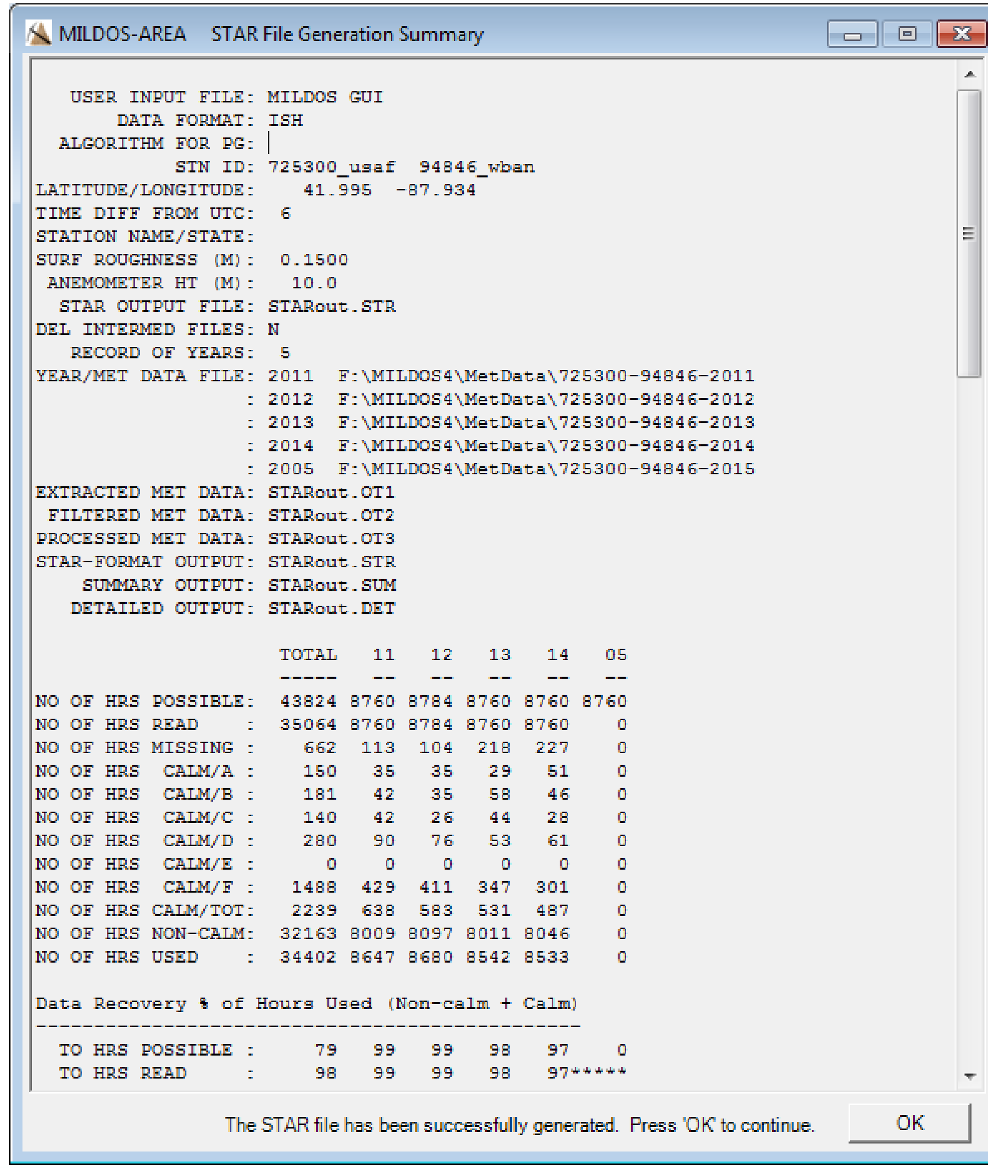
Meteorological Data Import Options (cont.)

- **From 'isd-inventory.csv' file at NCEI ftp web site**
  - Determine what annual data is available
  - Try for minimum of 5 years, if possible
- **Go to desired annual folder and download file(s) of interest**
  - e.g. , ftp://ftp.ncdc.noaa.gov/pub/data/noaa/2015/725300-94846-2015.gz
  - *.gz compressed file type on Windows requires a utility program such as WinZip or 7-Zip to open

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	USAF	WBAN	YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
438521	725300	94846	2002	961	870	1007	952	949	967	860	861	834	863	843	872
438522	725300	94846	2003	868	780	866	838	863	828	869	866	845	868	845	866
438523	725300	94846	2004	862	812	871	836	862	833	856	856	840	856	959	1022
438524	725300	94846	2005	1259	950	1056	915	961	931	955	952	953	973	970	1091
438525	725300	94846	2006	1072	920	1111	968	1078	910	1009	1034	1022	1026	1047	1088
438526	725300	94846	2007	1142	1032	1130	988	991	975	984	1081	917	1023	980	1336
438527	725300	94846	2008	1212	1188	1118	997	986	1011	1004	976	1039	971	965	1232
438528	725300	94846	2009	1155	1033	1094	1068	1025	1037	977	1061	1031	1129	987	1304
438529	725300	94846	2010	1151	1086	1113	1000	1070	1079	1008	976	951	948	986	1214
438530	725300	94846	2011	1171	1137	1074	1110	1108	1069	998	994	996	961	1033	1129
438531	725300	94846	2012	1146	1042	1061	957	1051	901	1011	972	946	1087	949	1214
438532	725300	94846	2013	1163	1117	1125	1098	1041	1022	985	973	957	1059	1010	1240
438533	725300	94846	2014	1284	1077	1144	1050	1051	1099	1011	1068	1010	1087	1083	1123
438534	725300	94846	2015	1206	1067	1098	1026	1143	1145	1050	1023	976	1015	1067	1312
438535	725300	94846	2016	1122	1082	1153	1141	331	0	0	0	0	0	0	0
438536	725305	94892	2006	1109	852	1110	862	999	822	951	999	1002	1031	1015	1103
438537	725305	94892	2007	1211	1035	1129	935	879	955	961	1127	869	980	931	1356

Import Meteorological Data





ISH Data Input

- **UTC time zone offset**

Time Zones in the United States

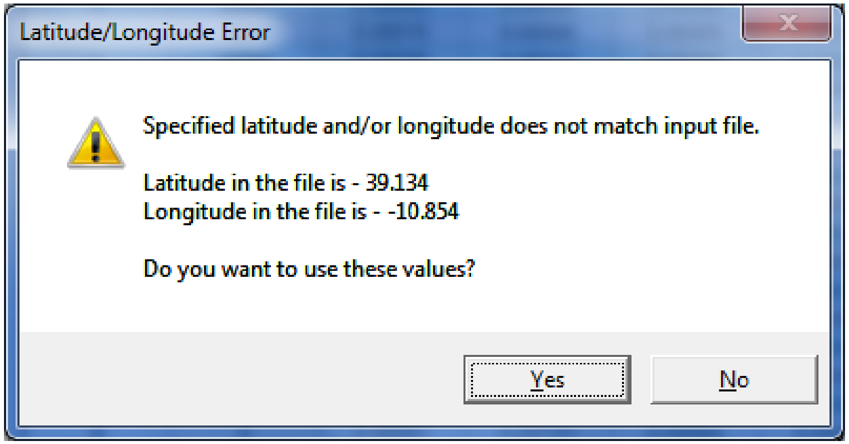
Standard Time	UTC Offset
Eastern	5h
Central	6h
Mountain	7h
Pacific	8h

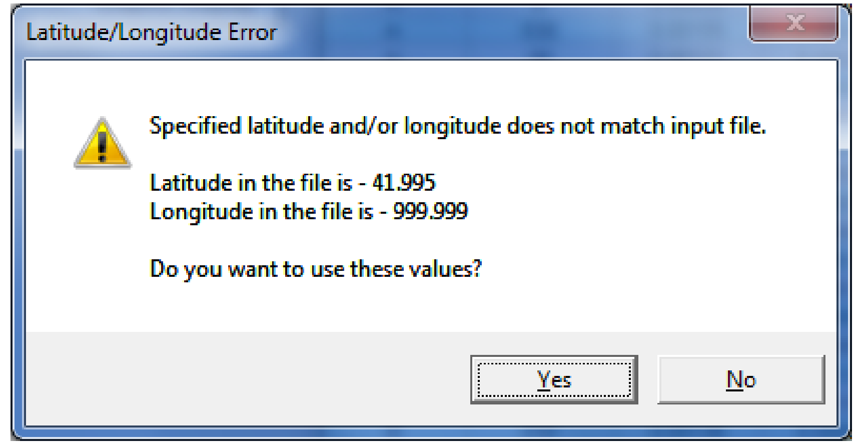
- **Can view the USAF ID, WBAN ID, latitude, and longitude in the data file**

```
0185725300948462013010100004+41983-087900FM-12+0205KORD V0203301
0273725300948462013010100517+41995-087934FM-15+0205KORD V0303405
0256725300948462013010102517+41995-087934FM-15+0205KORD V0303505
0245725300948462013010102587+41995-087934FM-16+0205KORD V0303505
0245725300948462013010103257+41995-087934FM-16+0205KORD V0303605
0246725300948462013010103417+41995-087934FM-16+0205KORD V0303405
0198725300948462013010103517+41995-087934FM-15+0205KORD V0303505
```

Meteorological Data Issues

- Sometimes ISH data from NCEI has a few characters (or more) out of place



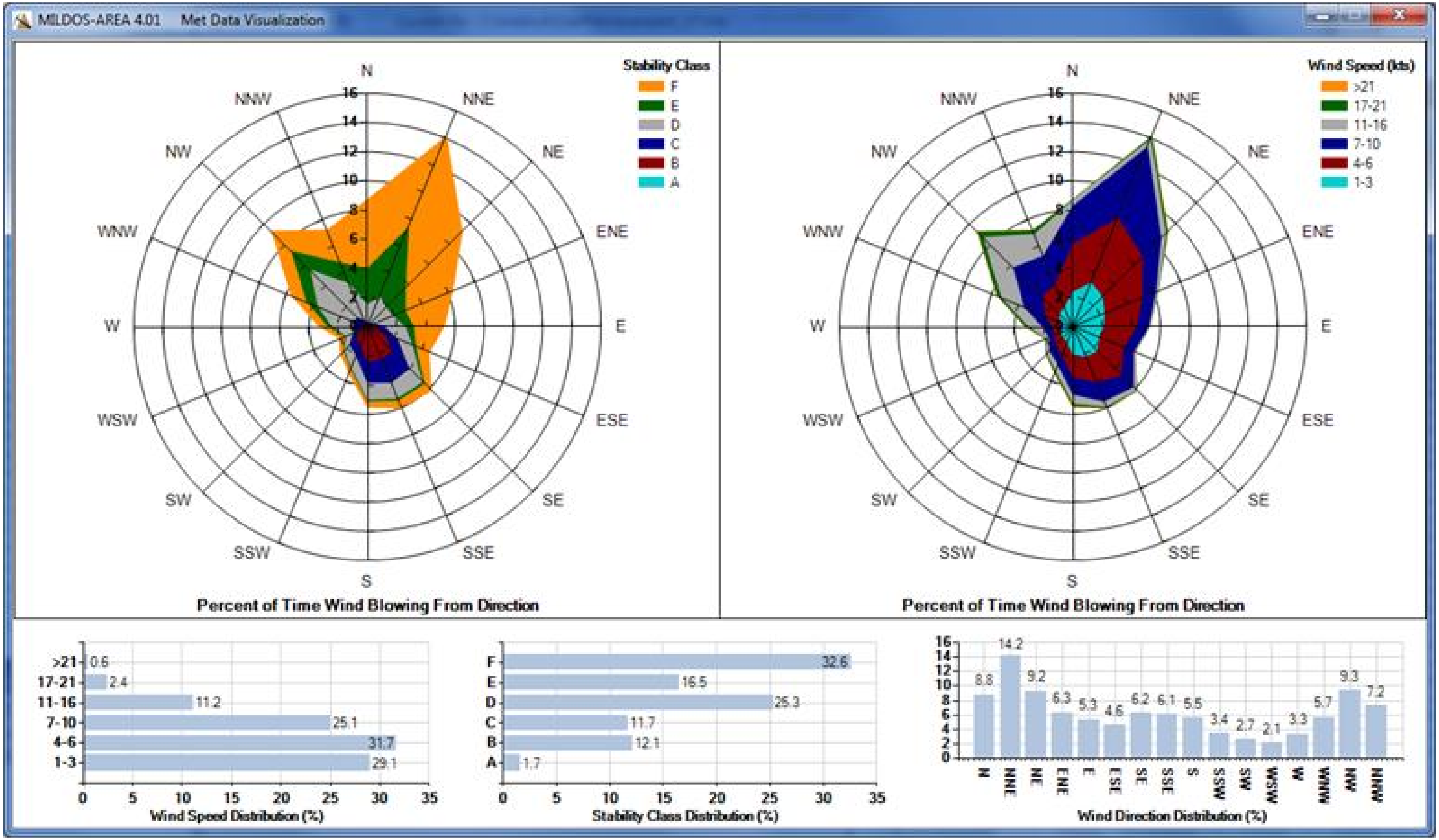


- Found problems by importing into Excel using fixed width columns and sorting on the longitude column (could then search original file and 'fix')

11602	1.48E+26	39117	-108517	FM-12+14739999	9V
11603	1.48E+26	39117	-108517	FM-12+14739999	9V
11604	1.48E+26	39117	-108517	FM-12+14739999	9V
11605	1.48E+26	39117	-108517	FM-12+14739999	9V
11606	1.48E+26	39117	-108517	FM-12+14739999	9V
11607	1.96E+26	39117	-108517	FM-12+14739999	9V
11608	2.45E+26	39134	-10854	SY-MT+1475KGJT	V0
11609					

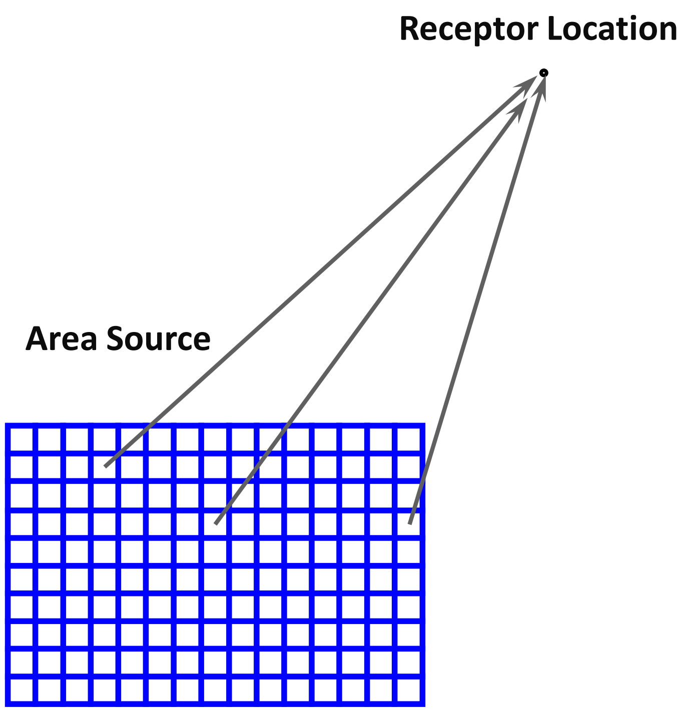
12786	2.597E+26	+41995-	87934	FM-16+02	V0302605N002	
12787	2.637E+26	+41995-	87934	FM-15+02	V0302605N002	
12788	2.737E+26	+41995-	87934	FM-15+02	V0302705I	(K
12789	3.707E+26	+41995-	87934	FM-15+02	V0309999	4:
12790	1.473E+25	+41995+	999999	FM-15+02	V030999999	
12791						
12792						

Example Case – Imported Meteorological Data



Area Source Model

- Source areas segmented into uniform grids
- Point-to-point dispersion estimates
- Normalized air concentration at receptor is average from all source grid points
- Air concentration at receptor is calculated from normalized air concentration and release from all source grid points



Ground Concentrations

$$C_g(i,p,x,t) = V_{d_p}\,\overline{C_{\text{sec}}}(i,p,x,t)\,\frac{1-\exp\left[-(\lambda_i+\lambda_e)t\right]}{\lambda_i+\lambda_e}$$

$C_g(\text{i},p,x,t)$ = ground concentration of radionuclide *i* associated with particle size *p* at a distance *x* (in m) after time t (Ci/m^2),

V_{d_p} = deposition velocity for particle size *p* (m/s),

$\overline{C_{\text{sec}}}(i,p,x,t)$ = sector-averaged air concentration of radionuclide *i* at a distance *x* (in m) from the source (Ci/m^3) during time *t* (here the dependence on particle size is being explicitly pointed out),

λ_i = radioactive decay constant for radionuclide *i* (1/s), and

λ_e = decay constant to account for environmental loss from soil (1/s)

$$C_g(i,p,x,t_j) = V_{d_p}\,\overline{C_{\text{sec}}}(i,p,x,t_{s_j})\,\frac{1-\exp\left[-(\lambda_i+\lambda_e)t_{s_j}\right]}{\lambda_i+\lambda_e} + \sum_{k=1}^{j-1}\left(C_g(i,p,x,t_k)\exp\left[-(\lambda_i+\lambda_e)t_{j-k}\right]\right)$$

$C_g(i,p,x,t_j)$ = ground concentration of radionuclide *i* on particle size *p* at a distance *x* (in m) after time step *j* (Ci/m^2),

$C_g(i,p,x,t_{j-1})$ = ground concentration of radionuclide *i* on particle size *p* at a distance *x* (in m) after time step *j-1* (Ci/m^2), and

t_{sj} = length of time assigned to time step *j* (s)

Resuspension

$$R(t) = \begin{cases} \dfrac{V_{d_r}}{V_{d_p}} R_I \exp(-\lambda_r t), \text{for t} \le \text{t}_\text{R} \\ \dfrac{V_{d_r}}{V_{d_p}} R_F, \text{for t} > \text{t}_\text{R} \end{cases},$$

$R(t)$ = ratio of resuspended air concentration to ground concentration for a ground concentration at time t after deposition (1/m),

V_{dr} = deposition velocity for the reference particle size that corresponds to the values of R_I and R_F (m/s),

V_{dp} = deposition velocity for particle size p (m/s),

R_I = initial value of the resuspension factor for fresh deposits (1/m),

λ_r = resuspension factor decay constant (1/yr) [(ln 2)/resuspension half-life],

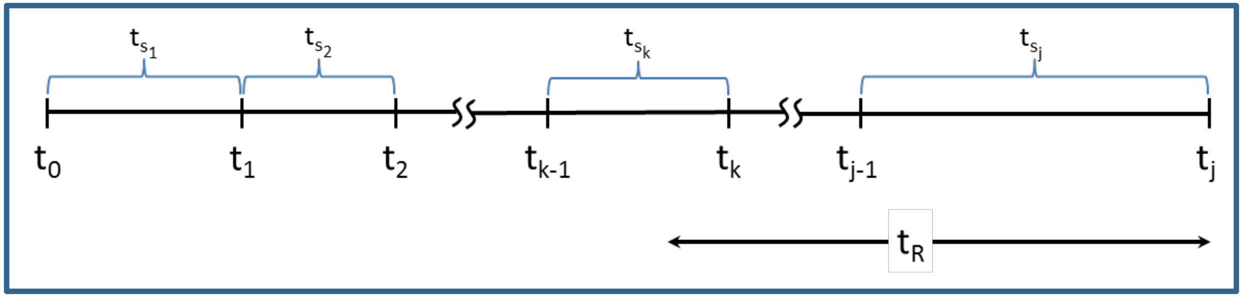
R_F = final value of the resuspension factor after time (1/m), and

t_R = time required for the resuspension factor to decrease from its initial to final value (yr), $t = t_R$, when

$$\frac{V_{d_r}}{V_{d_p}} R_F = \frac{V_{d_r}}{V_{d_p}} R_I \exp(-\lambda_r t_R) \longrightarrow t_R = -\frac{1}{\lambda_r} \ln \frac{R_F}{R_I}.$$

Resuspended Air Concentration

$$C_{air_R}(i,p,x,t_j) = R(t)C_g(i,p,x,t_j)$$



$$C_{air_R}(i,p,x,t_j) = \sum_{m=1}^{k-1} \overline{C_{\text{sec}}}(i,p,x,t_{s_m}) V_{d_r} R_F \frac{\exp[-(\lambda_i+\lambda_e)(t_j-t_m)] - \exp[-(\lambda_i+\lambda_e)(t_j-t_m+t_{s_m})]}{\lambda_i+\lambda_e} +$$

$$\sum_{m=k+1}^{j} \overline{C_{\text{sec}}}(i,p,x,t_{s_m}) V_{d_r} R_I \frac{\exp[-(\lambda_i+\lambda_e+\lambda_r)(t_j-t_m)] - \exp[-(\lambda_i+\lambda_e+\lambda_r)(t_j-t_m+t_{s_m})]}{\lambda_i+\lambda_e+\lambda_r} +$$

$$\overline{C_{\text{sec}}}(i,p,x,t_{s_k}) V_{d_r} \left[R_F \left(\frac{\exp[-(\lambda_i+\lambda_e)t_R] - \exp[-(\lambda_i+\lambda_e)(t_j-t_{k-1})]}{\lambda_i+\lambda_e} \right) + R_I \left(\frac{\exp[-(\lambda_i+\lambda_e+\lambda_r)(t_j-t_k)] - \exp[-(\lambda_i+\lambda_e+\lambda_r)t_R]}{\lambda_i+\lambda_e+\lambda_r} \right) \right]$$

$$t_j = \sum_{m=1}^{j} t_{s_m}$$

k = time step of the transition interval where both initial and final resuspension factor contributions occur when t_j is $>t_R$

Total Air Concentrations

- **Particulates (for a given radionuclide)**
  - Sum of direct and resuspended air concentrations
  - Summed over all particulate sizes
- **Radon**
  - Shorter half-lives, need to account for decay

$$Q_{x\_Rn} = \left(3.17 \times 10^{-8}\ \mathrm{yr/s}\right) Q_{0\_Rn} \exp\left(-\lambda_{Rn}\tau\right)$$ downwind source strength

$$\overline{C_{\mathrm{sec}}}\left(Rn, x, t_j\right) = \left(\frac{\chi}{Q}\right)_{gas} Q_{x\_Rn}$$ radon air concentration

Q_{x_Rn} = depleted downwind source strength of Rn at distance *x* downwind (Ci/s),

Q_{0_Rn} = source strength of Rn at the release point (Ci/yr),

λ_{Rn} = radon decay constant (1/s) [(ln 2)/(Rn decay half-life)],

τ = transit time between source and receptor, calculated as the downwind distance divided by the average wind speed (x/u_H) (s),

$\overline{C_{\mathrm{sec}}}(Rn, x, t_j)$ = sector-averaged air concentration of radon at a distance x (in m) from the source during time step j (Ci/m^3) and

$(\chi/Q)_{gas}$ = normalized air concentration for a gas (i.e., a nondepositing molecule) (s/m^3)

Total Air Concentrations (cont.)

- **Radon Daughter Radionuclides**

$$\overline{C_{\text{sec}}}\left(i_n, x, t_j\right) = \overline{C_{\text{sec}}}\left(Rn, x, t_0\right)\left(\prod_{i=2}^{n} \lambda_i\right)\left\{\sum_{i=1}^{n}\left[\frac{\exp\left(-\lambda_i \tau\right)}{\prod_{\substack{m=1 \\ m \neq i}}^{n}\left(\lambda_m - \lambda_i\right)}\right]\right\}$$

for n = 2,…,4 for Rn-220 and n = 2,…,7 for Rn-222,

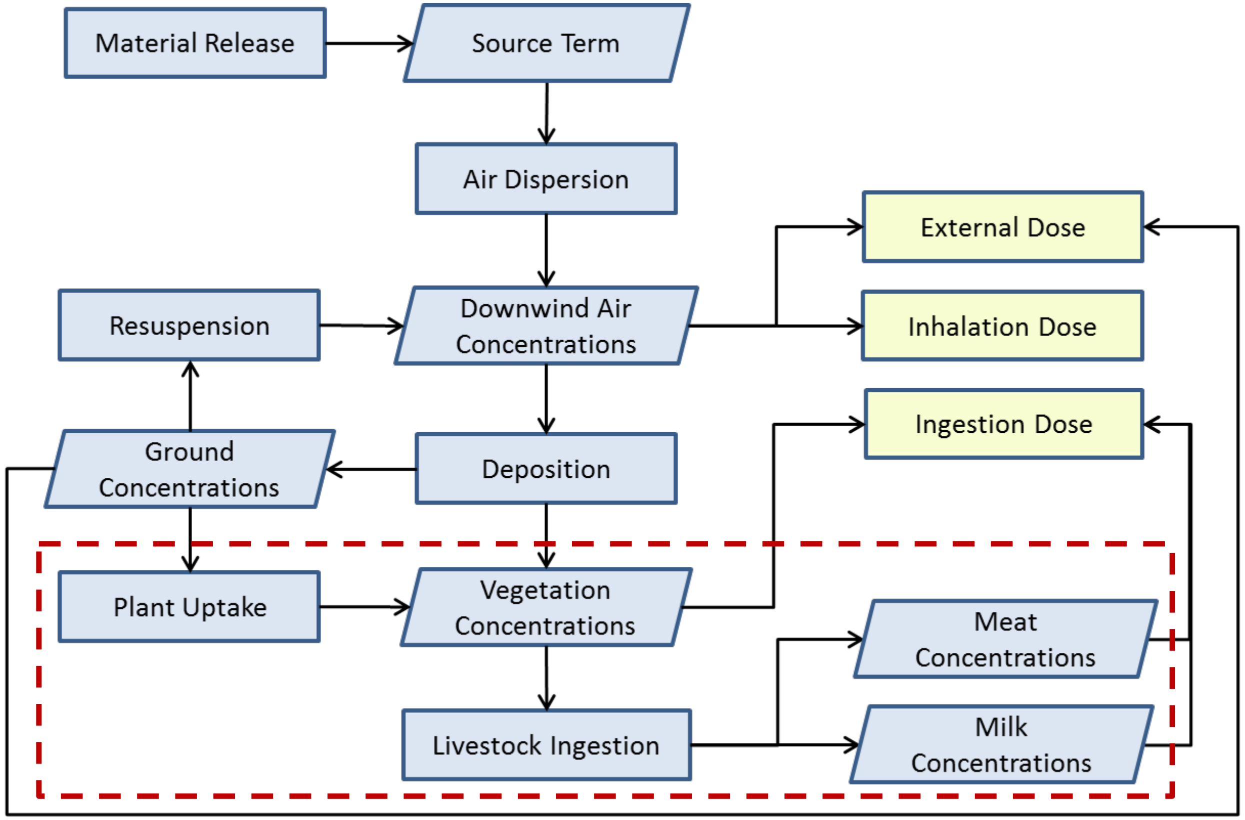
where

$\overline{C_{\text{sec}}}(i_n, x, t_j)$ = sector-averaged air concentration of radon daughter i_n at a distance x (in m) from the source during time step j (Ci/m^3),

λ_i and λ_m = radioactive decay constants for radon daughters (1/s), and

$\overline{C_{\text{sec}}}(Rn, x, t_0)$ = what would be the sector-averaged air concentration of radon at a distance x (in m) from the source (Ci/m^3) without accounting for radioactive decay

Concentrations in Food



Ingestion Pathway

- **Radionuclide concentration in plants from air and ground concentrations**
  - edible above-ground vegetables
  - potatoes
  - other edible below-ground vegetables
  - pasture grass
  - hay
- **Pasture grass and hay for the meat and milk ingestion pathways**
- **The plants become contaminated from root uptake and foliar deposition**

Plant concentrations

$$C_v(i,p,x,t_j) = 10^{12}\,\frac{C_g(i,p,x,t_j)B_v(i)}{\rho} + 8.64\times10^{16}\,C_{air}(i,p,x,t_j)V_{d_p}F_rE_v\,\frac{1-\exp(-\lambda_w t_v)}{Y_v\lambda_w}$$

$C_v(i,p,x,t_j)$ = concentration of radionuclide *i* from particle size *p* in vegetation type *v* during time step *j* (pCi/kg) (wet weight),

10^{12} = unit conversion factor (pCi/Ci),

8.64×10^{16} = unit conversion factor (pCi-s/Ci-d),

$B_v(i)$ = soil-to-plant transfer coefficient for radionuclide *i* and vegetation type *v* (pCi/kg [wet] plant per pCi/kg [dry] soil),

ρ = soil areal density for surface mixing (kg/m^2) (dry weight),

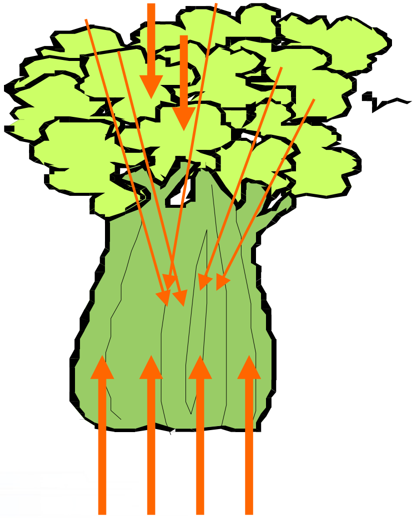
F_r = fraction of the total deposition retained on plant surfaces,

E_v = fraction of the foliar deposition reaching edible portions of vegetation *v*,

λ_w = decay constant accounting for weathering losses [ln 2/plant weathering decay half-life] (1/d),

t_v = duration of exposure while vegetation *v* is growing (d), and

Y_v = yield density of vegetation *v* (kg/m^2) (wet weight)



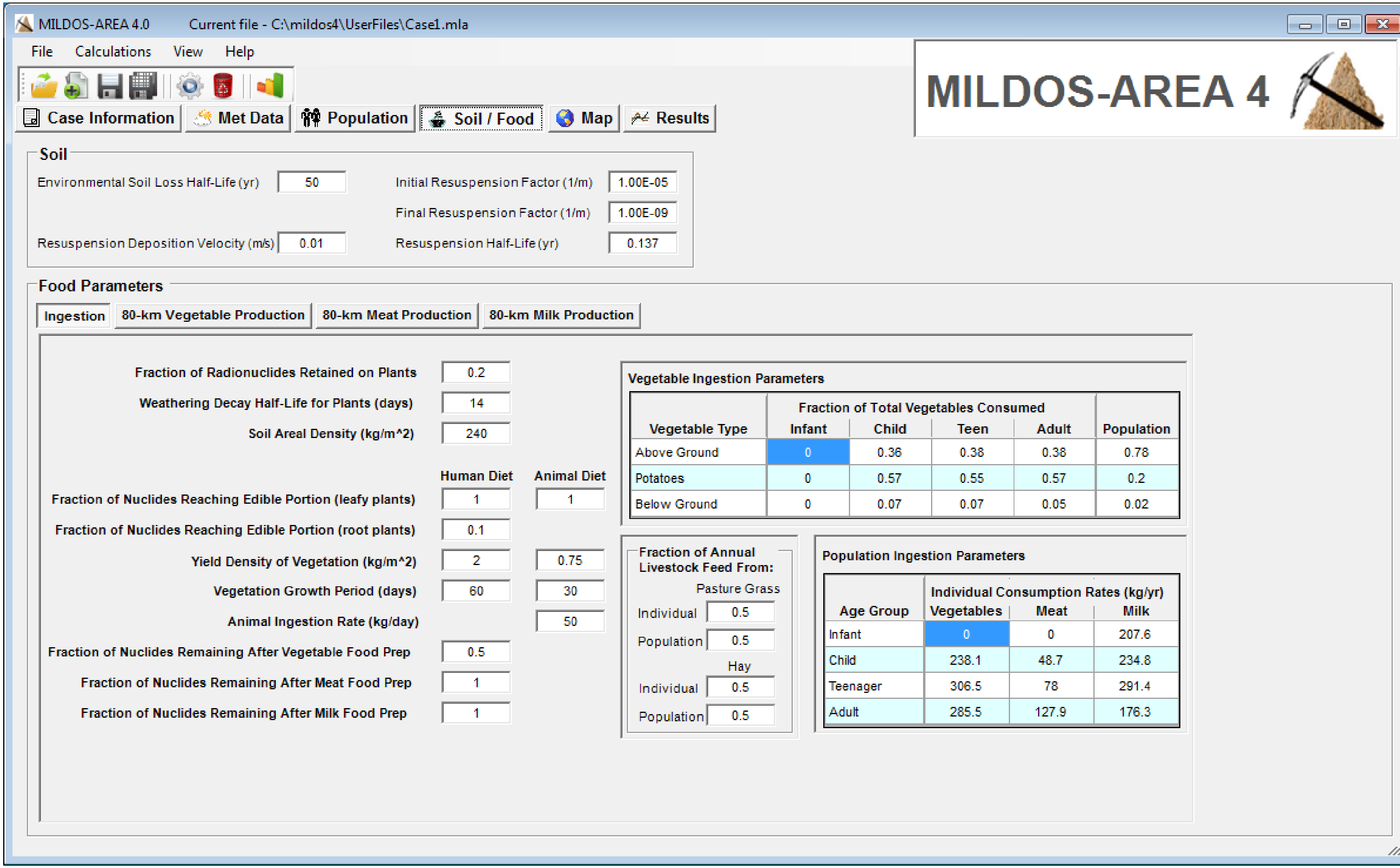
Meat and Milk concentrations

$$C_b(i,x,t_j) = QF_b(i)\left(F_{pg}C_{v_{pg}}(i,x,t_j) + F_hC_{v_h}(i,x,t_j)\right)$$ **meat**

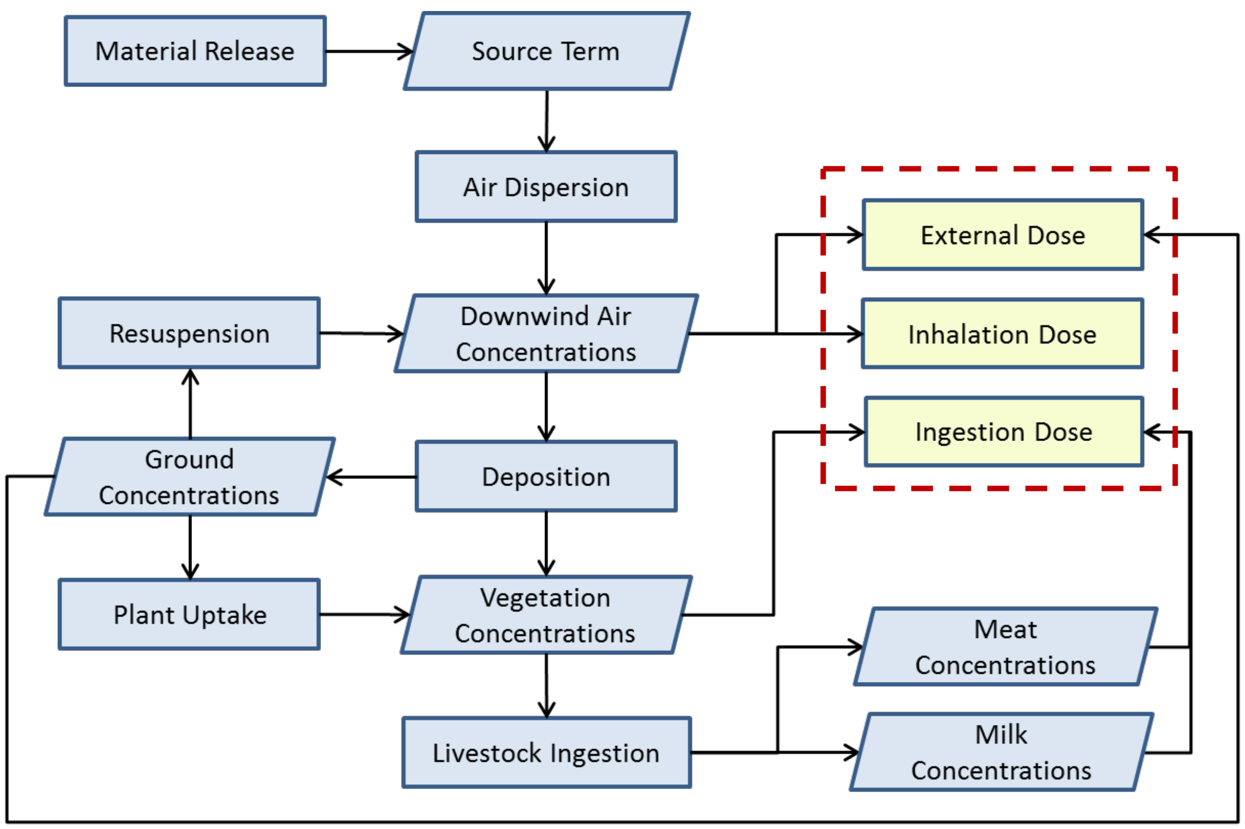
$$C_m(i,x,t_j) = QF_m(i)\left(F_{pg}C_{v_{pg}}(i,x,t_j) + F_hC_{v_h}(i,x,t_j)\right)$$ **milk**

$C_b(i,x,t_j)$ = average meat concentration for radionuclide *i* during time step *j* (pCi/kg),
$C_m(i,x,t_j)$ = average milk concentration for radionuclide i during time step *j* (pCi/L),
Q = feed ingestion rate (kg/d) (wet weight),
Fm(i) = feed-to-milk transfer coefficient for radionuclide *i* (pCi/L per pCi/d),
$F_b(i)$ = feed-to-meat transfer coefficient for radionuclide *i* (pCi/kg per pCi/d),
F_{pg}, F_h = fraction of the total annual feed requirement that is assumed to be satisfied by pasture grass or locally grown feed (hay), respectively,
$C_{v\,pg}(i,x,t_j)$ = concentration of radionuclide *i* in pasture grass (pCi/kg) (wet weight),
$C_{v_h}(i,x,t_j)$ = concentration of radionuclide *i* in hay or other stored feed (pCi/kg) (wet weight)

Example Case - Setup Soil and Ingestion Parameters

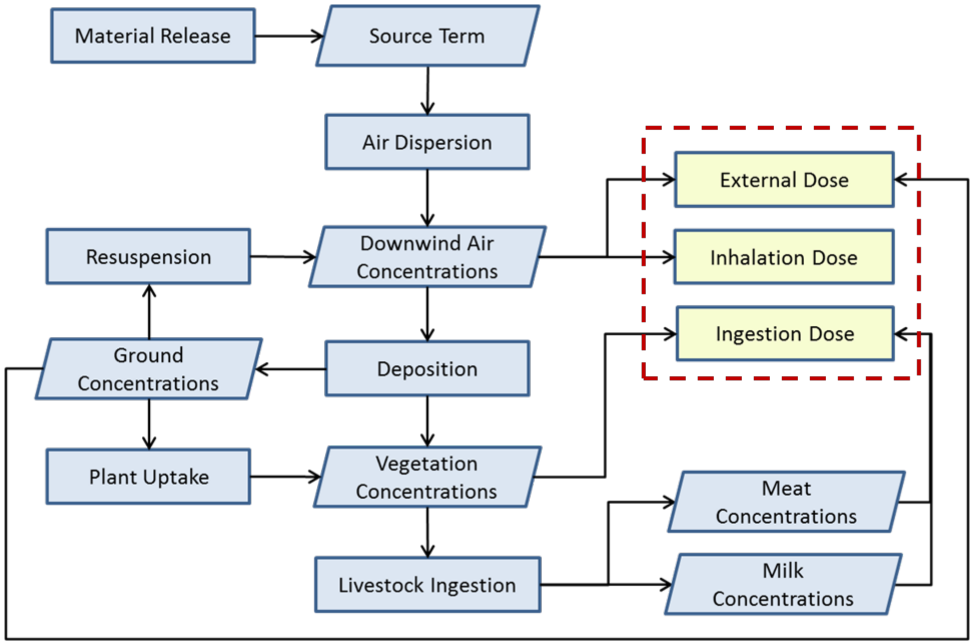


Exposure Calculations



Pathway Doses

- **External:**
  - immersion in air particulates
  - groundshine
- **Inhalation:**
  - plume passage (direct)
  - resuspension
  - radon
- **Ingestion**
  - Plants, meat and milk
  - Originally fixed at 50% removed from plants by processing
- **Accounts for age, organ, location of receptor**
- **Population ingestion dose considers yields**



External (Cloudshine and Groundshinte)

$$D_{ext,o}(x,t_j) = 10^{12}\left(F_{in}S_{in} + F_{out}\right)\left(\sum_i \left[DC_{cld,io}\overline{C_{air}}\left(i,x,t_j\right) + DC_{gnd,io}C_g(i,x,t_j)\right]\right)$$

- **External dose by:**
  - Nuclide (i)
  - Organ (o)
  - Location (x)
  - Time (t)

$D_{ext,o}(x,t_j)$ = external dose rate to organ *o* in individual from outside airborne and deposited activity at distance *x* and time step *j* (mrem/yr),
10^{12} = unit conversion factor (pCi/Ci),
F_{in}, F_{out} = indoor and outdoor occupancy fractions, respectively (unitless),
S_{in} = indoor shielding factor (unitless),
$\overline{C_{air}}(i,x,t_j)$ = total air concentration of radionuclide *i* during time step t_j at distance *x* (Ci/m^3),
$C_g(i,x,t_j)$ = ground concentration of radionuclide *i* from a given source after time step *j* (Ci/m^2),
$DC_{cld,io}$ = external air immersion dose coefficient for radionuclide *i* in organ *o* (mrem/yr per pCi/m^3), and
$DC_{gnd,io}$ = external groundshine dose coefficient for radionuclide *i* in organ *o* (mrem/yr per pCi/m^2)

Inhalation (Particulates)

- **Inhalation dose by:**
  - Nuclide (i) [for selected lung clearance class]
  - Particle size (p)
  - Organ (o)
  - Age group (k)
  - Location (x)
  - Time (t)

$$D_{inh,kop}(x,t_j) = 10^{12} \sum_p \sum_i \overline{C_{air}}\left(i, p, x, t_j\right) DC_{inh,ikop} IR$$

$D_{inh,kop}(x,t_j)$ = inhalation dose rate to organ *o* in an individual in age group *k* from particulates from time step t_j (mrem/yr),

10^{12} = unit conversion factor (pCi/Ci),

$\overline{C_{air}}(i,p,x,t_j)$ = total air concentration of radionuclide *i* on particle size *p* during time step t_j at distance *x* (Ci/m^3),

$DC_{inh,ikop}$ = inhalation dose coefficient for radionuclide *i*, age group *k*, organ *o*, and particle size *p* (mrem/pCi), and

IR = inhalation rate (7,300 m^3/yr)

Inhalation (Rn-222)

- **Uses Rn-222 air concentration and includes contribution from daughters**

$$D_{inh,Rn222}(x,t_j) = 10^{12}\overline{C_{air}}\left(Rn222, x, t_j\right) IR \times \left[DC_{inh,Rn222}\left(F_{in} + F_{out}\right) + DC_{inh,Rn222\_D}\left(F_{in}E_{in\_eq} + F_{out}E_{out\_eq}\right)\right]$$

- **Option to estimate outdoor equilibrium fraction**
  - Divides the working level (WL) at receptor location by WL if Rn-222 and daughters were in equilibrium

$$E_{out\_eq} = \frac{1.03\times10^{-6}A + 5.07\times10^{-6}B + 3.73\times10^{-6}C}{1.03\times10^{-6} + 5.07\times10^{-6} + 3.73\times10^{-6}}$$

$D_{inh,Rn222}(x,t_j)$ = inhalation dose rate to an individual from Rn-222 from time step t_j (mrem/yr),
10^{12} = unit conversion factor (pCi/Ci),
$\overline{C_{air}}(Rn222, x, t_j)$ = air concentration of Rn-222 during time step t_j at distance x (Ci/m^3),
F_{in}, F_{out} = indoor and outdoor occupancy fractions, respectively (unitless),
E_{in_eq}, E_{out_eq} = equilibrium fraction of radon daughters with radon in indoor and outdoor air, respectively (unitless),
$DC_{inh,Rn222}$ = inhalation dose coefficient for Rn-222 (mrem/pCi), and
$DC_{inh,Rn222\_D}$ = inhalation dose coefficient for all Rn-222 daughters (mrem/pCi)

A, B, and C are the air concentrations of Po-218, Pb-214, and Bi-214, respectively, relative to the Rn-222 air concentration

Inhalation (Rn-220)

- **No equilibrium with daughters**
- **Uses the working level**

$$D_{inh,Rn220}(x,t_j) = \left(F_{in} + F_{out}\right)WL_{Rn220}\left(x,t_j\right)DC_{inh,Rn220}$$

$$WL_{Rn220} = 9.48\times10^{-10}A' + 1.23\times10^{-4}B' + 1.17\times10^{-5}C'$$

$D_{inh,Rn220}(x,t_j)$ = inhalation dose rate to an individual from Rn-220 from time step t_j (mrem/yr),

$WL_{Rn220}(x,t_j)$ = WL of Rn-220 during time step t_j at distance x (WL), and

$DC_{inh,Rn220}$ = inhalation dose coefficient for Rn-220 (mrem/yr per *WL*)

A’, B’, and C’ are the air concentrations (pCi/m^3), respectively, of Po-216, Pb-212, and Bi-212 at the receptor location

Ingestion

$$D_{ing,ko}(i,x,t_j) = I_k(i,x,t_j)DC_{ing,iko}$$

$$I_k(i,x,t_j) = U_{mk}C_m(i,x,t_j) + U_{bk}C_b(i,x,t_j) + F_{va}U_{vk}\sum_v F_{vck}C_v(i,x,t_j)$$

- **Ingestion of milk, meat, and plant food**
- **External dose by:**
  - Nuclide (i)
  - Organ (o)
  - Age group (k)
  - Location (x)
  - Time (t)

$I_k(i,x,t_j)$ = ingestion rate of radionuclide *i* by an individual in age group *k* during time step t_j (pCi/yr),

U_{mk}, U_{bk} = milk (L/yr) and meat (kg/yr) ingestion rates for age group *k*,

$C_m(i,x,t_j)$ = average milk concentration for radionuclide *i* during time step *j* (pCi/L),

$C_b(i,x,t_j)$ = average meat concentration for radionuclide *i* during time step *j* (pCi/kg),

F_{va} = fraction of radionuclide activity remaining in vegetables after food preparation (unitless),

U_{vk} = vegetable ingestion rate for age group *k* (kg/yr)(wet weight),

F_{vck} = fraction of vegetable category *c* consumed by age group *k* (unitless),

$C_v(i,x,t_j)$ = concentration of radionuclide *i* in vegetation type *v* during time step *j* (pCi/kg) (wet weight),

$D_{ing,ko}(i,x,t_j)$ = ingestion dose rate to organ *o* from radionuclide *i* of an individual in age group *k* from time step t_j (mrem/yr), and

$DC_{ing,iko}$ = ingestion dose coefficient for radionuclide *i* in organ *o* of an individual in age group *k* (mrem/pCi ingested).

Population Dose

- **Inhalation & External**
  - Multiply individual dose by segment population and sum

$$PD_{ext,o}(t_j) = 10^{-3} \sum_s \left(n_s D_{ext,o}(s,t_j) \right)$$

$PD_{ext,o}(t_j)$ = total population external dose to organ o from time step j (person-rem/yr),

10^{-3} = unit conversion factor (rem/mrem),

n_s = number of people residing in population segment s, and

$D_{ext,o}(s,t_j)$ = external dose rate to organ o in an individual from a given source from time step j (mrem/yr) where the midpoint of segment s corresponds to distance x. For population calculations, 100 percent occupancy is assumed for all individuals, with an indoor occupancy of 14 h/day at a shielding factor of 0.7 (that is, F_{in} = 14/24, F_{out} = 10/24, and S_{in} = 0.7).

$$PD_{inh,o}(t_j) = 10^{-3} \sum_s \sum_k n_{ks} D_{inh,ko}(s,t_j)$$

$PD_{inh,o}(t_j)$ = total population inhalation dose rate to organ o from time step t_j (person-rem/yr),

10^{-3} = unit conversion factor (rem/mrem),

n_{ks} = number of people in age group k residing in population segment s, and

$D_{inh,ko}(s,t_j)$ = inhalation dose rate to organ o in an individual in age group k from a given source from time step t_j (mrem/yr) wheree the midpoint of segment s corresponds to distance x].

Population Dose - Ingestion

- **Calculate the average radionuclide concentration in vegetables**

$$C_{v\_avg}(i,s,t_j) = \sum_v W_{vs} C_{vs}(i,x,t_j)$$

- **Find total activity in foodstuffs grown in the area**

$$Q_f(i,t_j) = \sum_s \sum_f P_{fs} C_f(i,s,t_j)$$

$C_{v\_avg}(i,s,t_j)$ = concentration of radionuclide *i* in vegetables averaged over all vegetable types in population segment *s* during time step *j* (pCi/kg) (wet weight),

$C_{vs}(i,x,t_j)$ = concentration of radionuclide *i* in vegetation type *v* during time step *j* (pCi/kg) (wet weight),

W_{vs} = weighting factor for vegetable type *v* in population segment *s* (fraction of total production) (unitless),

$Q_f(i,t_j)$ = total amount of radionuclide *i* in food type *f* (vegetables, meat, and milk) produced in the region during time step *j* (pCi/yr) (wet weight),

$C_f(i,s,t_j)$ = concentration of radionuclide *i* in food type *f* in population segment *s* during time step *j* (pCi/kg) (wet weight), and

P_{fs} = annual production rate of food type *f* in population segment *s* (kg/yr).

Population Dose – Ingestion (cont.)

- **Find the fraction eaten by each age group**

$$F_{fk} = \frac{F_{pk} U_{fk}}{\sum_k F_{pk} U_{fk}}$$

- **Distribute all of the food grown and account for food processing loss**

$$PD_{ing,ko}(i,t_j) = 10^{-3} \sum_f \sum_i \sum_k F_{fa} Q_f(i,t_j) F_{fk} DC_{ing,iko}$$

F_{fk} = fraction of food type *f* consumed by individuals in age group *k* (unitless),

F_{pk} = fraction of the population belonging to age group *k* (unitless),

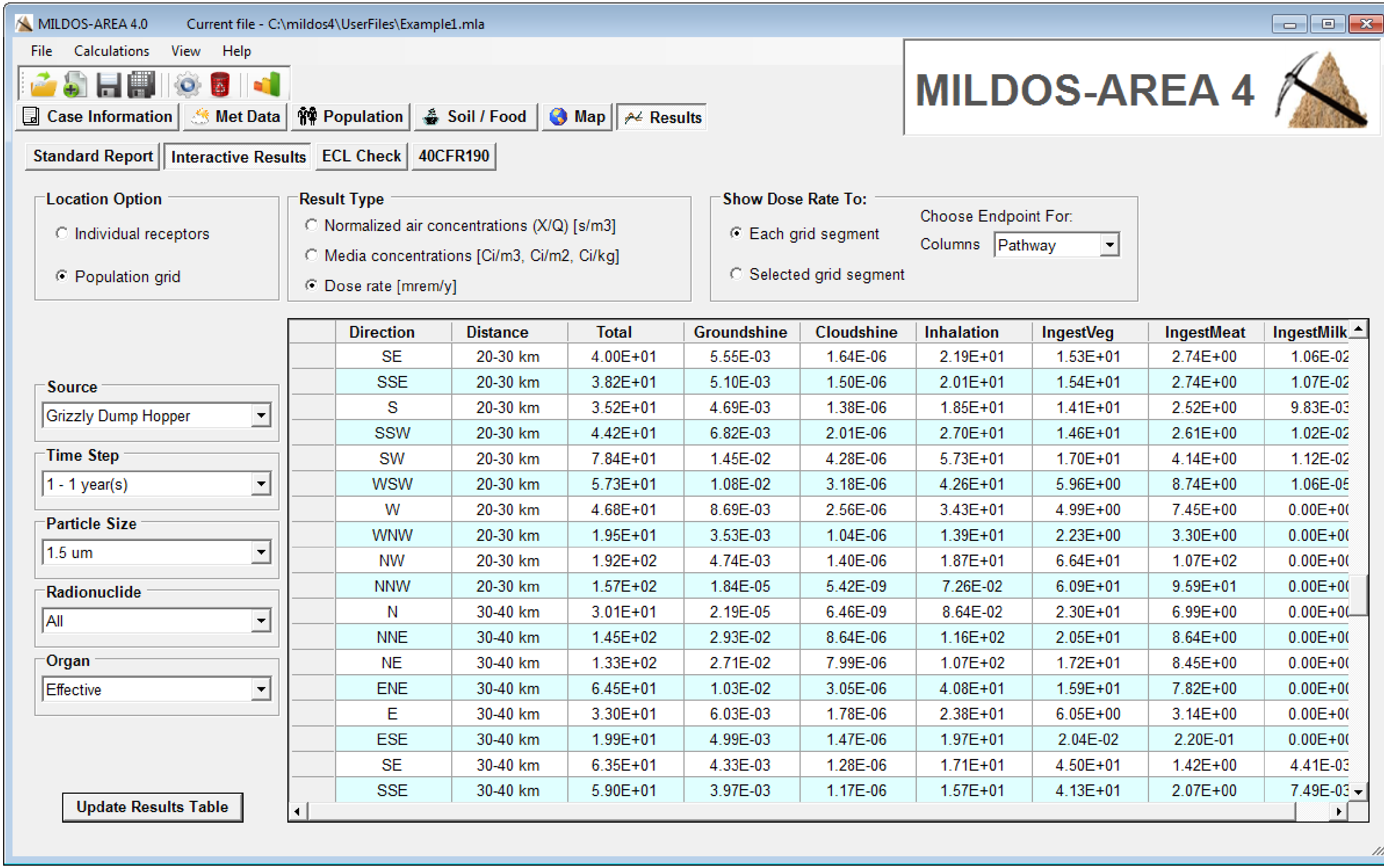
U_{fk} = average consumption rate of food type *f* for an individual in age group *k* (kg/yr for vegetables and meat, L/yr for milk),

$PD_{ing,ko}(i,tj)$ = population ingestion dose rate to organ *o* from radionuclide *i* of an individual in age group *k* from time step t_j (person-rem/yr),

$DC_{ing,iko}$ = ingestion dose coefficient for radionuclide *i* in organ *o* of an individual in age group *k* (mrem/pCi ingested), and

F_{fa} = fraction of radionuclide activity remaining in food type *f* after food preparation (unitless).

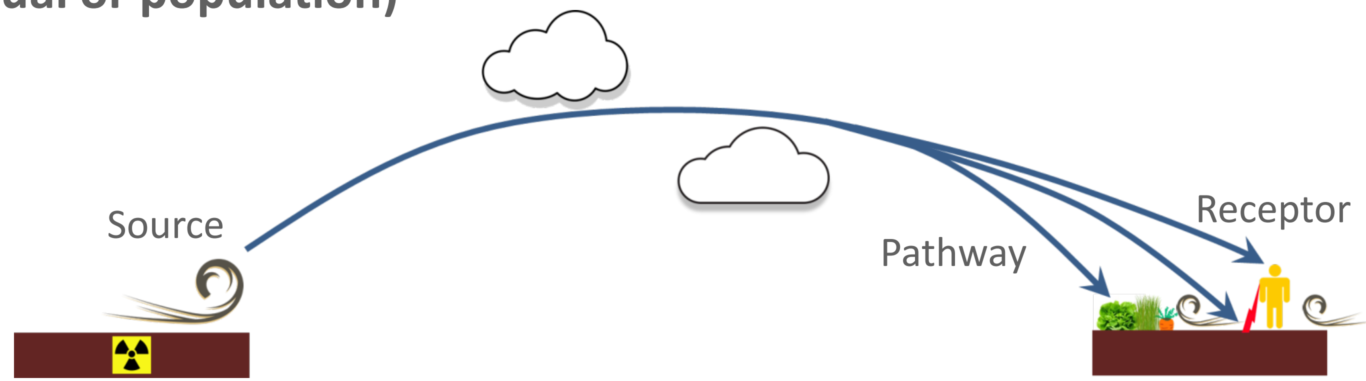
Run Example Case and View Results

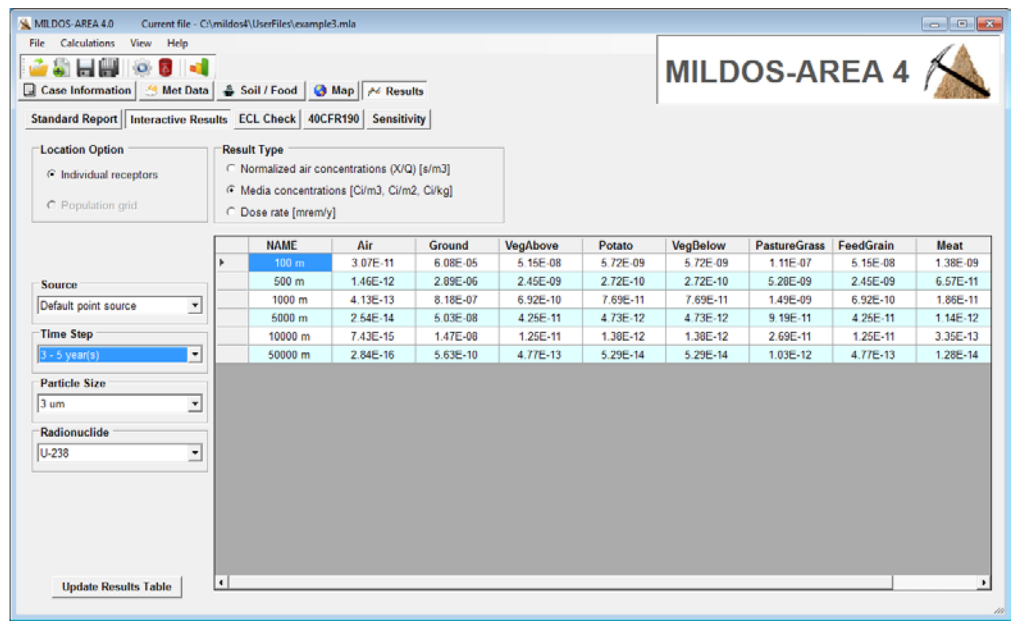


Direction	Distance	Total	Groundshine	Cloudshine	Inhalation	IngestVeg	IngestMeat	IngestMilk
SE	20-30 km	4.00E+01	5.55E-03	1.64E-06	2.19E+01	1.53E+01	2.74E+00	1.06E-02
SSE	20-30 km	3.82E+01	5.10E-03	1.50E-06	2.01E+01	1.54E+01	2.74E+00	1.07E-02
S	20-30 km	3.52E+01	4.69E-03	1.38E-06	1.85E+01	1.41E+01	2.52E+00	9.83E-03
SSW	20-30 km	4.42E+01	6.82E-03	2.01E-06	2.70E+01	1.46E+01	2.61E+00	1.02E-02
SW	20-30 km	7.84E+01	1.45E-02	4.28E-06	5.73E+01	1.70E+01	4.14E+00	1.12E-02
WSW	20-30 km	5.73E+01	1.08E-02	3.18E-06	4.26E+01	5.96E+00	8.74E+00	1.06E-05
W	20-30 km	4.68E+01	8.69E-03	2.56E-06	3.43E+01	4.99E+00	7.45E+00	0.00E+00
WNW	20-30 km	1.95E+01	3.53E-03	1.04E-06	1.39E+01	2.23E+00	3.30E+00	0.00E+00
NW	20-30 km	1.92E+02	4.74E-03	1.40E-06	1.87E+01	6.64E+01	1.07E+02	0.00E+00
NNW	20-30 km	1.57E+02	1.84E-05	5.42E-09	7.26E-02	6.09E+01	9.59E+01	0.00E+00
N	30-40 km	3.01E+01	2.19E-05	6.46E-09	8.64E-02	2.30E+01	6.99E+00	0.00E+00
NNE	30-40 km	1.45E+02	2.93E-02	8.64E-06	1.16E+02	2.05E+01	8.64E+00	0.00E+00
NE	30-40 km	1.33E+02	2.71E-02	7.99E-06	1.07E+02	1.72E+01	8.45E+00	0.00E+00
ENE	30-40 km	6.45E+01	1.03E-02	3.05E-06	4.08E+01	1.59E+01	7.82E+00	0.00E+00
E	30-40 km	3.30E+01	6.03E-03	1.78E-06	2.38E+01	6.05E+00	3.14E+00	0.00E+00
ESE	30-40 km	1.99E+01	4.99E-03	1.47E-06	1.97E+01	2.04E-02	2.20E-01	0.00E+00
SE	30-40 km	6.35E+01	4.33E-03	1.28E-06	1.71E+01	4.50E+01	1.42E+00	4.41E-03
SSE	30-40 km	5.90E+01	3.97E-03	1.17E-06	1.57E+01	4.13E+01	2.07E+00	7.49E-03

Data Dimensions

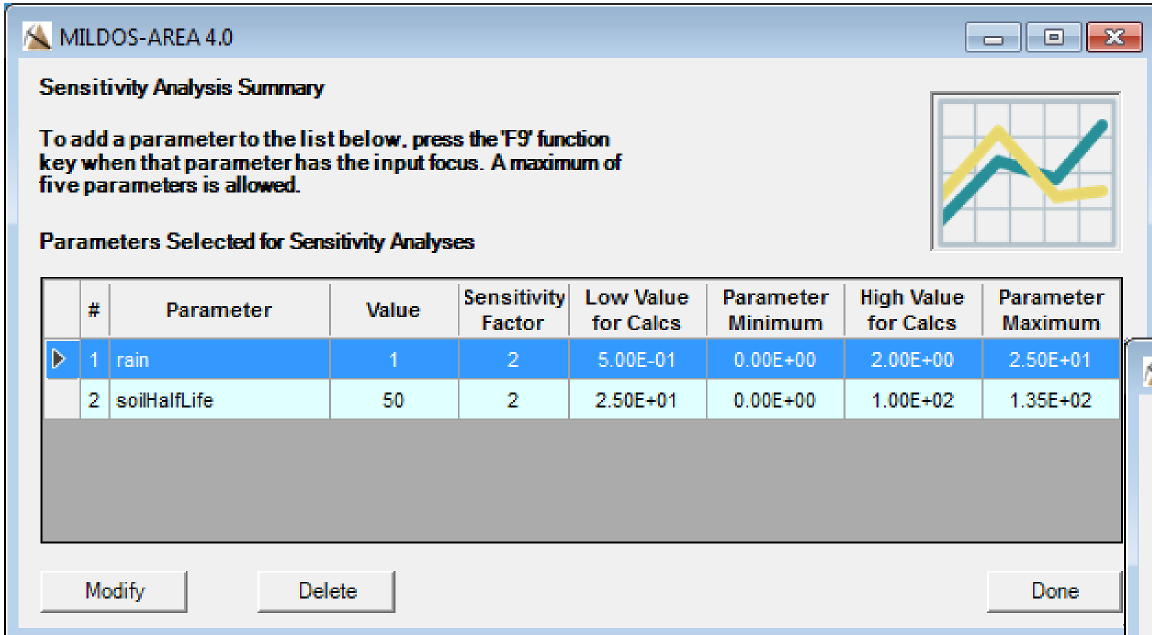
- **Receptor (individual or population)**
  - Location
  - Age Group
  - Organ (nuclide)
- **Source**
  - Nuclide
  - Particle size
  - Lung clearance class
- **Pathway**
  - External
    - Groundshine
    - Cloudshine
  - Inhalation
    - Particulate
    - Radon
  - Ingestion
    - Meat, milk, vegetables
- **Time**



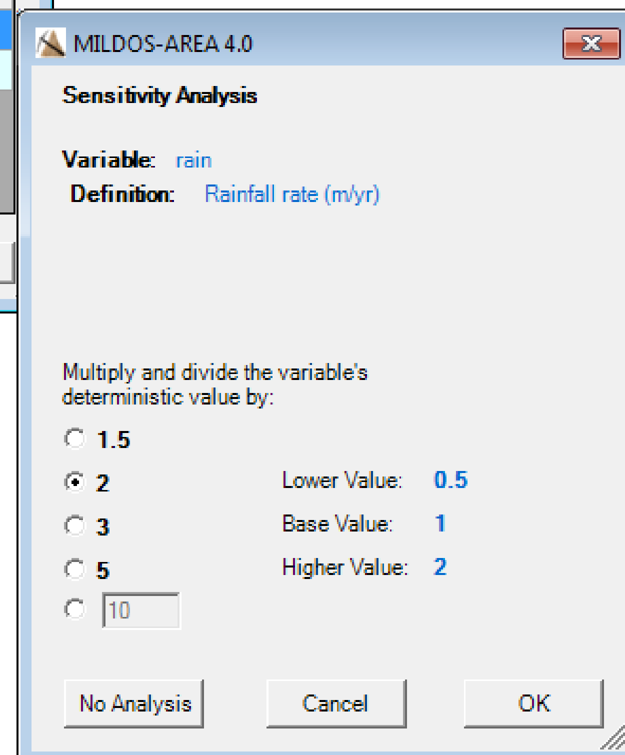


NAME	Air	Ground	VegAbove	Potato	VegBelow	PastureGrass	FeedGrain	Meat
100 m	3.07E-11	6.08E-05	5.15E-08	5.72E-09	5.72E-09	1.11E-07	5.15E-08	1.38E-09
500 m	1.46E-12	2.89E-06	2.45E-09	2.72E-10	2.72E-10	5.28E-09	2.45E-09	6.57E-11
1000 m	4.13E-13	8.18E-07	6.92E-10	7.69E-11	7.69E-11	1.49E-09	6.92E-10	1.86E-11
5000 m	2.54E-14	5.03E-08	4.25E-11	4.73E-12	4.73E-12	9.19E-11	4.25E-11	1.14E-12
10000 m	7.43E-15	1.47E-08	1.25E-11	1.38E-12	1.38E-12	2.69E-11	1.25E-11	3.35E-13
50000 m	2.84E-16	5.63E-10	4.77E-13	5.29E-14	5.29E-14	1.03E-12	4.77E-13	1.28E-14

Sensitivity Analysis



Press 'F9'



Press 'Alt + Z' or use menu bar item

Sensitivity Implementation

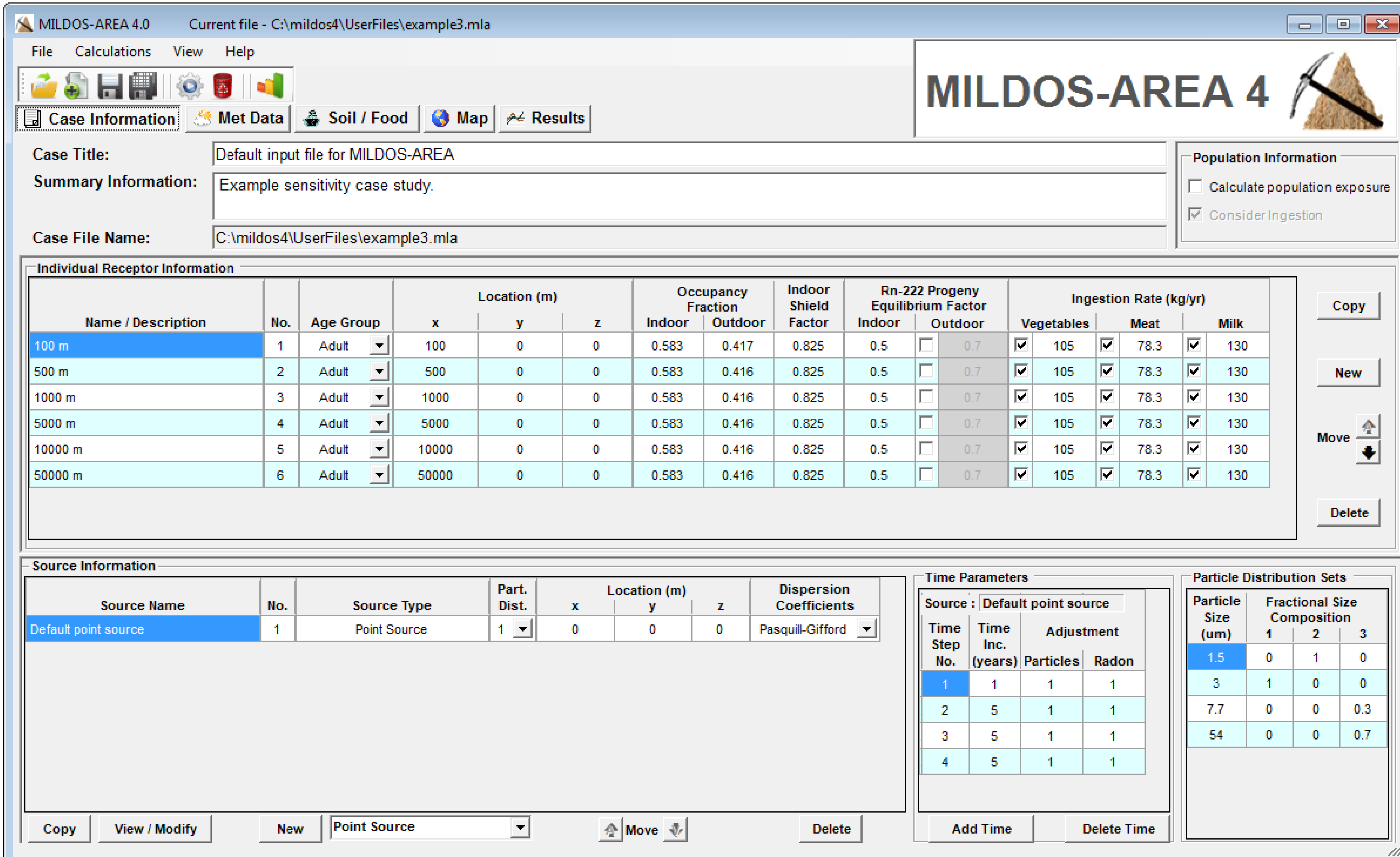
- **3 runs of MILDOS 4 for the selected parameter**
  - Base value of the parameter (specified input value for the parameter)
  - Lower value of the parameter determined by sensitivity factor
  - Higher value of the parameter determined by sensitivity factor

- **Values of other parameters are fixed and do not change**

- **If more than one parameter selected for sensitivity analysis**
  - First run is with all parameters at their base value
  - Then 2 runs for each selected parameter (low and high values) using the base values for the other selected parameters

- **Not all input parameters are available for sensitivity analysis**
  - For example, parameters such as x, y, z location positions and meteorological joint frequency distribution fractions cannot be selected for sensitivity analysis

Sensitivity Example



Sensitivity Results

- **Side-by-side comparison of end points under the Results/Sensitivity tabs**
- **End point value depends on all of the dimensions involved**
  - Can have a broad range of results for same end point over same and/or different sites, for example:
    - Rain fall rate – affects (increasing rate decreases) particulate nuclide air concentrations
      - Smaller or larger delta air concentrations will result depending on such other dimensions as distance and direction (i.e. wind speed and stability class combinations)
      - Which in turn affects other media concentrations and ultimately exposure
    - Soil half-life – affects (shorter life decreases) particulate ground concentrations
      - In this case, larger delta ground concentrations with time (larger delta between low and high input results at later time steps)
      - Which in turn affects resuspended air concentrations, produce concentrations and ultimately exposure

More Information

- **Web sites**

  mildos.evs.anl.gov
  www.usnrc-ramp.com

- **Contacts**

Argonne NATIONAL LABORATORY

Bruce Biwer
(630) 252-5761
bbiwer@anl.gov

Dave LePoire
(630) 252-5566
dlepoire@anl.gov

U.S.NRC United States Nuclear Regulatory Commission *Protecting People and the Environment*

Casper Sun – NRC project manager
(301) 415-1646
casper.sun@nrc.gov

James Webb – NRC technical monitor
(301) 415-6252
james.webb@nrc.gov

For technical support, send questions or comments to mildos@anl.gov