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Module 4b: Environmental Dose Assessment

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Lectures in Module 4b

- Lecture 4b.1: Environmental Releases and Exposures
- Lecture 4b.2: Guidance and Recommendations
- Lecture 4b.3: Environmental Dose Assessment Concepts
- Lecture 4b.4: Environmental Dose Assessment, Contaminated Air and Ground
- Lecture 4b.5: Environmental Dose Assessment, Contaminated Food

Lecture 4b.1

Objectives:

- Understand potential environmental release scenarios
- Understand potential exposure pathways
- Understand radionuclide source terms of concern
- Understand potential for acute and chronic exposures

Lecture 4b.2

Objectives:

- Review applicable IAEA guidance and recommendations
- Review applicable ICRP guidance and recommendations
- Review applicable United States guidance and recommendations
- Review acute and chronic risk

Lecture 4b.3

Objectives:

- Understand major radiological dose pathways from contaminated air and ground
- Understand factors that effect the radiation dose resulting from environmental contamination

Lecture 4b.3

Objectives:

- Review internal and external radiological assessment methods for contaminated air and ground
- To become familiar with the Turbo FRMAC © radiological assessment tool to assess the dose from contaminated air and ground (SNL, 2015a)

Lecture 4b.5

Objectives:

- Understand food products of concern
- Review radiological assessment methods for contaminated food
- To become familiar with the Turbo FRMAC © radiological assessment tool to assess the dose from food (SNL. 2015a)

Lecture 4b

Learning Outcomes:

- To recognize potential sources of environmental radiation exposures
- To recognize environmental dose assessment methods
- To estimate doses from radiologically contaminated air, ground and food using manual methods and the Turbo FRMAC © software tool (SNL, 2015a)

Lecture 4b.1

Environmental Releases

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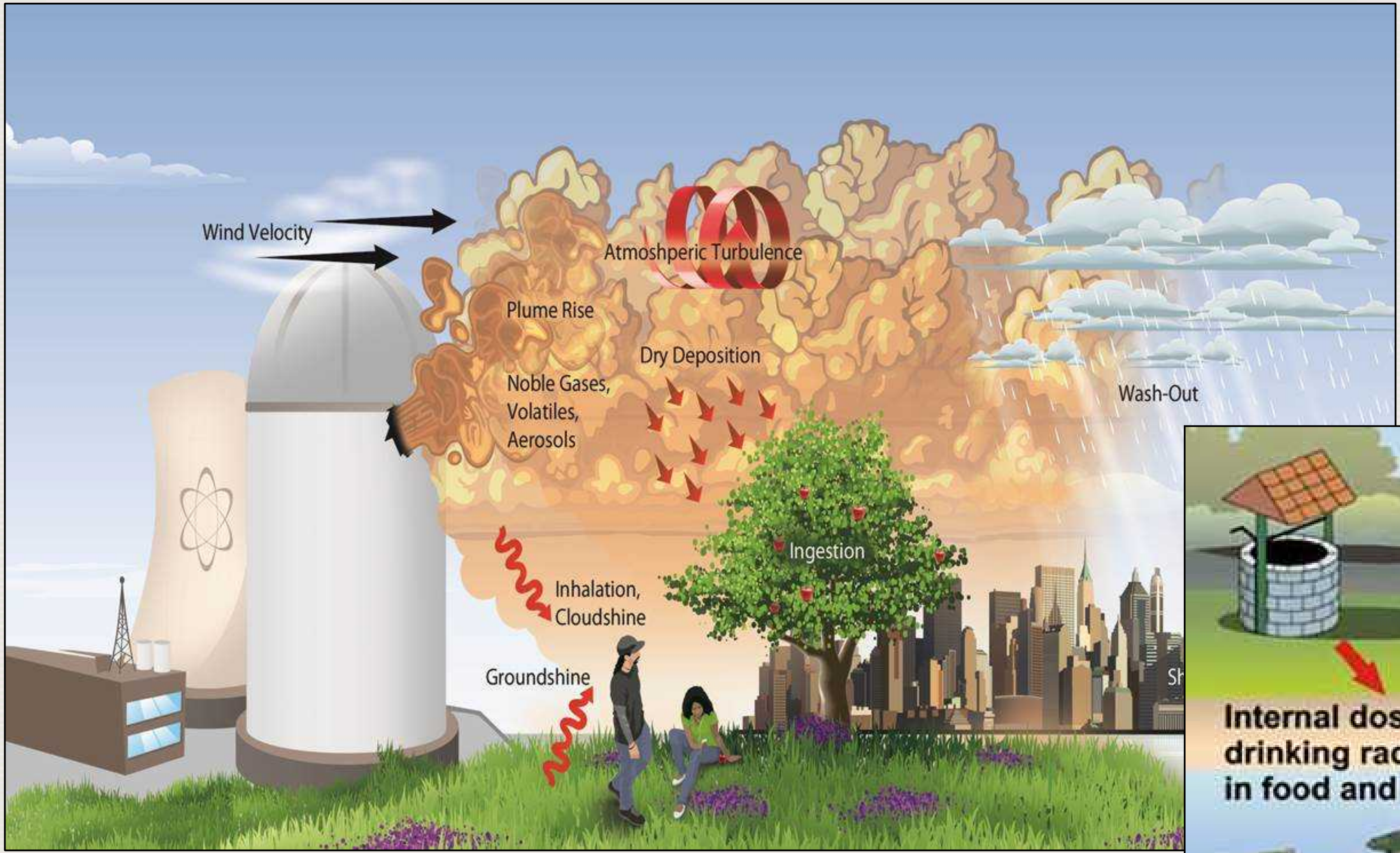
Environmental Release Mechanisms

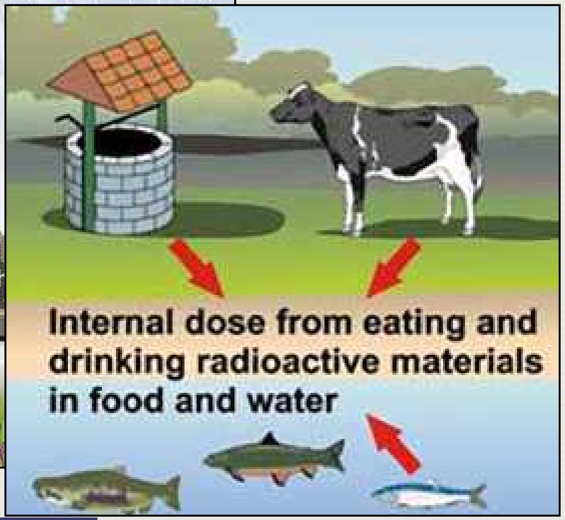
Potential radiological release mechanisms:

- Nuclear Power Plant (NPP) – accident or sabotage
- Radiological Dispersal Devices (RDD)
- Nuclear detonation (prompt and fallout)
- Transportation accidents involving nuclear weapons, legacy wastes, spent fuel, etc.
- Sprayer devices
- Fire, wind, etc.

Environmental Exposure Pathways

Example of exposure pathways





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Radionuclides of Concern

Medical and Industrial Devices

Radionuclides of concern include:

- Am-241,
- Cf-252,
- Cm-244,
- Co-60,
- Cs-137,
- Ir-192,
- Po-210,
- Pu-238,
- Pu-239,
- Ra-226,
- Sr-90, and
- Tc-99m

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Radionuclides of Concern

Nuclear Power Plant Source Term (example)

Radio-Nuclide	(MBq)
Am-241	1.42E+00
Ba-139	4.38E+07
Ba-140	4.44E+08
Ce-141	1.98E+07
Ce-143	1.63E+07
Ce-144	1.60E+07
Cm-242	4.94E+05
Cs-134	1.41E+08
Cs-136	5.70E+07
Cs-137	9.78E+07
Cs-138	1.36E+07
I-131	9.52E+08
I-132	1.25E+09
I-133	1.66E+09
I-134	8.25E+07
I-135	1.12E+09
Kr-83m	9.63E+07
Kr-85	3.51E+07
Kr-85m	4.89E+08
Kr-87	2.12E+08
Kr-88	9.14E+08
La-140	3.61E+07
La-141	7.90E+06
La-142	2.21E+06

Radio-Nuclide	(MBq)
Mo-99	1.45E+07
Nb-95	1.99E+07
Nb-95m	5.60E+03
Nb-97	7.87E+05
Nd-147	7.63E+06
Np-239	2.42E+08
Pm-147	1.21E+03
Pr-143	1.75E+07
Pr-144	1.60E+07
Pu-238	2.34E+00
Pu-239	4.26E+00
Pu-241	1.50E+06
Rb-86	2.03E+06
Rb-88	8.74E+08
Rh-103m	1.28E+07
Rh-105	8.49E+06
Ru-103	1.34E+07
Ru-105	4.48E+06
Ru-106	3.73E+06
Sb-127	5.46E+07
Sb-129	9.25E+07
Sr-89	2.27E+08
Sr-90	1.75E+07
Sr-91	1.96E+08

Radio-Nuclide	(MBq)
Sr-92	8.77E+07
Tc-99m	1.33E+07
Te-127	5.88E+07
Te-127m	9.44E+06
Te-129	3.73E+07
Te-129m	3.99E+07
Te-131	2.56E+07
Te-131m	1.14E+08
Te-132	8.65E+08
Xe-131m	5.86E+07
Xe-133	8.59E+09
Xe-133m	2.62E+08
Xe-135	3.13E+09
Xe-135m	5.94E+08
Xe-138	1.68E+06
Y-90	1.45E+06
Y-91	1.43E+07
Y-91m	8.04E+07
Y-92	3.86E+07
Y-93	7.83E+06
Zr-95	1.96E+07
Zr-97	1.51E+07

List does not include radioactive decay products

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Radionuclides of Concern

Radionuclides of potential significance at nuclear installations (IAEA Safety Series 81, 1986)

TABLE IV. RADIONUCLIDES WHICH MAY BE OF POTENTIAL SIGNIFICANCE FOR ACCIDENTS AT NUCLEAR INSTALLATIONS

Of significance for reactor accidents	Of significance for accidents at fuel reprocessing plants
Kr-85m	Sr-89
Kr-87	Sr-90
Kr-88	I-131
Sr-89	Ru-103
Sr-90	Ru-106
Zr-95	Cs-134
Ru-103	Cs-137
Ru-106	Ce-144
Te-132	Pu-238
I-131	Pu-239
I-132	Pu-240
I-133	Pu-241
I-135	Am-241
Xe-133	Cm-242
Xe-135	Cm-244
Cs-134	
Cs-137	
Ba-140	
La-140	
Ce-144	
Np-239	

Note: Reference should be made to Refs [36–39] for a more comprehensive summary of nuclides of potential radiological significance.

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Radionuclides of Concern

Nuclear Weapon Fallout Source Terms

- Includes more radionuclides than a NPP source term
- Includes many radionuclides with very short half-lives
- Includes nuclear fission products and neutron activation products

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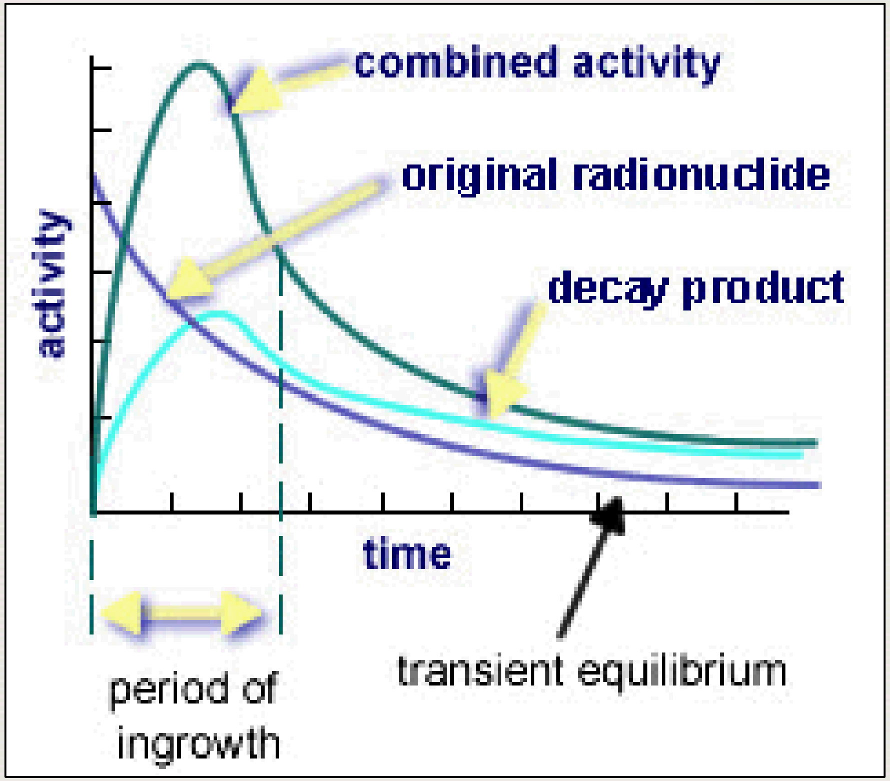
Potential for Acute and Chronic Exposures

- Different radionuclides deliver dose at different rates
- Dose rate delivery is largely determined by:
  - Amount (Radioactivity)
  - Concentration (Bq/m^2)
  - Half-life of parent radionuclides
  - Half-life of radioactive decay products
  - Types of radiation emitted (alpha, beta, gamma)
  - Energy of radiation emitted



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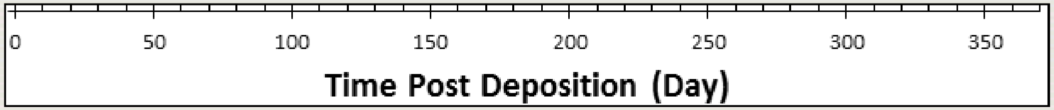
Potential for Acute and Chronic Exposures

- Exposure scenario:
  - Receptor is standing outside (unshielded) on contaminated ground
  - Receptor stays at the same location for a 1-year long period starting immediately after ground deposition
- At what rate will the receptor accumulate radiation dose from NPP, nuclear fallout and Cs-137 sources?



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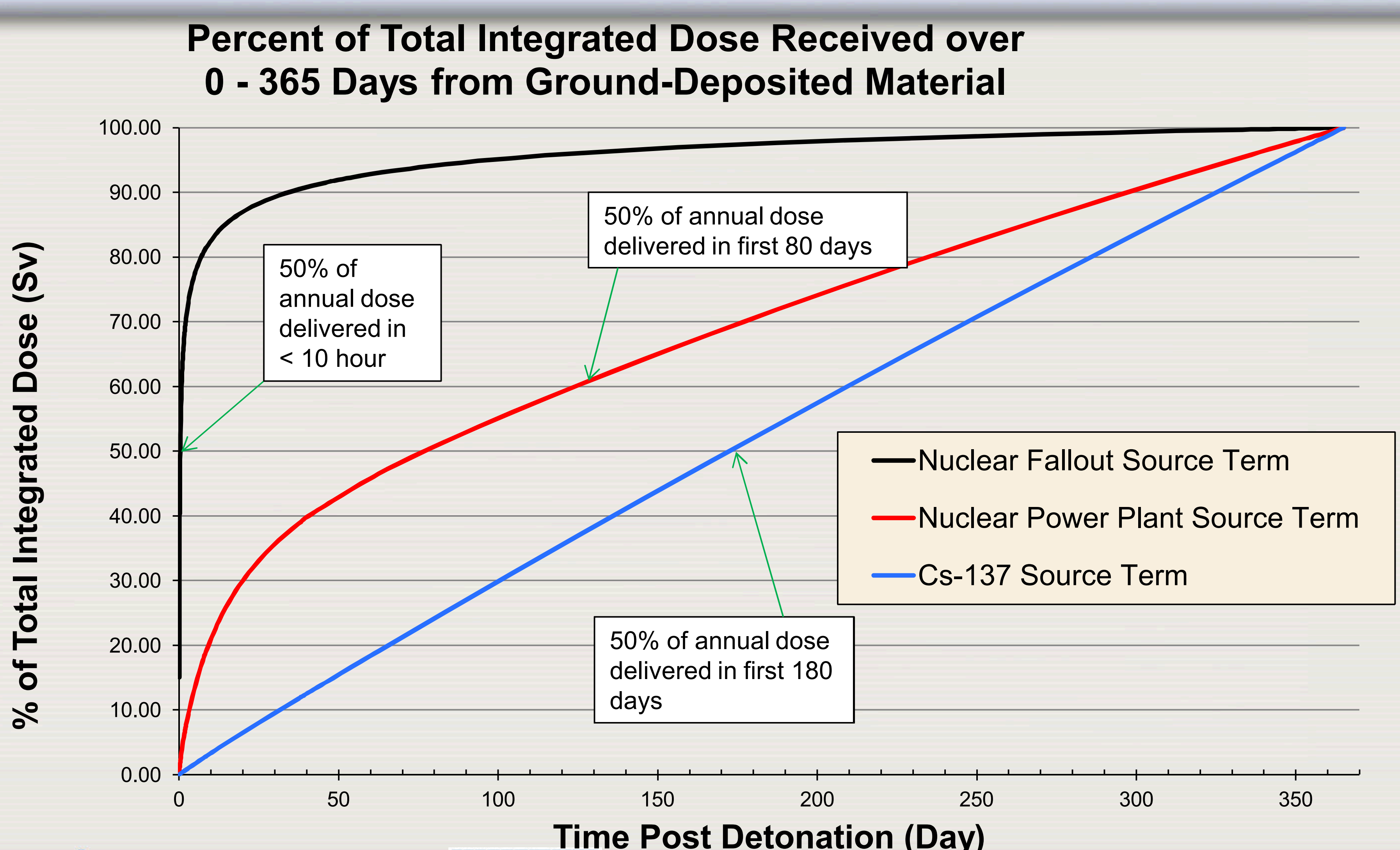
Potential for Acute and Chronic Exposures

All radionuclide source terms **ARE NOT** created equal!



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Potential for Acute and Chronic Exposures

- Many environmental releases do not have the potential to result in acute (deterministic) exposures.
- Medical sources and industrial sources are typically relatively long-lived and are not likely to result in acute exposures unless large activities are dispersed into the environment at high concentrations.
- Radiopharmaceuticals usually have short-lives and it is difficult to get enough of them together and disperse them before they undergo significant radioactive decay. Therefore, they are not likely to be a source of acute exposures.

Potential for Acute and Chronic Exposures

- NPP source terms include many short-lived radionuclides and have the potential for acute exposures if they are dispersed into the environment at high concentrations.
- Nuclear fallout includes many short-lived radionuclides and may be dispersed into the environment at high concentrations and are a potential source of acute exposures.

Lecture 4b.1

- Summary of Key Points:
  - Environmental assessments may involve numerous radionuclides
  - Environmental assessments must consider inhalation, external exposure, and ingestion pathways
  - NPP accidents, nuclear fuel cycle, RDDs, nuclear weapons, and accidents may releases radionuclides to the environment
  - The rate at which environmental contaminants deliver dose vary widely and are radionuclide specific
  - Nuclear fallout certainly has the potential to produce deterministic (acute) effects

Lecture 4b.2

Regulatory Guidance and Recommendations

IAEA Safety Standards, Philosophy

IAEA's role in protecting the public and the environment (IAEA Pub. 1578, 2014):

- The IAEA's Statute authorizes the Agency to "establish or adopt… standards of safety for protection of health and minimization of danger to life and property."
- The IAEA safety standards reflect an international consensus on what constitutes a high level of safety for protecting people and the environment from harmful effects of ionizing radiation.
- The Safety Guides present international good practices, and increasingly they reflect best practices, to help users striving to achieve high levels of safety. The recommendations provided in Safety Guides are expressed as 'should' statements.

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IAEA Safety Standards

IAEA recommendations and guidance for protecting people and the environment, include:

- *Preparedness and Response for a Nuclear or Radiological Emergency*, IAEA Safety Standards Series No. GS-R-7 (IAEA 2015)
- *Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards*, General Safety requirements Part 3, No. GSR Part 3 (IAEA Pub. 1578, 2014)
- *Criteria for Use in Preparedness and response for a Nuclear or Radiological Emergency*, IAEA General Safety Guide No. GSG-2 (IAEA Pub. 1467, 2011)
- *Generic procedures for assessment and response during a radiological* emergency, IAEA-TECDOC-1162 (IAEA, 2000)

Generic Dose Levels - Deterministic

TABLE IV.1. Generic Criteria for Acute Doses Received within a Short Period … to Avoid or to Minimize Severe Deterministic Effects (IAEA, Pub. 1578, 2014)

Acute external exposure (<10 h)		If the dose is projected:
$AD_{red\ marrow}$ [a]	1 Gy	— Take precautionary urgent protective actions immediately (even under difficult conditions) to keep doses below the generic criteria
AD_{fetus}	0.1 Gy	— Provide public information and warnings
AD_{tissue} [b]	25 Gy at 0.5 cm	— Carry out urgent decontamination
AD_{skin} [c]	10 Gy to 100 cm^2	
Acute internal exposure due to an intake (Δ = 30 d) [d]		
$AD(\Delta)_{red\ marrow}$	0.2 Gy for radionuclides with atomic number $Z \geq 90$ [e] 2 Gy for radionuclides with an atomic number $Z \leq 89$ [e]	If the dose has been received: — Perform immediate medical examination, consultation and indicated medical treatment
$AD(\Delta)_{thyroid}$	2 Gy	— Carry out contamination control
$AD(\Delta)_{lung}$ [g]	30 Gy	— Carry out immediate decorporation[f] (if applicable)
$AD(\Delta)_{colon}$	20 Gy	— Carry out registration for longer term medical follow-up
$AD(\Delta')_{fetus}$ [h]	0.1 Gy	— Provide comprehensive psychological counselling

IAEA Generic Dose Levels - Stochastic

Table A-1. Generic Criteria for Protective Actions and Other Response Actions in Emergency Exposure Situations to Reduce the Risk of Stochastic Effects (IAEA Pub. 1578, 2014)

Generic criteria		Examples of protective actions and other response actions
Projected dose that exceeds the following generic criteria: Take urgent protective actions and other response actions		
$H_{thyroid}$	50 mSv in the first 7 days	Iodine thyroid blocking
E	100 mSv in the first 7 days	Sheltering; evacuation; decontamination; restrictions on food, milk and drinking water; contamination control; reassurance of the public
H_{fetus}	100 mSv in the first 7 days	

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IAEA Generic Dose Levels - Stochastic

Table A-1. (continued)

Projected dose that exceeds the following generic criteria: Take early protective actions and other response actions		
E	100 mSv in the first year	Temporary relocation; decontamination; restrictions on food, milk and drinking water; reassurance of the public
H_{fetus}	100 mSv for the full period of in utero development	
Dose that has been received and that exceeds the following generic criteria: Take longer term medical actions to detect and to effectively treat radiation induced health effects		
E	100 mSv in a month	Health screening based on equivalent doses to specific radiosensitive organs (as a basis for medical follow-up); counselling
H_{fetus}	100 mSv for the full period of in utero development	Counselling to allow informed decisions to be made in individual circumstances

Radiation Protection Philosophy

- Regulatory philosophy to protect the public
  - Avoid severe *deterministic* effects,
  - Limit *stochastic* effects
  - Limit adverse effects on the environment and property
  - Protective actions should achieve more good than harm,
  - Duration of an *intervention* should be optimized so that it will produce a maximum net benefit, considering the radiological detriment and the social and economical costs

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Acceptable Risk

- Do not receive a dose to any organ approaching that resulting in severe deterministic effects.
  - Table 2 (IAEA 2011) list the thresholds for the onset of severe deterministic effects.
- Do not receive a dose above which the risk of health effects (e.g. cancers) is sufficiently high to justify taking protective actions during an emergency
  - generic criterion is 100 mSv per annum.
  - protective actions are not always justified below 100 mSv per annum and will be taken (if at all) on the basis of justified criteria developed, with interested parties, after careful consideration of the conditions, including the impact of any protective action.

OILs and EALs

- Operational Intervention Levels (OILs) and Emergency Action Levels (EALs),are measureable or observable criteria that can be used as a surrogate for the generic dose criteria
- OILs and EALs are operational criteria can be used immediately and directly to determine the need for appropriate protective actions and other response actions.
- EALs are predetermined, observable operational criteria used to detect, recognize and determine the emergency class of an event at facilities

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OIL1 (IAEA Pub. 1467, 2011)

- OIL1 is a measured value of ground contamination calling for:
  - Urgent protective actions (e.g. evacuation) to keep the dose to any person living in a contaminated area below the generic criteria for urgent protective actions provided in Table 3
  - Medical actions, as required, because the dose received by evacuees may be above the generic criteria for medical actions provided in Table 3

OIL2 and OIL3 (IAEA Pub. 1467, 2011)

- OIL2 is a measured value of ground contamination calling for early protective actions to keep the dose for one year to any person living in the area below the generic criteria for taking actions to reasonably reduce the risk of stochastic effects provided in Table 3.
- OIL3 is a measured value of ground contamination calling for immediate restrictions on the consumption of leaf vegetables, milk from animals grazing in the area and rainwater collected for drinking to keep the dose to any person below the generic criteria for taking the urgent protective actions provided in Table 3.

OIL4, 5 and 6 (IAEA Pub. 1467, 2011)

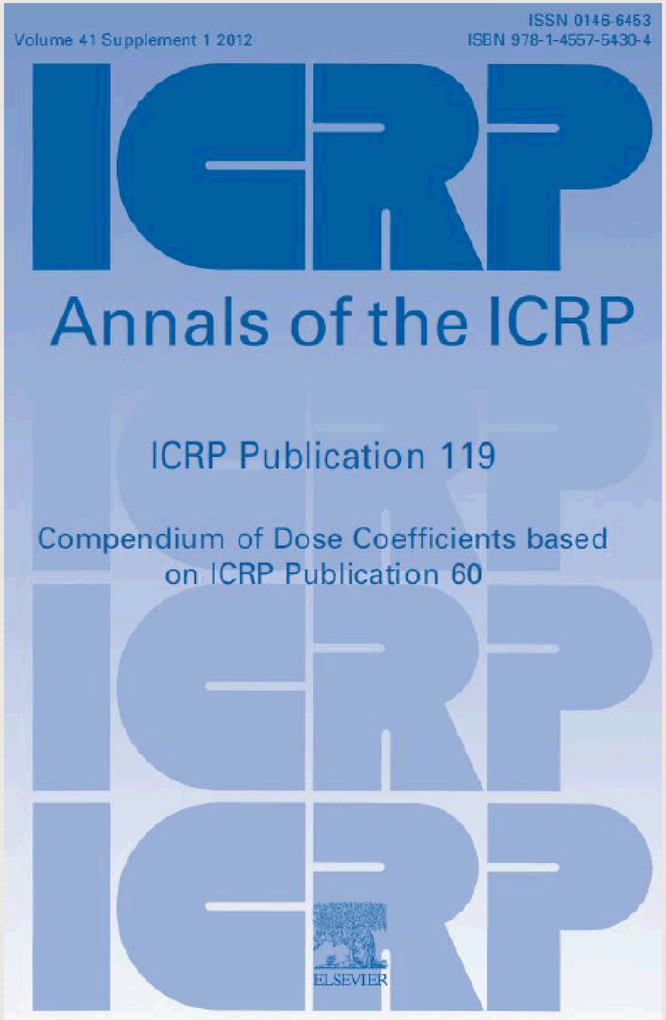
- OIL4 is a measured value of skin contamination calling for performing decontamination or providing instructions for self-decontamination and for limiting inadvertent ingestion
- OIL5 and OIL6 are measured values of concentrations in food, milk or water that warrant the consideration of restrictions on consumption so as to keep the effective dose to any person **below 10 mSv per annum**.

ICRP Radiological Protection Recommendations

- Radiation protection recommendations, biokinetic models and DCs are periodically updated
- We are transitioning to updated recommendations
- Current ICRP recommendations:
  - ICRP 38, *Radionuclide Transformations, Energy and intensity of Emissions*, defines the radiological decay data (e.g., half-life, decay constant, decay chain)
  - ICRP 60, *1990 Recommendations of the ICRP*, defines dosimetric quantities, tissue and radiation weighting factors, radiation protection framework (e.g., dose limits), acute and deterministic effects, and detriment estimators.
  - ICRP 66, *Human Respiratory Tract Model for Radiological Protection*, defines physiological parameters, deposition, clearance
  - ICRP 68, *Dose Coefficients for Intakes of Radionuclides by Workers*

ICRP Radiological Protection Recommendations

- Current ICRP recommendations (continued):
  - ICRP 67, 69, and 72: ingestion DCs
  - ICRP 70, *Basic Anatomical and Physiological Data for use in Radiological Protection: The Skeleton*
  - ICRP 71,72:
  - ICRP 74, Conversion Coefficients for use in Radiological Protection against External Radiation: absorbed dose, radiation weighting factors,
  - ICRP 119, Compendium of Dose Coefficients based on ICRP Publication 60



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ICRP Radiological Protection Recommendations

- New ICRP recommendations:
  - ICRP Pub. 100, *Human Alimentary Tract Model for Radiological Protection*, Elsevier
  - ICRP Pub. 103, *The 2007 Recommendations of the International Commission on Radiological Protection*, replace ICRP 60
  - ICRP Pub. 107, *Nuclear Decay Data for Dosimetric Calculations*
  - ICRP Pub. 110, *Adult Reference Computational Phantoms*
  - ICRP Pub. 116, *Conversion Coefficients for Radiological Protection Quantities for External Radiation Exposures*
- It is expected that the updated external dose coefficients will be available in the U.S. in 2016
- Updated inhalation and ingestion DCs may not be available for 3 – 5 years

ICRP Radiological Protection Recommendations

- New ICRP recommendations (continued):
- Main differences between the ICRP 38, 60 and 50-80 dosimetry models, and the ICRP 103, 107 series dosimetry models include:
  - Updated biokinetic models
  - Different tissue weighting factors,
  - Different radiation weighting factors
  - Updating radiation detriment estimators
  - Applying system of justification and optimization to radiation protection
  - Updated radiological decay for some radionuclides
- **Can we mix-and-match DCs based on ICRP 60 and 103 recommendations while we wait for complete set of ICRP 103-based DCs?**

IAEA Radiation Exposure Risk Estimates

- Radiation risk estimators are developed from acute (deterministic) exposure data (e.g., Hiroshima, Nagasaki)
- Stochastic radiation risk estimators (ICRP Pub. 103, 2007)
  - Linear No Threshold (LNT) risk estimators assume a linear dose response and that there is no dose threshold below which there is no risk
  - Combined detriment to whole population due to excess cancer (fatal and non-fatal) and heritable effects is $\mathbf{5.7 \times 10^{-2}\ Sv^{-1}}$
  - Detriment to whole population due to excess cancer (fatal and non-fatal) is $\mathbf{5.5 \times 10^{-2}\ Sv^{-1}}$
  - Detriment to whole population for heritable effects is $\mathbf{2 \times 10^{-3}\ Sv^{-1}}$
- Risk estimators are typically applied to both acute (deterministic) and chronic (stochastic) exposures
- Risk estimators *may* overestimate the risk from low-level, chronic exposures

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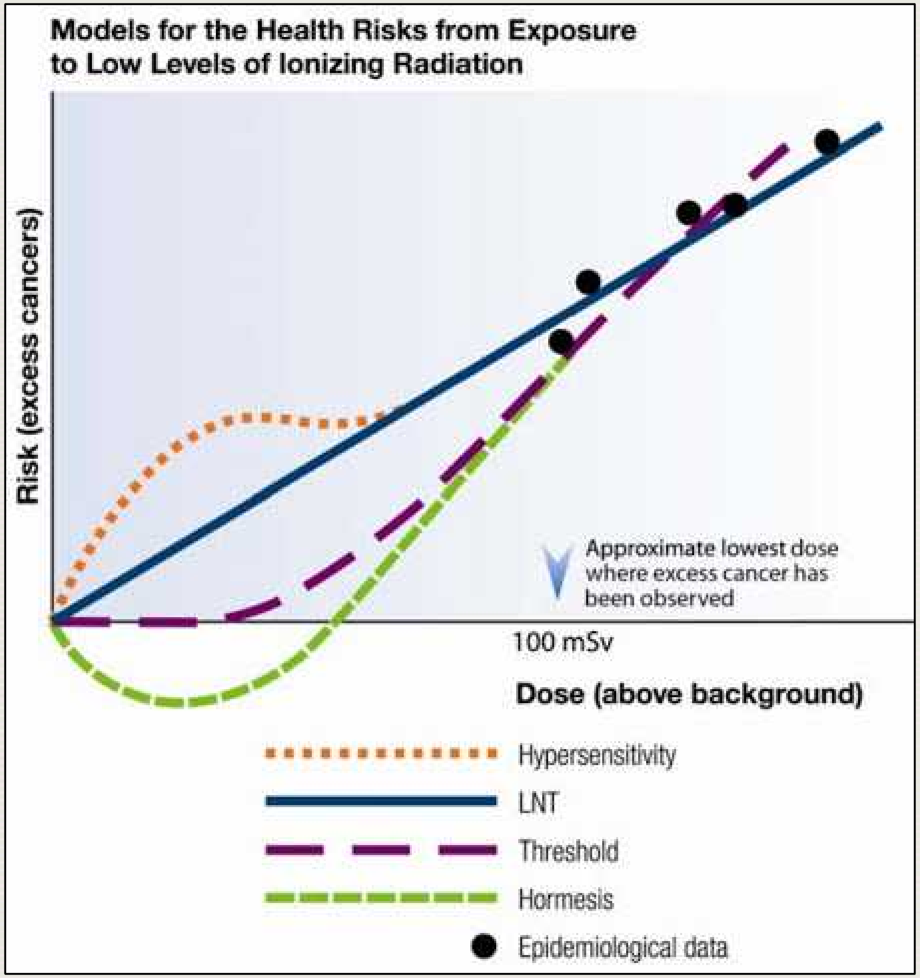
Radiation Exposure Risk Estimates

- Radiation protection standards are based on the Linear No Threshold theory (LNL)
  - Assumes that long-term biological damage (e.g., cancer) is directly proportional to dose
  - Assumes there is no dose threshold below which there is no risk
- Are risk estimators based on acute exposures appropriate for chronic exposures?



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Radiation Exposure Risk Estimates

- Risk of drinking water based on LNT theory
- 2007 Drinking water contest to win a video game
  - 18 contestants drank up to 6 L of water over 3 hours
  - 1 of the contestant later died of hyponatremia
- Assuming the LNT model, how much water could one drink to limit their risk of dying to 1 in 10,000?
  - Assume all 18 contestants drank 6 L of water

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Radiation Exposure Risk Estimates

$$\frac{\text{Death}}{\text{ml}_{water}} = \frac{1\ \text{death} / 18\ \text{contestants}}{\left(6\ \text{L}/\text{contestant} \times 1{,}000\ \text{ml}/\text{L}\right)} = \frac{9.29\text{E-06 death}}{\text{ml}_{water}}$$

If the LNT risk of drinking water (acute exposure) is 9.29E-06/ml, how much water can be drunk in 3 hours to limit the risk of death to 1 in 10,000 (1.0E-04)?

$$\text{ml}_{water} = \frac{1.0\text{E-04}}{9.29\text{E-06 death} / \text{ml}_{water}} = 10.8\ \text{ml}_{water}$$

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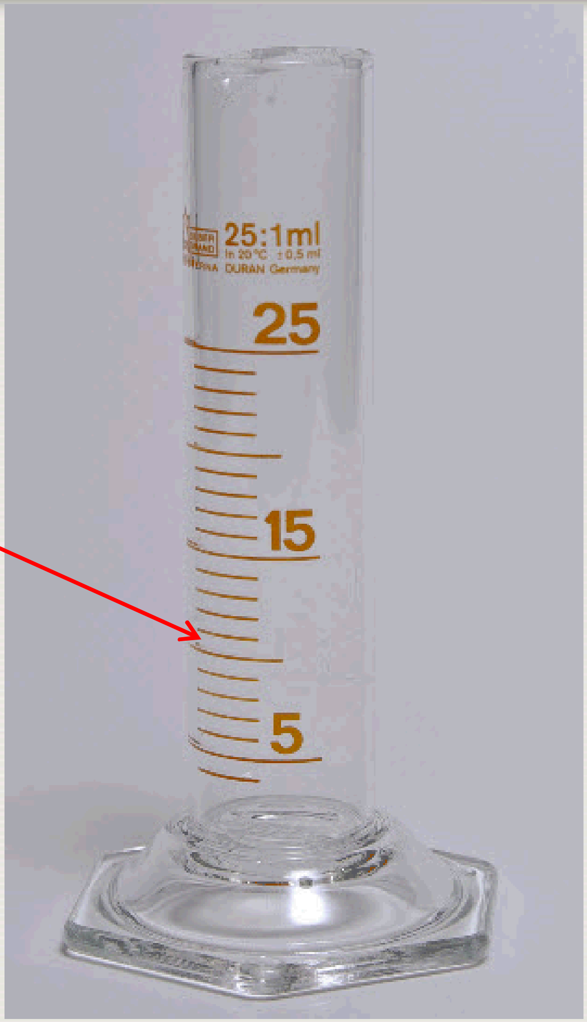
Radiation Exposure Risk Estimates

- Therefore, based on this analysis, the safe drinking water limit should be established at 10.8 ml per 3 hours to limit the risk of death to 1 in 10,000
- **Is it reasonable to use risk estimators based on acute exposures to estimate the risk from low-level chronic exposures?**



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United States Guidance and References

- *Protective Action Guides and Planning Guidance for Radiological Incidents*, Draft for Interim Use and public comment, U.S. Environmental Protection Agency, Washington, DC, March 2013.
- *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*, EPA 400-R-92-001, U.S. Environmental Protection Agency, Washington, DC, 1992.
- *Accidental Radioactive Contamination of Human Foods and Animal Feeds: Recommendations for State and Local Agencies*, U.S. Food and Drug Administration, Washington, DC, August 13, 1998.
- *Potassium Iodide as a Thyroid Blocking Agent in Radiation Emergencies*, U.S. Food and Drug Administration, Washington, DC, December 2001.

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Lecture 4b.2

- Summary of Key Points:
  - IAEA guidance provides operational intervention levels (OILs) and generic dose criteria for environmental assessments
  - IAEA guidance provides generic assessment methods for environmental assessments
  - OILs and EALs are operational criteria can be used immediately and directly to determine the need for appropriate protective actions and other response actions.
  - ICRP provides radiation protection recommendations, biokinetic models and dose coefficients
  - Radiation risk estimators are conservative when applied to stochastic (chronic) exposures, assume that biological damage (e.g., cancer) is directly proportional to dose, and assume there is no dose threshold below which there is no risk

Lecture 4b.3

Environmental Dose Assessment Concepts

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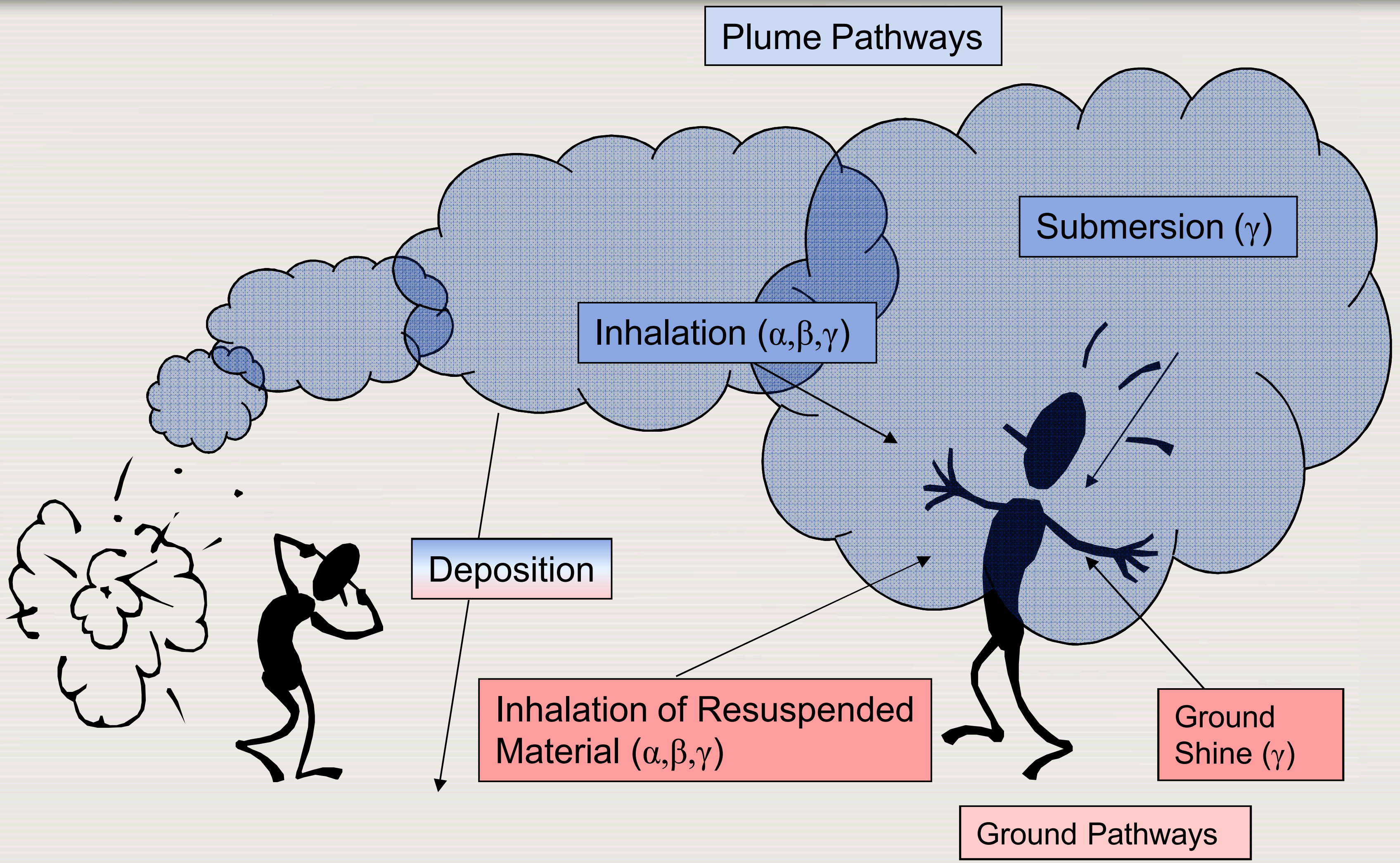
Major Dose Pathways From an Environmental Release



Environmental Dose Assessment Concepts

Factors that effect environmental dose, include:

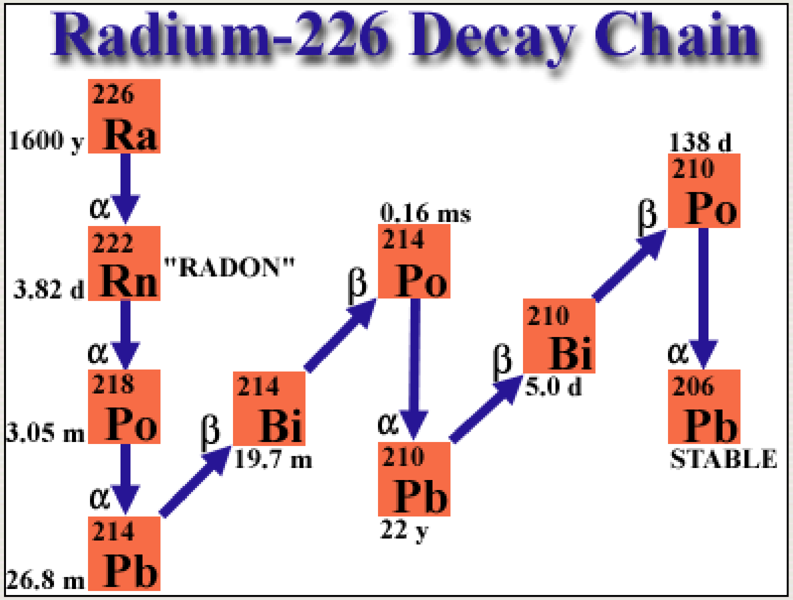
- Radionuclide source terms
- Radioactive decay and in-growth
- Dose Coefficients (Parent-Daughter Relationship)
- Dose Coefficients vary by age groups
- Dose calculation depends on the time period (time phase) that the receptor was exposed
- Weathering of radionuclides into the environments
- Resuspension of radionuclides in the environment
- Ground roughness
- Deposition Velocity
- Breathing rates

Environmental Dose Assessment Concepts: External and Internal Dose Coefficients

- Dose coefficients are provided for multiple age groups:
  - Adult,
  - 15 year old,
  - 10 year old,
  - 5 year old,
  - 1 year old, and
  - infant (3 months old)
- Dose coefficients are provided for multiple organs
  - ~20 Organ-specific DCs
  - 1 DC for Remainder tissues
  - 1 DC for Effective Dose
- DCs include the organ-specific tissue weighting factors

Environmental Dose Assessment Concepts: External Dose Coefficients

- External dose coefficients are **specific to one radionuclide and do not include** the dose from decay products
  - For example, Ra-226 external dose coefficient **does not** include the external dose from Rn-222 to Po-210
  - If decay chain radionuclides are present, the external dose from decay products must be included to estimate the total dose



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Environmental Dose Assessment Concepts: Internal Dose Coefficients

- Internal dose coefficients (i.e., inhalation and ingestion) **do** include the dose from decay products that grow in
  - For example, Ra-226 inhalation DC **does** include the dose from Rn-222 to Po-210 that are formed by the transformation of inhaled Ra-226
- Internal dose coefficients are not provided for short-lived radionuclides (e.g., < 10 minutes)
- Internal dose coefficient decay chain truncation:
  - Decay chains are truncated after the last potentially significant decay chain member
  - Decay chains typically truncated when the cumulative energies for alpha, electron, and photon radiation over a 100-year period are changed less than 1% by the addition of subsequent chain members

Environmental Dose Assessment Concepts: Internal Dose Coefficients

- Internal Dose Coefficient basic facts:
  - Decay products are generally assigned the same biokinetics as the parent radionuclide
- Exceptions where decay products are assigned different biokinetics than the parent radionuclide include (ICRP 71):
  - Radioiodine formed by transformation of tellurium
  - Radioisotopes of thallium, astatine, and francium formed in thorium and uranium decay chains.
  - Radon produced in soft tissues or bone surfaces

Environmental Dose Assessment Concepts: Internal Dose Coefficients

- Internal (inhalation, ingestion) dose coefficient basic facts:
  - Commitment periods for **stochastic** dose estimates vary with age at intake
    - 50 years for adults and
    - 70 years for children
  - Commitment period for **deterministic** dose estimates is 30 days

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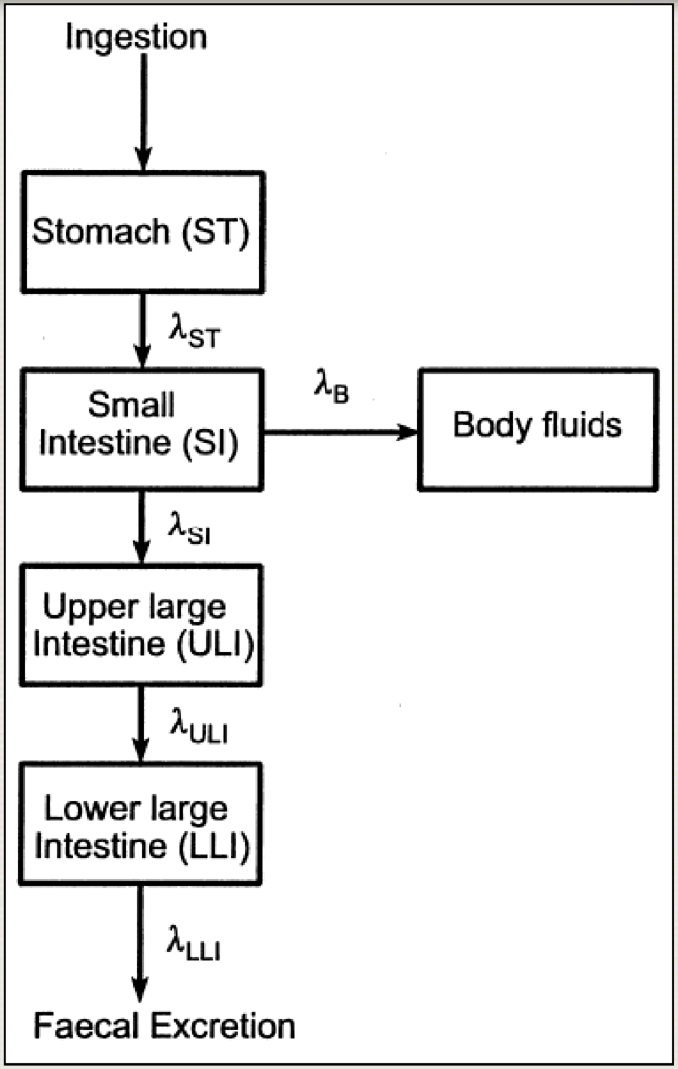
Environmental Dose Assessment Concepts: Ingestion Dose Coefficients

- ICRP Publication 30 specifies the biokinetic model of the gastrointestinal (GI) tract (1979)

  Note: ICRP Publication 100 (2005) specifies an updated human alimentary tract model, but a set of ingestion dose coefficients has not yet been developed using the updated model



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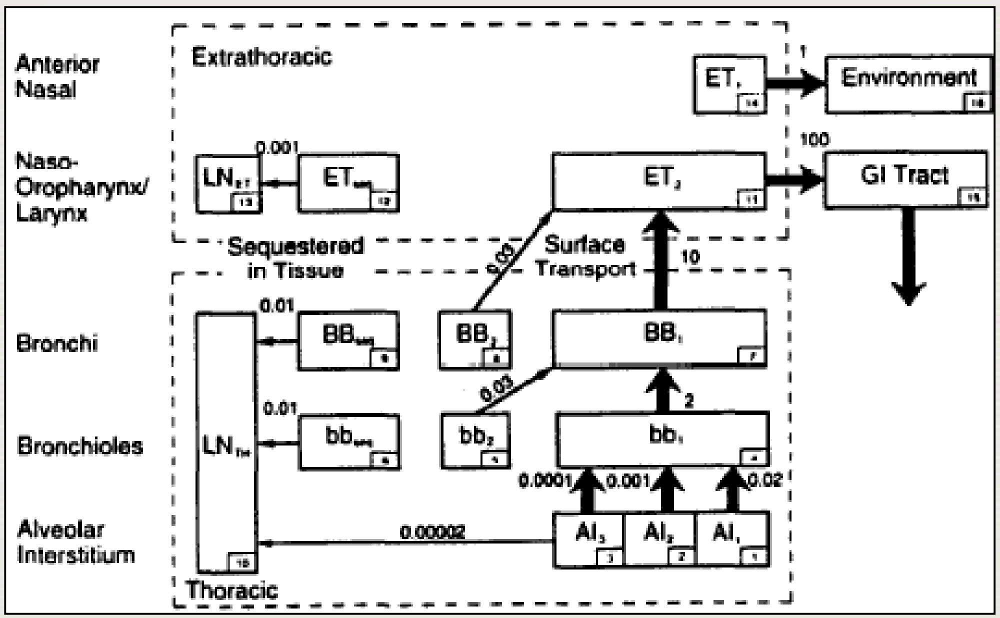
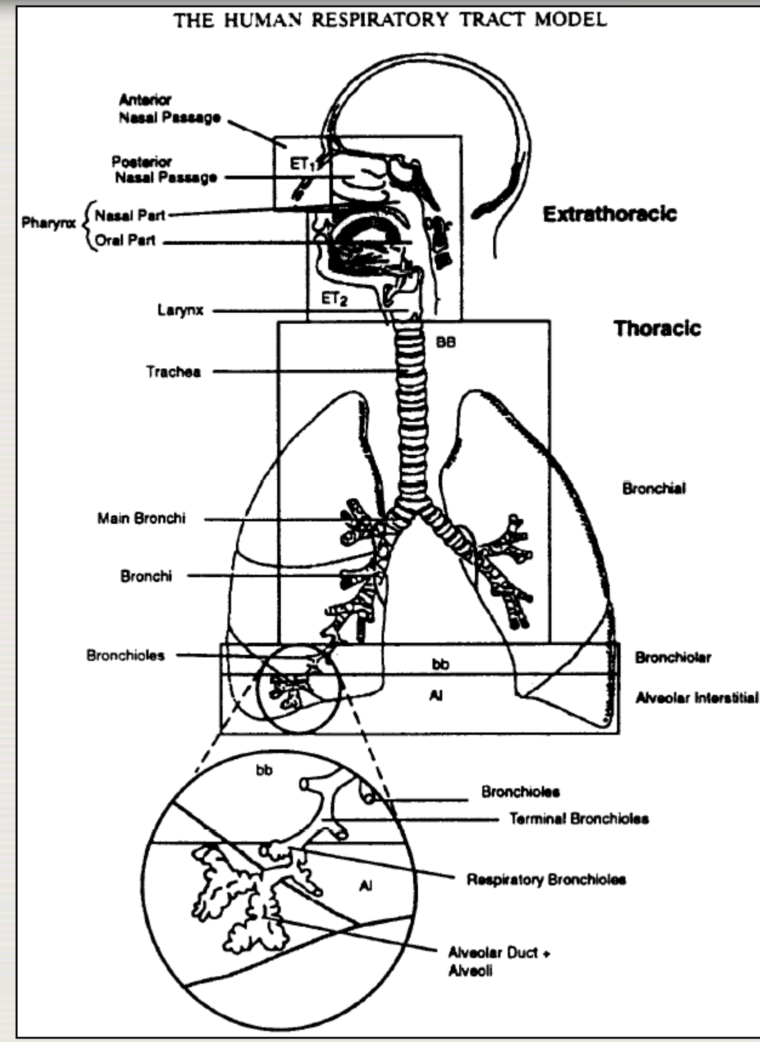
Environmental Dose Assessment Concepts: Inhalation Dose Coefficients

- ICRP Publication 66 specifies the biokinetic model of the respiratory tract (IAEA 1994)





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Environmental Dose Assessment Concepts: Inhalation Dose Coefficients

- Inhalation DCs are available for different chemical forms of radionuclide **aerosols** that have different lung clearance types (absorption rates) into the blood from the respiratory tract

Type **F**	**100% absorbed with a half-time of 10 min.** There is rapid absorption of almost all material deposited in BB, bb, and AI, and 50% of material deposited in ET2 is cleared to the GI tract by particle transport.
Type **M**	**10% absorbed with a half-time of 10 min and 90% with a half-time of 140 d.** There is rapid absorption of about 10% of the deposit in BB and bb; and 5% of material deposited in ET2. About 70% of the deposit in AI eventually reaches body fluids.
Type **S**	**0.1% absorbed with a half-time of 10 min and 99.9% with a half-time of 7000 d.** There is little absorption from ET, BB, or bb, and about 10% of the deposit in AI eventually reaches body fluids.

Environmental Dose Assessment Concepts: Inhalation Dose Coefficients

- Type V (very fast), instantaneously absorbed into blood (only applies to certain vapours and gases)
- **NOTE: Inhalation DCs may vary greatly for different lung clearance types!**

Pu-239 Lung Clearance Type	Adult, Committed Effective Inhalation DC (mSv/Bq)
Fast	0.119
Medium	0.0502
Slow	0.0160

Environmental Dose Assessment Concepts: Inhalation Dose Coefficients

ICRP 68 provides lung clearance type recommendations for various chemical forms (ICRP 1994):

ANNEXE F. COMPOUNDS, LUNG CLEARANCE TYPES AND f_1 VALUES USED FOR THE CALCULATION OF INHALATION DOSE COEFFICIENTS FOR WORKERS

Table F.1.

Element	Type	f_1	Compounds
Beryllium	M	0.005	Unspecified compounds
	S	0.005	Oxides, halides and nitrates
Fluorine	F	1.000	Determined by combining cation
	M	1.000	Determined by combining cation
	S	1.000	Determined by combining cation
Sodium	F	1.000	All compounds
Magnesium	F	0.500	Unspecified compounds
	M	0.500	Oxides, hydroxides, carbides, halides and nitrates
Aluminium	F	0.010	Unspecified compounds
	M	0.010	Oxides, hydroxides, carbides, halides, nitrates and metallic

Environmental Dose Assessment Concepts: Inhalation Dose Coefficients

- ICRP 71 recommendations (ICRP 1996):
  - Use lung clearance Type M when material-specific lung clearance type information is not available and the material is not one of the 31 elements considered in ICRP 72
  - In the absence of more specific information on absorption characteristics, use Type M as a default for environmental exposure of members of the public to radioisotopes in particulate form.
- ICRP 72 recommendations (ICRP 1996):
  - Use material-specific lung clearance types when data is available
  - Use recommended lung clearance types for the 31 elements specified in ICRP 72 if material-specific lung clearance types data is not available

Environmental Dose Assessment Concepts: Inhalation Dose Coefficients

ICRP 72, Table 2 (ICRP 1996)

Table 2. Biokinetic data and models used to calculate committed effective dose per unit intake via inhalation for exposure to particulate aerosols or to gases and vapours for members of the public

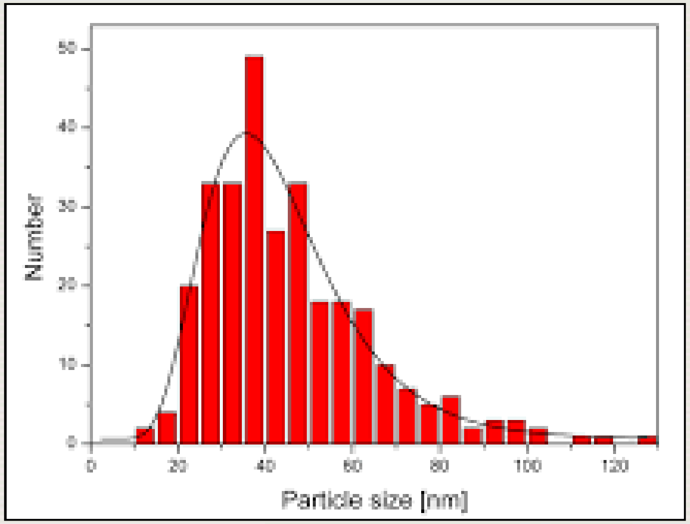
Element	Lung absorption Type(s)[a]	Classes for gases/vapours[c]	ICRP for details of biokinetic model[d] and absorption Type(s)
Hydrogen	F, M[b], S	SR-1, SR-2[d]	*56, 67* and *71*
Beryllium	M, S		*30, Part 3*
Carbon	F, M[b], S	SR-1, SR-2[e]	*56, 67* and *71*
Fluorine	F, M, S		*30, Part 2*
Sodium	F		*30, Part 2*
Magnesium	F, M		*30, Part 3*
Aluminium	F, M		*30, Part 3*
Silicon	F, M, S		*30, Part 3*
Phosphorus	F, M		*30, Part 1*
Sulphur	[illegible]	SR-1	*67* and *71*
Protactinium	M, S		*30, Part 3*
Uranium	F, M[b], S		*69* and *71*
Neptunium	F, M[b], S		*69* and *71*
Plutonium	F, M[b], S		*67* and *71*
Americium	F, M[b], S		*67* and *71*
Curium	F, M[b], S		*71*
Berkelium	M		*30, Part 4*
Californium	M		*30, Part 4*
Einsteinium	M		*30, Part 4*
Fermium	M		*30, Part 4*
Mendelevium	M		30, Part 4

[a]For particulates: F, fast; M, moderate; S, slow. [b]Recommended default absorption Type for particulate aerosol when no specific information is available (see *ICRP Publication 71*, 1996). [c]Also for ingestion dose coefficients. [d]Tritium gas and tritiated methane, class SR-1; tritiated water and unspecified compounds, class SR-2. [e]Carbon monoxide, class SR-1; carbon dioxide and organic compounds, class SR-2.

Environmental Dose Assessment Concepts: Internal Dose Coefficients

Inhalation DCs also depend on the particle size distribution (PSD) of the particles:

- Different types of PSDs:
  - Lognormal
  - Uniform
  - Monodispersed



Example of lognormal particle size distribution

- PSDs assumptions when no specific information is available:
  - Workers - Lognormal distribution, 5 µm, Activity median aerodynamic diameter (AMAD), geometric standard deviation = 2.5
  - Public/environmental - Lognormal distribution, 1 µm-AMAD, geometric standard deviation = 2.5

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Environmental Dose Assessment Concepts: Dose Coefficients

- Dose Coefficients (DCs) are established by the ICRP
- Types of DCs
  - Inhalation of contaminated air (Sv/Bq)
  - External exposure from contamination in the air (plume submersion) ($Sv \cdot m^3/Bq \cdot h$)
  - External exposure from contamination on surfaces (ground) ($Sv \cdot m^2/Bq \cdot h$)
  - External exposure from contamination on the skin ($Sv \cdot m^2/Bq \cdot h$)
  - External exposure from immersion in contaminated water ($Sv \cdot m^3/Bq \cdot h$)
  - Ingestion of contaminated food and drink (Sv/Bq)

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Environmental Dose Assessment Concepts: Dose Coefficients

Example of external dose coefficient (adult age group) for Cs-137 deposited on the ground

Cs-137 Stochastic Surface Dose Coefficients

Dose Coefficients

- External
  - Surface
  - 1 cm Soil Depth
  - 5 cm Soil Depth
  - 15 cm Soil Depth
  - Infinite Soil Depth
  - Air Submersion
  - Water Immersion
- Inhalation
- Ingestion

Surface

Organ	Dose Coefficient
Adrenal	1.77E-19
Bone Surface	8.31E-19
Brain	1.81E-19
Breasts	3.54E-19
Kidneys	2.23E-19
Liver	2.07E-19
Lower Large Intestine	1.80E-19
Lung	2.28E-19
Muscle	2.98E-19
Ovaries	1.71E-19
Pancreas	1.62E-19
Red Marrow	2.03E-19
Skin	2.88E-16
Small Intestine	1.73E-19
Spleen	2.07E-19
Stomach	2.07E-19
Testes	3.39E-19
Thymus/Esophagus	2.18E-19
Thyroid	2.57E-19
Upper Large Intestine	1.85E-19
Urinary Bladder	2.08E-19
Uterus	1.71E-19

Effective Dose 3.13E-18

Sv • m^2

Bq • s

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Environmental Dose Assessment Concepts: Radioactive Decay and In-growth

- Bateman equations used to calculate decay chain activities (Cambridge, 1910)
- Decay and in-growth equations become very complicated when multiple radionuclides having radioactive decay products are concerned

  - Equation to calculates the activity of the "n^th" daughter (assuming an initial mix of parent only) at time t_n
  - ***You don't want to do this by hand!***
  - Need software to perform these calculations quickly and accurately

$$A_{d_n,t_n} = A_{p,0} \times \left(C_1 e^{-\lambda_p t_n} + C_2 e^{-\lambda_{d_1} t_n} + C_3 e^{-\lambda_{d_2} t_n} + \ldots + C_n e^{-\lambda_{d_n} t_n} \right)$$

where:

$$C_1 = \frac{\lambda_{d_1} \lambda_{d_2} \ldots \lambda_{d_n}}{(\lambda_{d_1} - \lambda_p)(\lambda_{d_2} - \lambda_p)\ldots(\lambda_{d_n} - \lambda_p)}$$

$$C_2 = \frac{\lambda_{d_1} \lambda_{d_2} \ldots \lambda_{d_n}}{(\lambda_p - \lambda_{d_1})(\lambda_{d_2} - \lambda_{d_1})\ldots(\lambda_{d_n} - \lambda_{d_1})}$$

$$\vdots$$

$$C_n = \frac{\lambda_{d_1} \lambda_{d_2} \ldots \lambda_{d_n}}{(\lambda_p - \lambda_{d_n})(\lambda_{d_1} - \lambda_{d_n})\ldots(\lambda_{d_{n-1}} - \lambda_{d_n})}$$

Environmental Dose Assessment Concepts: Weathering in the Environment

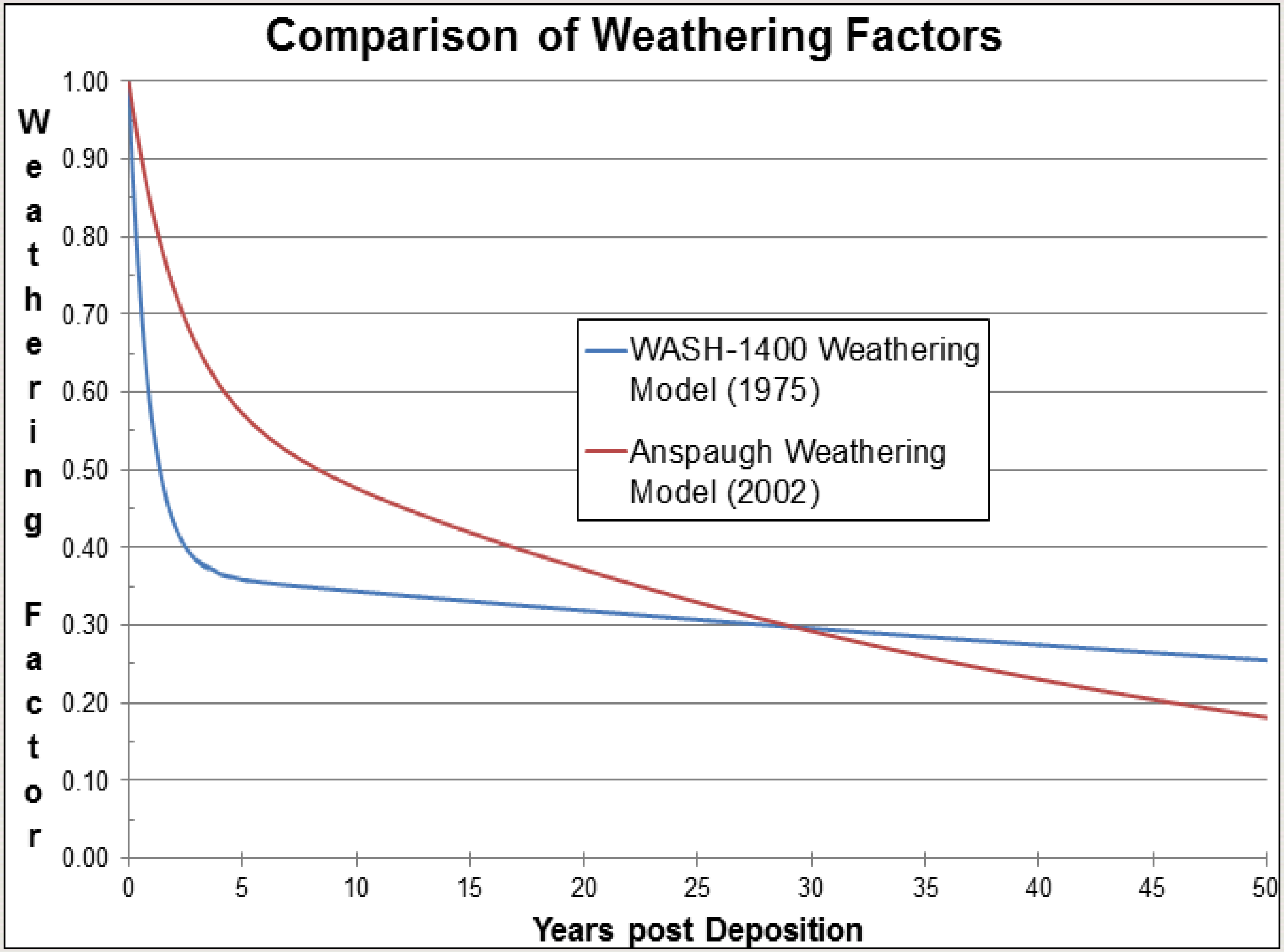
Weathering Factor and Weathering Parameter

- The effects of Weathering tend to decrease the external dose over time as the material is weathered deeper into the soil column
- Weathering effects vary with climate, soil type, land use, etc.
- Multiple weathering factor models exist

Environmental Dose Assessment Concepts: Weathering in the Environment

Comparison of various Weathering Factor Models

- ***Which one is correct?***
  - Depends!



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Environmental Dose Assessment Concepts: Weathering in the Environment

Weathering Parameter includes effects of weathering and radioactive decay and in-growth over time phase

$$WP_{i,TP} = \int_{t_1}^{t_2} \left(WF_t \times Dp_{i,t} \right) dt$$

where:

$Wp_{i,TP}$ = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure over the time phase under consideration (*TP*), Bq•s/m^2;

WF_t = Weathering Factor, the adjustment for the decrease that occurs over time as the deposited material is removed by a physical process (e.g., migration into the soil column or wind) from t_0 (deposition) to t_n (Evaluation Time), dimensionless; (HPS, 2002); and

Environmental Dose Assessment Concepts: Weathering in the Environment

where (continued):

Dp_i = Deposition concentration of radionuclide *i* at time *t*, Bq/m^2

NOTE: calculated using Bateman Equations (Bateman, 1910)

t_1 = the start of the time phase (integration period) under consideration, s; and

t_2 = the end of the time phase (integration period) under consideration, s.

$$WF_t = 0.4 \times e^{-1.46\text{E-}08t} + 0.6 \times e^{-4.44\text{E-}10t}$$

where:

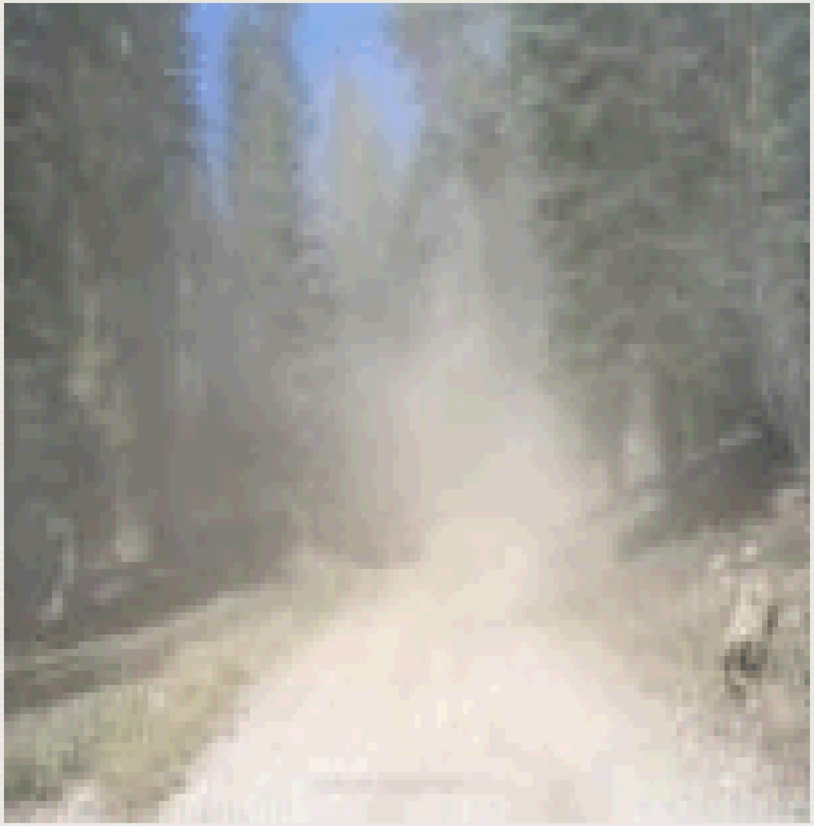
WF_t = Weathering Factor at time *t*, dimensionless; and

t_1 = Time post deposition, s.

Environmental Dose Assessment Concepts: Resuspension in the Environment

Resuspension Factor and Parameter

- Resuspension tends to decrease over time
- Resuspension rates can vary by orders of magnitude
- Conservative resuspension rates are often assumed
- Use known resuspension factor, if known
- Resuspension factors vary with many factors (e.g., surface type, climate, weather, activities)
- Many resuspension factor models exist, but they tend to converge at times greater than 50 days post deposition



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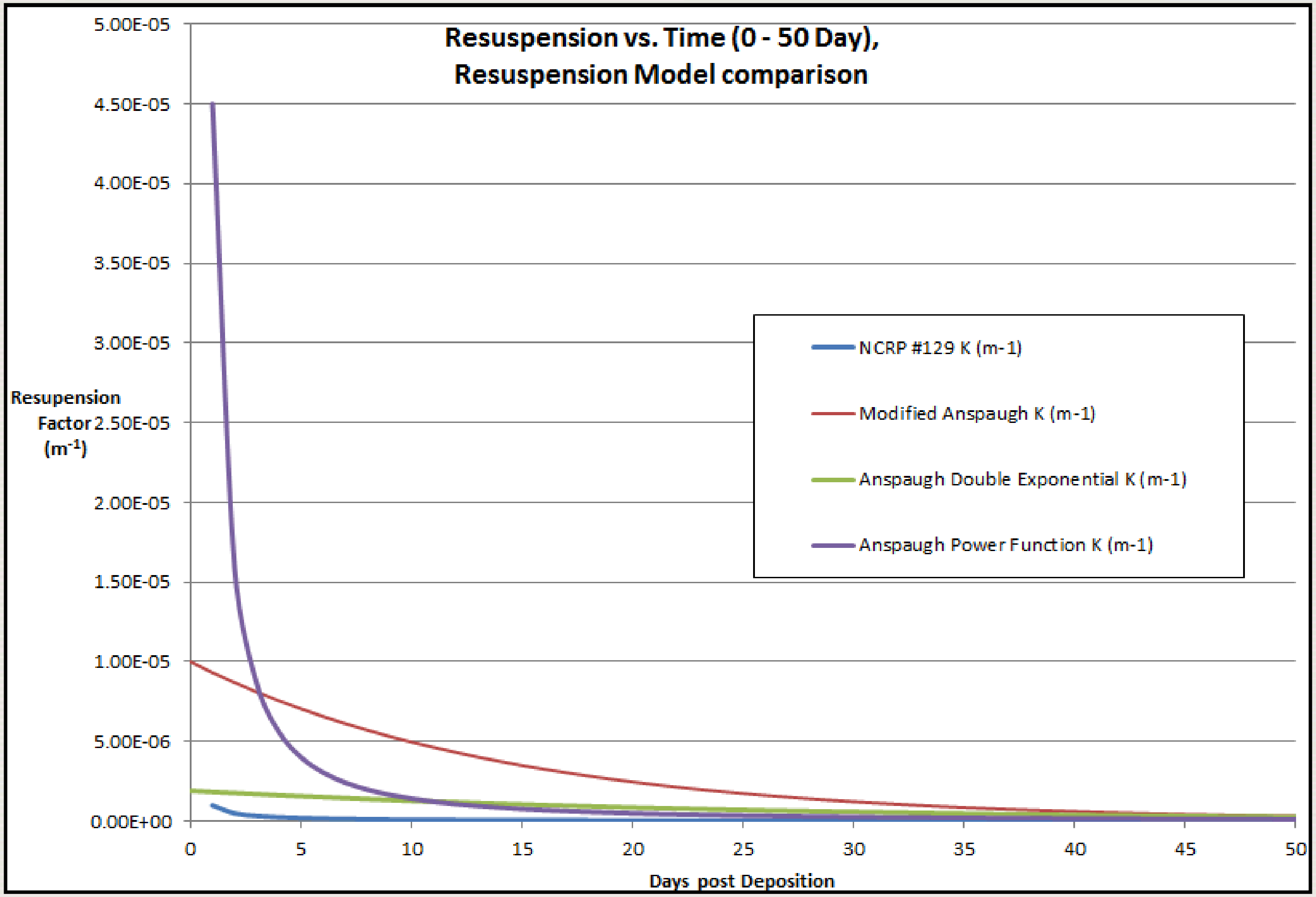
Environmental Dose Assessment Concepts: Resuspension in the Environment

Comparison of various Resuspension Factor Models

- ***Which one is correct?***
    - Depends!



Environmental Dose Assessment Concepts: Resuspension in the Environment

Resuspension Parameter includes effects of resuspension and radioactive decay and in-growth over time phase

$$KP_{i,TP} = \int_{t_1}^{t_2} \left(K_t \times Dp_{i,t} \right) dt$$

where:

$KP_{i,TP}$ = Resupension Parameter, value that adjusts the airborne radioactivity level of radionuclide *i* over the time phase under consideration (*TP*) for radioactive decay and in-growth, and the time-dependent resuspension factor (K_t), Bq•s/m^3;

K_t = Resuspension Factor, The fraction of radioactive material transferred from the surface to the atmosphere at a given time (*t*) after initial deposition, m^{-1}, (HPS, 2011); and

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Environmental Dose Assessment Concepts: Resuspension in the Environment

where (continued):

Dp_i = Deposition concentration of radionuclide *i* at time *t*, Bq/m^2

NOTE: calculated using Bateman Equations (Bateman, 1910)

t_1 = the start of the time phase (integration period) under consideration, s; and

t_2 = the end of the time phase (integration period) under consideration, s.

$$K_t = \left(1.0\text{E-}05 \times e^{-8.1\text{E-}07 \times t}\right) + \left(7.0\text{E-}09 \times e^{-2.31\text{E-}08 \times t}\right) + 1.0\text{E-}09$$

where:

K_t = Resupension Factor at time *t*, m^{-1}; and

t_1 = Time post deposition, s.

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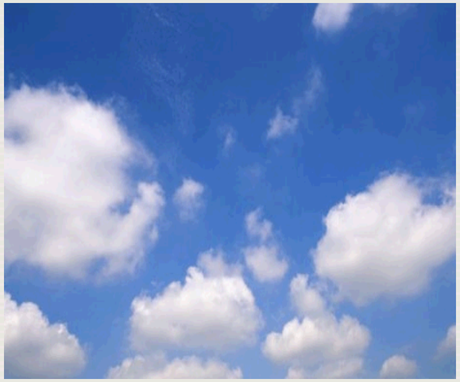
Environmental Dose Assessment Concepts: Resuspension in the Environment

Alternatively, K may be expressed as:

- A constant value (e.g., 1.00E-06 m^{-1}), or
- The ratio of air concentration to ground concentration (determined from samples)
- For Example:
  - Air sample = 1.60E-01 Bq/m^3
  - Ground sample = 4.50E+05 Bq/m^2



$K =$ (fraction: numerator image / denominator image)

$$K = \frac{\text{air sample}}{\text{ground sample}} = \frac{1.6\text{E-}01\,\frac{\text{Bq}}{\text{m}^3}}{4.5\text{E+}05\,\frac{\text{Bq}}{\text{m}^2}} = 3.6\text{E-}07\text{m}^{-1}$$

Environmental Dose Assessment Concepts: Deposition Velocity

Deposition Velocity (V_d)

- Deposition of gases and particles is a complex physical phenomenon, including:
  - Aerodynamic, surface and transfer resistance,
  - Dry or wet (rain, snow), and
  - Gravitational settling
- The Federal Radiological Monitoring and Assessment Center (FRMAC) in the United States uses simplified "Effective" Default Assumptions for Deposition Velocity (V_d):
  - 3.0E-03 m/s = V_d for Particulate (non-iodine) aerosols,
  - 6.5E-03 m/s = V_d for Particulate iodine aerosols
  - 6.4E-03 m/s = V_d for Reactive Gases (e.g., iodine gas released from a NPP), and
  - V_d = 0.0 m/s = V_d for Noble Gases (i.e., noble gases are assumed to remain airborne and are not deposited on the ground).

Environmental Dose Assessment Concepts: Deposition Velocity

Relationship between air and ground activity:

- To estimate the ground concentration from a known integrated air activity:

$$Dp_i = \tilde{A}_i * V_d \qquad \frac{\text{Bq}}{\text{m}^2} = \frac{\text{Bq} \times \text{s}}{\text{m}^3} \times \frac{\text{m}}{\text{s}}$$

- To estimate the integrated air activity from a known ground concentration:

$$\tilde{A}_i = \frac{Dp_i}{V_d} \qquad \frac{\mu\text{Ci} \times \text{s}}{\text{m}^3} = \frac{\text{Bq}}{\text{m}^2} \Big/ \frac{\text{m}}{\text{s}}$$

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Environmental Dose Assessment Concepts: Ground Roughness Factor

Ground Roughness Factor (GRF)

- The world is not an infinite flat plane
- GRF accounts for hills and valleys that tend to attenuate gamma radiation
- Typical values = 0.7 – 0.82, dimensionless
- Ground roughness correction should be applied, as appropriate

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Environmental Dose Assessment Concepts: Breathing Rates

Breathing rates vary by age group and activity

Age Group	Activity								Total Volume	Activity Avg. Rate
	Sleeping		Sitting		Light Exercise		Heavy Exercise			
	Rate m^3/hr	Time hr/day	Rate m^3/hr	Time hr/day	Rate m^3/hr	Time hr/day	Rate m^3/hr	Time hr/day	m^3/day	m^3/hr
Newborn (3 month)	0.09	17.0	NA	NA	0.19	7.0	NA	NA	2.86	0.12
Infant (1 year)	0.15	14.0	0.22	3.33	0.35	6.67	NA	NA	5.20	0.22
5 yr old	0.24	12.0	0.32	4.0	0.57	8.0	NA	NA	8.76	0.37
10 yr old	0.31	10.0	0.38	4.67	1.12	9.33	NA	NA	15.28	0.64
15 yr old (m)	0.42	10.0	0.48	5.5	1.38	7.5	2.92	1.0	20.10	0.84
15 yr old (f)	0.35	10.0	0.4	7.0	1.3	6.75	2.57	0.25	15.72	0.66
Adult (m) (Sedentary)	0.45	8.5	0.54	5.5	1.5	9.75	3.0	0.25	22.18	0.92
Adult (f) (Sedentary)	0.32	8.5	0.39	5.5	1.25	9.75	2.7	0.25	17.68	0.74
See ICRP 66, Tables 8, B.16A, and B.16B for methods to calculate breathing rates.										

Lecture 4b.3

- Summary of Key Points:
  - Many factors effect the dose from environmental contamination
  - Biokinetic modelling of radionuclides is a complex process and determine how much dose is delivered from radionuclide intakes
  - Environmental transport modelling is a complex process and we must make some assumptions to estimate doses
  - Radioactive decay and in-growth must be considered

Lecture 4b.4

Environmental Dose Assessment of Contaminated Air and Ground

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Environmental Releases – IAEA Generic Criteria and Methods

- IAEA General Safety Requirements Part 3, Radiation Protection safety of radiation Sources: International Basic Safety Standards (IAEA Pub. 1578, 2015) provides generic criteria for protection of workers and the public
- IAEA-TECDOC-1162, *Generic procedures for assessment and response during a radiological emergency* (IAEA, 2000), provides generic assessment methods
  - Point sources,
  - Line and spill sources,
  - Ground contamination,
  - Skin contamination,
  - Air contamination, and
  - Food contamination

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IAEA Methods for Ground Contamination

IAEA-TECDOC-1162 (2000) uses (dose) Conversion Factors from IAEA Safety Series 81 (1986) to estimate effective dose from exposure to ground contamination

- Section E, *Dose Assessment*, Specifies generic dose assessment methods

TABLE E3. CONVERSION FACTORS FOR EXPOSURE TO GROUND CONTAMINATION

Radionuclide	Conversion factor CF_3[a] Ambient dose rate from deposition [(mSv/h)/(kBq/m^2)]	Conversion factor CF_4[b] Effective dose from deposition [(mSv/kBq/m^2)]		
		1st Month	2nd Month	50 Year
H-3	0.0E+00	NC	NC	NC
C-14	5.7E-11	5.2E-07	4.9E-07	1.0E-04
Na-22	7.4E-06	3.7E-03	3.4E-03	8.4E-02
Na-24	1.3E-05	2.0E-04	0.0E+00	2.0E-04
P-32	1.0E-08	5.3E-06	1.2E-06	6.8E-06
P-33	1.6E-10	1.1E-06	4.4E-07	1.8E-06
S-35	5.9E-11	1.2E-06	8.7E-07	4.7E-06
Cl-36	2.4E-09	8.1E-06	7.7E-06	1.6E-03
K-40	5.2E-07	2.6E-04	2.5E-04	5.3E-02
K-42	9.4E-07	1.2E-05	0.0E+00	1.2E-05
Ca-45	1.6E-10	2.9E-06	2.4E-06	1.8E-05
Sc-46	6.8E-06	3.0E-03	2.2E-03	1.2E-02
Ti-44+Sc-44	7.8E-06	4.0E-03	3.8E-03	5.9E-01
V-48	9.8E-[illegible]	[illegible].8E-03	[illegible]	3.7E-0[illegible]

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IAEA Methods for Air Contamination

IAEA-TECDOC-1162 (2000) uses (inhalation dose) Conversion Factors to estimate effective dose from exposure to contaminated air

TABLE E6. COMMITTED EFFECTIVE DOSE FROM ONE HOUR'S INHALATION OF CONTAMINATED AIR — FOR AN ADULT

Radionuclide	Conversion factor CF_2 [(mSv/h)/(kBq/m^3)]	Radionuclide	Conversion factor CF_2 [(mSv/h)/(kBq/m^3)]
H-3[a]	7.8E-04	Ru-105	2.7E-04
C-14	8.7E-03	Ru-106	1.0E-01
Na-22	2.0E-03	Rh-103m	4.1E-06
Na-24	4.1E-04	Rh-105	5.3E-04
P-32	5.1E-03	Rh-106	1.7E-04
P-33	2.3E-03	Ag-110m	2.0E-02
S-35 org.	2.9E-03	Cd-109	1.2E-02
S-35 inorg.	2.1E-03	Cd-113m	1.7E-01
Cl-36	1.1E-02	Cd-115	1.7E-03
K-40	3.2E-03	In-113m	3.0E-05
K-42	1.8E-04	In-114m	1.4E-02
Ca-45	5.6E-03	In-115	5.9E-01
Sc-44	2.7E-04	In-115m	8.9E-05
Sc-46	1.0E-02	Sn-113	4.1E-03
Ti-44	2.0E-01	Sn-123	1.2E-02
V-48	3.6E-03	Sn-126	4.2E-02
Cr-51	5.6E-05	Sb-124	1.3E-02

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IAEA Methods for Ground Contamination

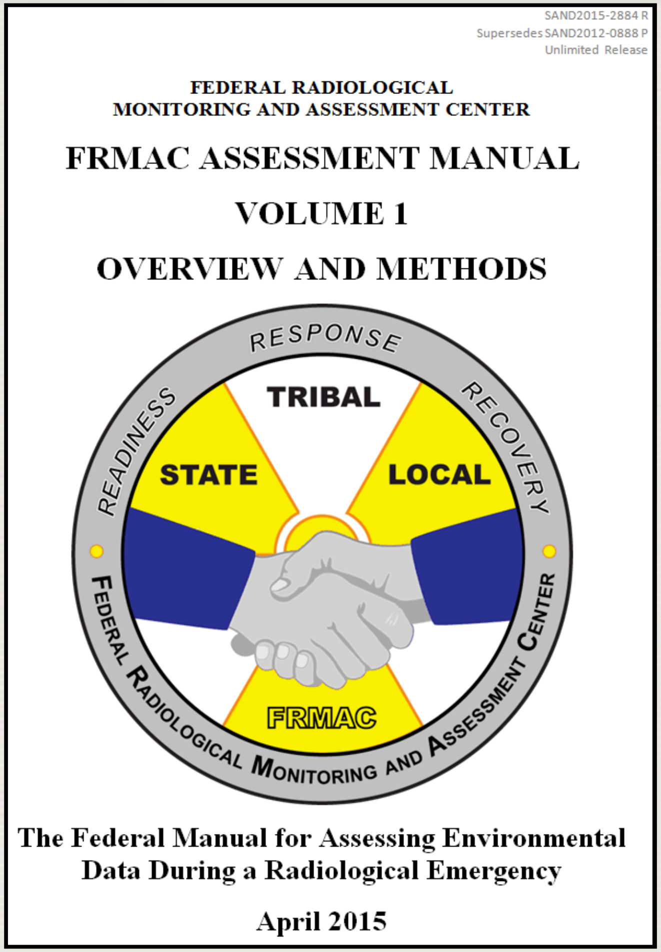
- IAEA-TECDOC-1162 dose Conversion Factors:
  - Include the external (groundshine) dose and dose from inhalation of resuspended material,
  - Specified for limited set of radionuclides,
  - Specified for limited set of exposures times (e.g., 1 month, 2nd month, 50 year),
  - Are based on older dosimetry models,
  - Calculation inputs (e.g., resuspension model) are not clearly identified, and
  - Are designed for public protection decisions (e.g., evacuation)
- Therefore, IAEA-TECDOC-1162 dose Conversion Factors are not real useful for doing scenario-specific dose assessments for non-default time periods

IAEA Methods for Air Contamination

- IAEA-TECDOC-1162 uses inhalation dose Conversion Factors from IAEA Safety Series No.115 (1996):
  - Specified for limited set of radionuclides,
  - Specified for 1 hour exposures, and
  - Are designed for public protection decisions (e.g., evacuation)
- IAEA Safety Series No.115 (1996) was superseded by General Safety Requirements No. GSR Part 3 (IAEA Publication 1578, 2014)
- Therefore, not sure if it is appropriate to use the IAEA-TECDOC-1162 inhalation dose Conversion Factors scenario-specific dose assessments.

United States Methods and Tools

- Federal Radiological Monitoring and Assessment Center (*FRMAC) Assessment Manual Volume 1, Overview and Methods*,, Sandia National Laboratories, Albuquerque, NM, April 2015 (SNL 2015b).
  - Specifies U.S. environmental assessment methods
  - Available at:


SAND2015-2884 R
Supersedes SAND2012-0888 P
Unlimited Release

FEDERAL RADIOLOGICAL
MONITORING AND ASSESSMENT CENTER

FRMAC ASSESSMENT MANUAL

VOLUME 1

OVERVIEW AND METHODS

The Federal Manual for Assessing Environmental
Data During a Radiological Emergency

April 2015

http://www.nv.doe.gov/nationalsecurity/homelandsecurity/frmac/manuals.aspx

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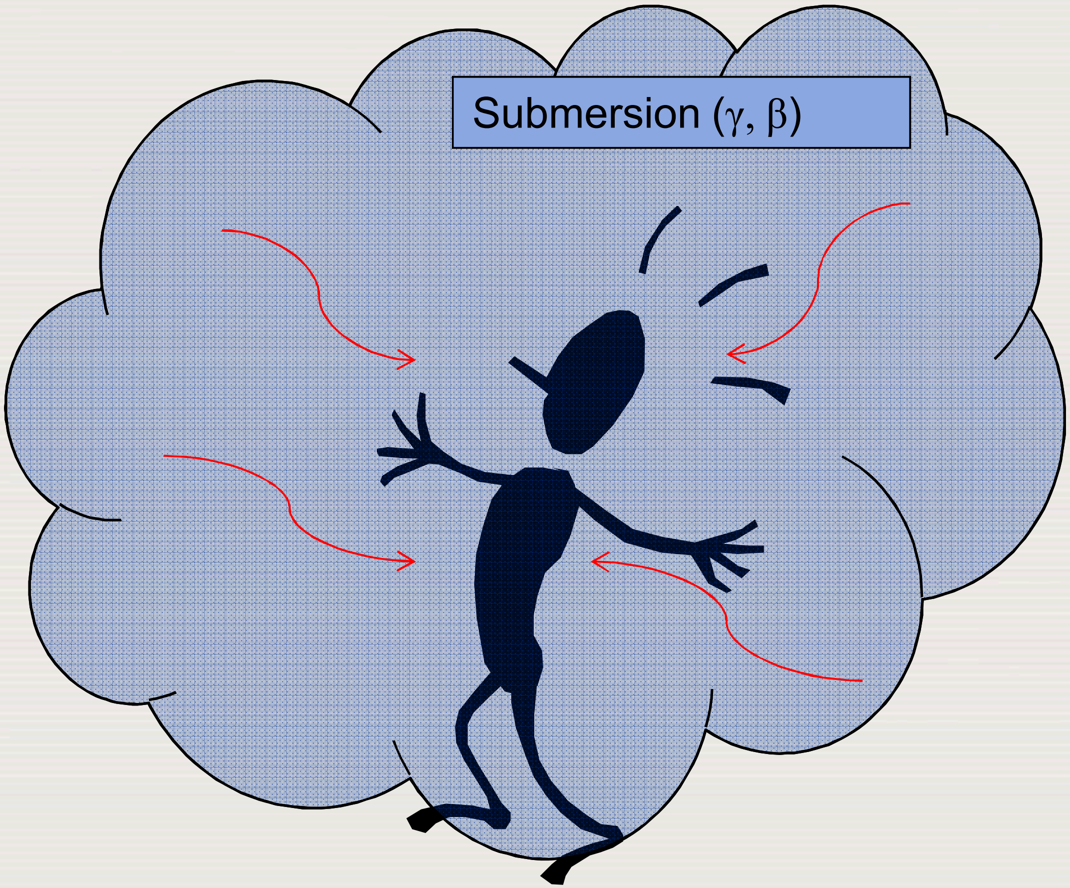
Turbo FRMAC© (TF) Software

Turbo FRMAC© (TF) Software (SNL, 2015a)

- Automates the methods in the FRMAC Assessment Manual
- Turbo FRMAC eliminates *most* human errors
- Greatly speeds up calculations and eliminates the need to make simplifying assumptions
- Turbo FRMAC runs on a laptop
- Latest Version is TF 2015
- Publically accessible at:
  http://nirp.sandia.gov

External Dose from Submersion in an Airborne Plume

External dose from submersion in an airborne plume



Radiation field from submersion in contaminated air

External Dose from Submersion in an Airborne Plume

External dose coefficients for air submersion:

- Assume semi-infinite cloud of uniformly-distributed contamination
- **Specific to one radionuclide**, not to a decay chain
  - For example, Cs-137 external dose coefficient does not include the external dose from Ba-137m

Additional Factors to Consider:

- Radioactive decay and in-growth modeling
- Are any radioactive decay products in equilibrium with parent radionuclides?
- Must sum external dose from the parent and all progeny radionuclides to estimate the external dose

External Dose from Submersion in an Airborne Plume

Example of external dose from submersion in a plume:

- A Sr-90 release has occurred
- The estimated **integrated** air concentration is 3.0E+11 Bq•s/m^3
- What is the Effective dose from external exposure to an adult receptor exposed to the plume?

Do you expect the decay product (Y-90) to also be present if Sr-90 is present?

- Assume Y-90 is in secular equilibrium

Decay Properties: Sr-90

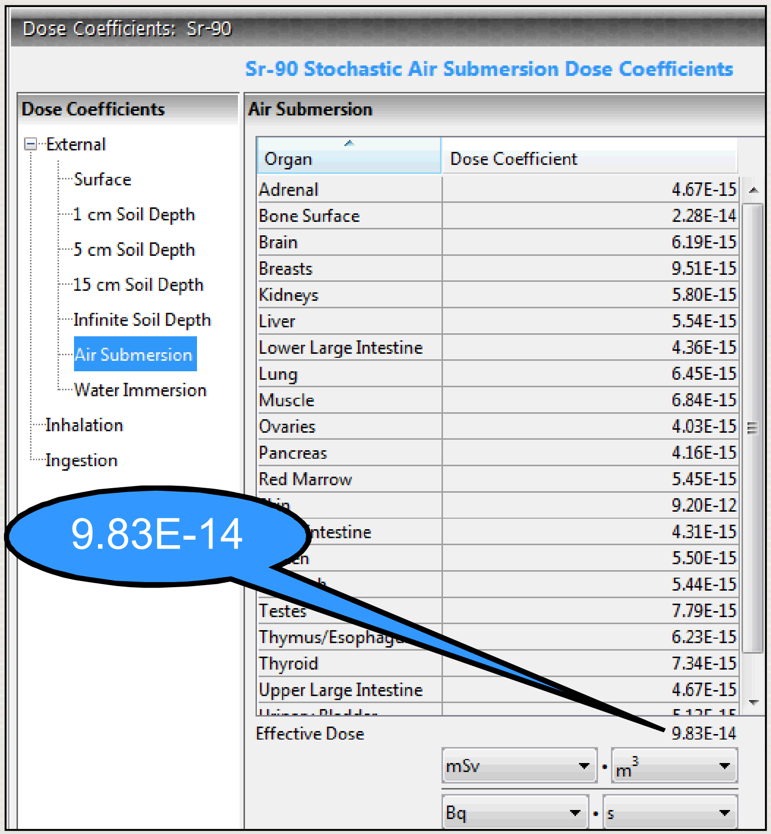
Columns | Show Legends

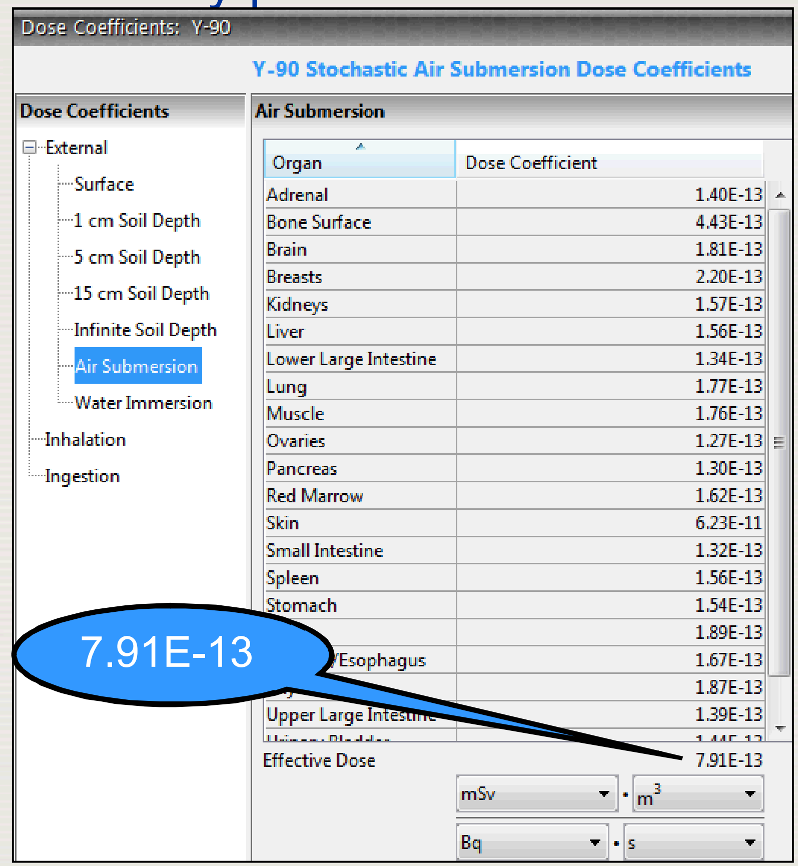
Radionuclide	Half-Life	Decay Mode	Decay Constant	Branch Factor
^{90}Sr	2.55E5	B-	2.72E-6	N/A
^{90}Y	64.0	B-	1.08E-2	1.00
	hr		hr^{-1}	Fraction

External Dose from Submersion in an Airborne Plume

Note that the Air Submersion DC for the decay product, Y-90, is 8 times greater than that for Sr-90

- Always remember to consider radioactive decay products!





External Dose from Submersion in an Airborne Plume

External dose calculation from submersion in a plume:

$$Pl\_ExDP = \sum_{i}^{n} (Pl\_ExDC_i \times \tilde{A}_i)$$

$$mSv = \frac{mSv \times m^3}{Bq \times s} \times \frac{Bq \times s}{m^3}$$

where:

Pl_ExDP = Plume External Dose Parameter, the external dose from submersion in an airborne plume of radionuclides, mSv

Pl_ExDC_i = Plume External Dose Coefficient, the external dose rate from submersion in radionuclide *i* in the plume, mSv•m^3/Bq•s; and

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in a release, Bq•s/m^3.

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External Dose from Submersion in an Airborne Plume

Example of external dose from plume submersion:

$$Pl\_ExDP = \sum_{i}^{n} (Pl\_ExDC_i \times \tilde{A}_i)$$

Radio-nuclide	Half-Life (y)	Branch Factor	External Air Submersion Dose Coefficient (mSv•m³/Bq•s)	Integrated Air Concentration (Bq•s/m³)	Effective Dose (mSv)
Sr-90	29.1	N/A	9.83E-14	3.0E+11	2.95E-02
Y-90	7.30E-03	1.0	7.91E-13	3.0E+11	2.37E-01
			Total =		2.66E-01

Therefore, the effective dose to an adult standing in an airborne plume of Sr-90 and Y-90, in secular equilibrium, at a concentration of 3.0E+11 Bq•s/m^3 is 0.27 mSv.

NOTE: > 89% of dose comes dose from the decay product, Y-90

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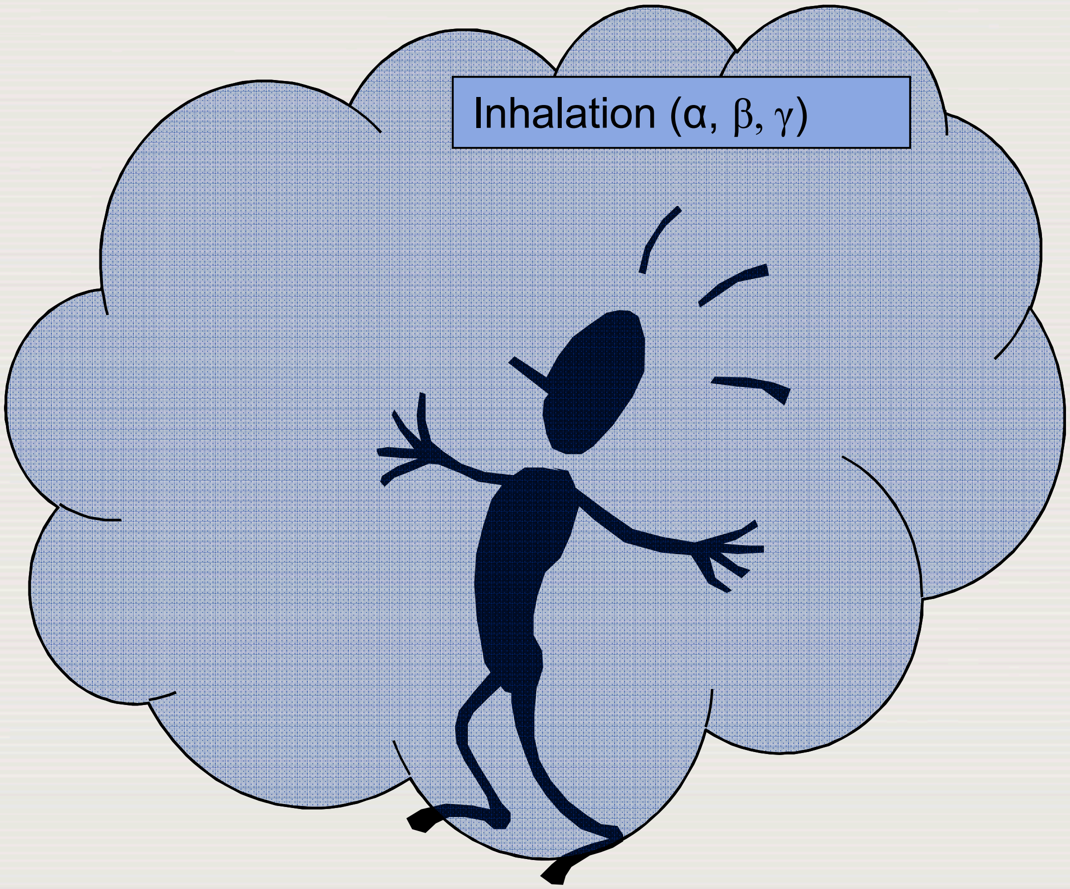
External Dose from Submersion in an Airborne Plume

Example of external dose from submersion in a plume using the Turbo FRMAC © software tool (SNL, 2015a)

Inhalation Dose from Submersion in an Airborne Plume

Inhalation dose from submersion in an airborne plume



Inhalation of radioactive materials in an airborne plume

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Inhalation Dose from Submersion in an Airborne Plume

- Inhalation DC basic facts:
  - DCs depend on the particle size distribution (PSD) of the particles
  - DCs depend on the lung clearance type (Fast, Medium, Slow)

- General assumptions for environmental dose assessments **when you do not know specific details**:
  - Physical form is particulate (aerosol) unless it is a noble gas
  - Workers - Lognormal distribution, 5 µm, Activity median aerodynamic diameter (AMAD), geometric standard deviation = 2.5
  - Public - Lognormal distribution, 1 µm, Activity median aerodynamic diameter (AMAD), geometric standard deviation = 2.5

Inhalation Dose from Submersion in an Airborne Plume

- General assumptions … **when you do not know specific details** (continued):
  - Public/environmental - Lognormal distribution, 1 µm-AMAD, geometric standard deviation = 2.5, and
  - See ICRP 68, 71, and 72 for guidance on Lung clearance type.
    - Assume the lung clearance type is Medium (M) if no information is available
  - Breathing rate
    - Assume adult, light-activity breathing rate, 1.5 m^3/h (4.17E-04 m^3/h)

Additional Factors to Consider:

- Radioactive decay and in-growth modeling
- Are any radioactive decay products in equilibrium with parent radionuclides?

Inhalation Dose from Submersion in an Airborne Plume

Example of inhalation dose from plume submersion when integrated air activity in known:

- A Sr-90 release has occurred
- The integrated air concentration is 3.0E+11 Bq•s/m^3
- What is the Committed Effective dose from inhalation to an adult receptor exposed to the plume?
  - Assume no respiratory protection

- **Do you expect the decay product (Y-90) to also be present if Sr-90 is present?**
  - Assume Y-90 is in secular equilibrium

Decay Properties: Sr-90

Columns | Show Legends

Radionuclide	Half-Life	Decay Mode	Decay Constant	Branch Factor
^{90}Sr	2.55E5	B-	2.72E-6	N/A
^{90}Y	64.0	B-	1.08E-2	1.00
	hr		hr^{-1}	Fraction

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Inhalation Dose from Submersion in an Airborne Plume

Inhalation dose coefficients:

- What PSD and lung clearance type do you assume?
  - Assume the PSD is 1 μm AMAD
  - Assume lung clearance type for Sr-90 is class "M" per ICRP Report 72, Table 2

Sr-90 Stochastic Inhalation Dose Coefficients

Inhalation

Organ	Dose Coefficient
Adrenal	2.80E-7
Bone Surface	1.61E-4
Brain	2.80E-7
Breasts	2.80E-7
Kidneys	2.80E-7
Liver	2.80E-7
Lower Large Intestine	8.70E-6
Lung	2.05E-4
Muscle	2.80E-7
Ovaries	2.80E-7
Pancreas	2.80E-7
Red Marrow	7.06E-5
Skin	2.80E-7
Small Intestine	5.36E-7
Spleen	2.80E-7
Stomach	3.86E-7
Testes	2.80E-7
Thymus/Esophagus	2.80E-7
Committed Effective Dose	3.56E-5

mSv / Bq

ICRP Guidance: ICRP 60
Age: Adult
Commitment Period: Chronic

View Particle Sizes for:
- Compound Distribution
- Vapor or Gas

Compound Distribution
View/Edit Distribu

Distribution Summary:
1 Monodispersed

Lung Clearance Class
- Maximum
- Fast (F)
- Medium (M) - **Most Likely**
- Slow (S)

Inhalation Dose from Submersion in an Airborne Plume

Inhalation dose calculation from submersion in a plume when integrated air concentration is known:

$$Pl\_InhDP = \sum_{i}^{n} (InhDC_i \times \tilde{A}_i \times BR_{LE})$$

$$mSv = \frac{mSv}{Bq} \times \frac{Bq \times s}{m^3} \times \frac{m^3}{s}$$

where:

Pl_InhDP = Plume Inhalation Dose Parameter, the committed dose from the inhalation of plume-borne radionuclides over the time phase under consideration (*TP*), mSv;

$InhDC_i$ = Inhalation Dose Coefficient, the committed dose from inhalation of plume-borne radionuclide *i*, mSv/Bq,

$\tilde{A}_i$ = Integrated air activity of radionuclide *i* in the airborne plume, Bq•s/m^3; and

BR_{LE} = Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP, 1994, Table 6), 4.17E-04 m^3/s.

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Inhalation Dose from Submersion in an Airborne Plume

Example of inhalation dose from plume submersion when integrated air concentration is known:

$$Pl\_InhDP = \sum_{i}^{n} (InhDC_i \times \tilde{A}_i \times BR_{LE})$$

Radio-nuclide	Half-Life (y)	Branch Factor	Integrated Air Concentration (Bq•s/m³)	Inhalation Dose Coefficient (mSv/Bq)	Breathing rate (m³/s)	Effective Dose (mSv)
Sr-90	29.1	N/A	3.0E+11	3.56E-05	4.17E-04	4.45E+03
Y-90	7.30E-03	1.0	3.0E+11	1.50E-06	4.17E-04	1.87E+02
					Total =	4.64E+03

Therefore, the Committed Effective dose from inhalation to an adult standing in an airborne plume of Sr-90 and Y-90, in secular equilibrium, at a concentration of 3.0E+11 Bq•s/m^3 is 4,640 mSv.

Inhalation Dose from Submersion in an Airborne Plume

Example of inhalation dose from plume submersion **when average air concentration in known**:

- A Sr-90 release has occurred
- The Sr-90 average air concentration is 1.0E+08 Bq•s/m^3
- An adult worker was in the plume for 1 hour (3,600 s)
- What is the Effective dose from inhalation to an adult receptor exposed to the plume?

Do you expect the decay product (Y-90) to also be present if Sr-90 is present?

- Assume Y-90 is in secular equilibrium

Decay Properties: Sr-90

Columns | Show Legends

Radionuclide	Half-Life	Decay Mode	Decay Constant	Branch Factor
^{90}Sr	2.55E5	B-	2.72E-6	N/A
^{90}Y	64.0	B-	1.08E-2	1.00
	hr		hr^{-1}	Fraction

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Inhalation Dose from Submersion in an Airborne Plume

Inhalation dose calculation from submersion in a plume when average air concentration is known:

$$Pl\_InhDP = \sum_{i}^{n} (InhDC_i \times C_i \times BR_{LE} \times t)$$

$$mSv = \frac{mSv}{Bq} \times \frac{Bq}{m^3} \times \frac{m^3}{s} \times s$$

where:

Pl_InhDP = Plume Inhalation Dose Parameter, the committed dose from the inhalation of plume-borne radionuclides over the time phase under consideration (*TP*), mSv;

$InhDC_i$ = Inhalation Dose Coefficient, the committed dose from inhalation of plume-borne radionuclide *i*, mSv/Bq,

C_i = average air activity concentration of radionuclide *i* in the airborne plume, Bq/m^3;

BR_{LE} = Light Exercise Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP, 1994, Table 6), 4.17E-04 m^3/s; and

t = time that the receptor was in the plume, s.

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Inhalation Dose from Submersion in an Airborne Plume

Example of inhalation dose from plume submersion when average air concentration is known:

$$Pl\_InhDP = \sum_{i}^{n} (InhDC_i \times C_i \times BR_{LE} \times t)$$

Radio-nuclide	Half-Life (y)	Branch Factor	Inhalation Dose Coefficient (mSv/Bq)	Air Concentration (Bq/m³)	Breathing rate (m³/s)	Time (s)	Effective Dose (mSv)
Sr-90	29.1	N/A	3.56E-05	1.0E+08	4.17E-04	3,600	5.34E+03
Y-90	7.30E-03	1.0	1.50E-06	1.0E+08	4.17E-04	3,600	2.25E+02
						Total =	5.57E+03

Therefore, the Committed Effective dose from inhalation to an adult standing in an airborne plume of Sr-90 and Y-90, in secular equilibrium, at an average concentration of 1.0E+08 Bq/m^3 is 5,570 mSv.

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Inhalation Dose from Submersion in an Airborne Plume

Example of inhalation dose from plume submersion using the Turbo FRMAC © software tool (SNL, 2015a)

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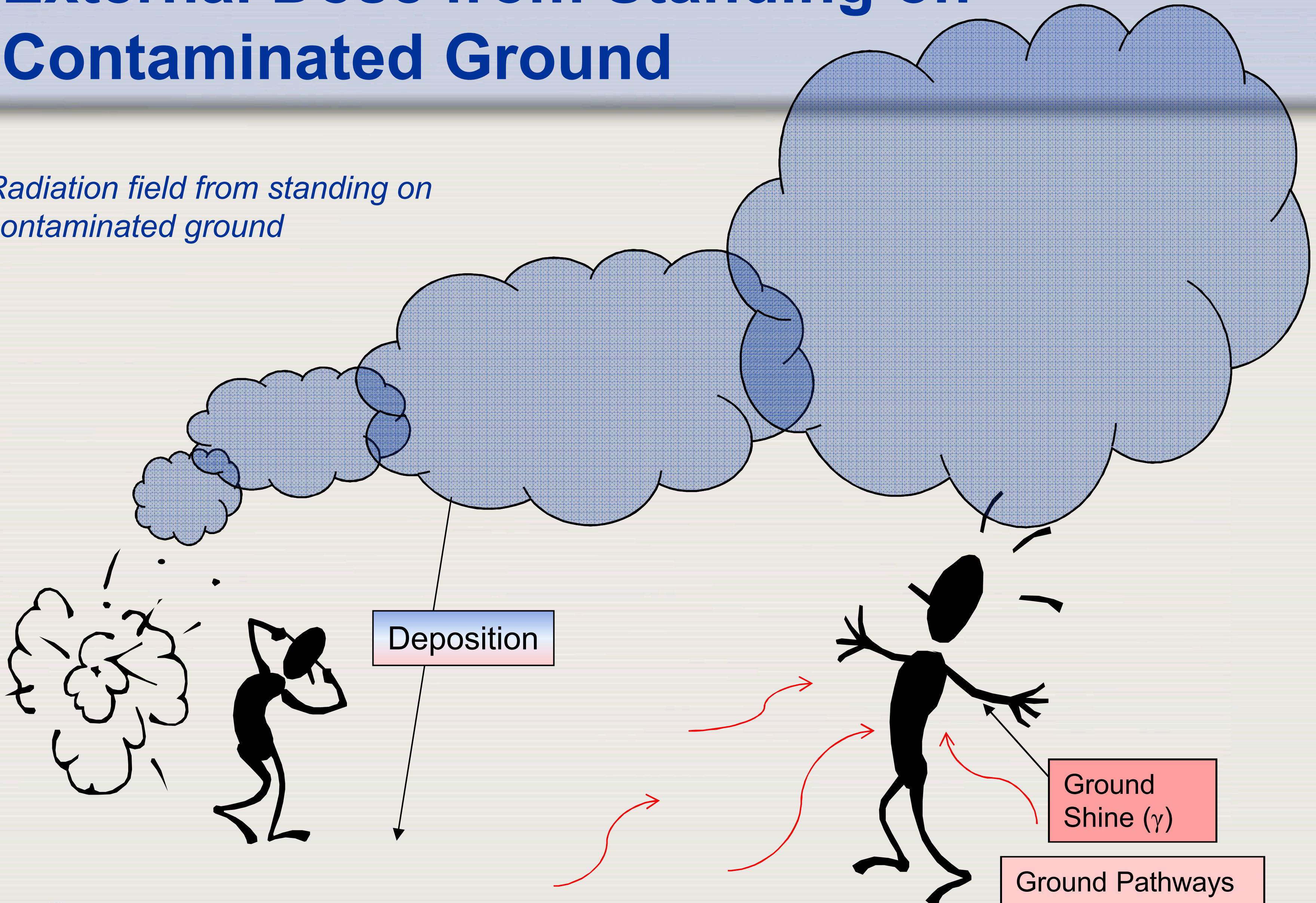
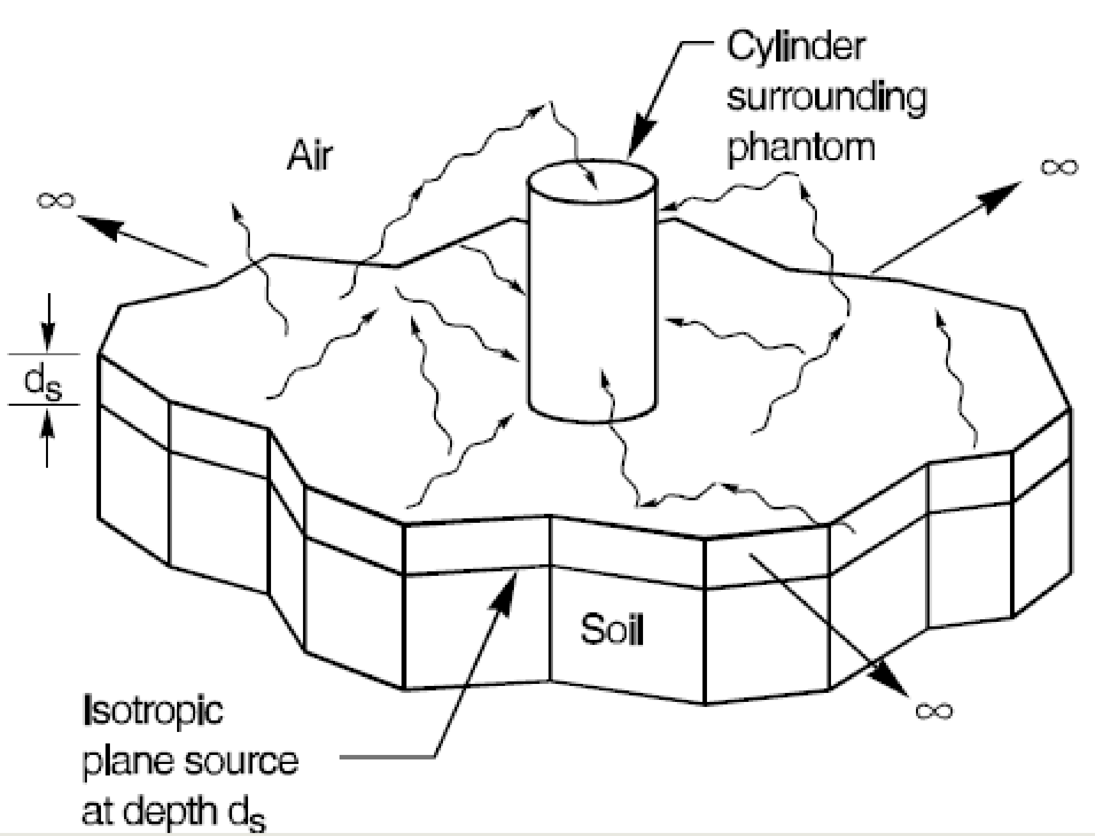
External Dose from Standing on Contaminated Ground

Radiation field from standing on contaminated ground



External Dose from Standing on Contaminated Ground

External dose from radionuclides deposited on the ground



Radiation field from contaminated ground plane (EPA-4020R-93-081)

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External Dose from Standing on Contaminated Ground

External dose coefficients for surface contamination:

- Assume an infinite, perfectly flat, plane is contaminated at a specified depth in the soil.
- **Specific to one radionuclide**, not to a decay chain
  - For example, Cs-137 external dose coefficient does not include the external dose from Ba-137m
- DCs specified for 5 depths:
  - Surface contamination
  - Mixed to depth of 1 cm
  - Mixed to depth of 5 cm
  - Mixed to depth of 10 cm
  - Mixed to depth of 15 cm
  - Mixed to infinite depth

External Dose from Standing on Contaminated Ground

Additional Factors to Consider:

- Radioactive decay and in-growth modeling
- Are any radioactive decay products in equilibrium with parent radionuclides?
- Ground Roughness Factor (GRF)
  - the world is not an infinite flat plane
- Weathering Factor and Weathering Parameter modeling

External Dose from Standing on Contaminated Ground

Example of external dose from surface contamination:

- A large surface area is contaminated with Cs-137 at 1.0E9 Bq/m^2
- What is the Effective dose to a receptor standing in the contaminated area for **10 hour, starting 8 hour after deposition**?

Do you expect the decay product (Ba-137m) to also be present if Cs-137 is present?

- Yes!

Decay Properties: Cs-137

Columns | Show Legends

Radionuclide	Half-Life	Decay Mode	Decay Constant	Branch Factor
^{137}Cs	1.58E7	B-	4.39E-8	N/A
^{137m}Ba	2.55	IT	0.272	0.946
	min		min^{-1}	Fraction

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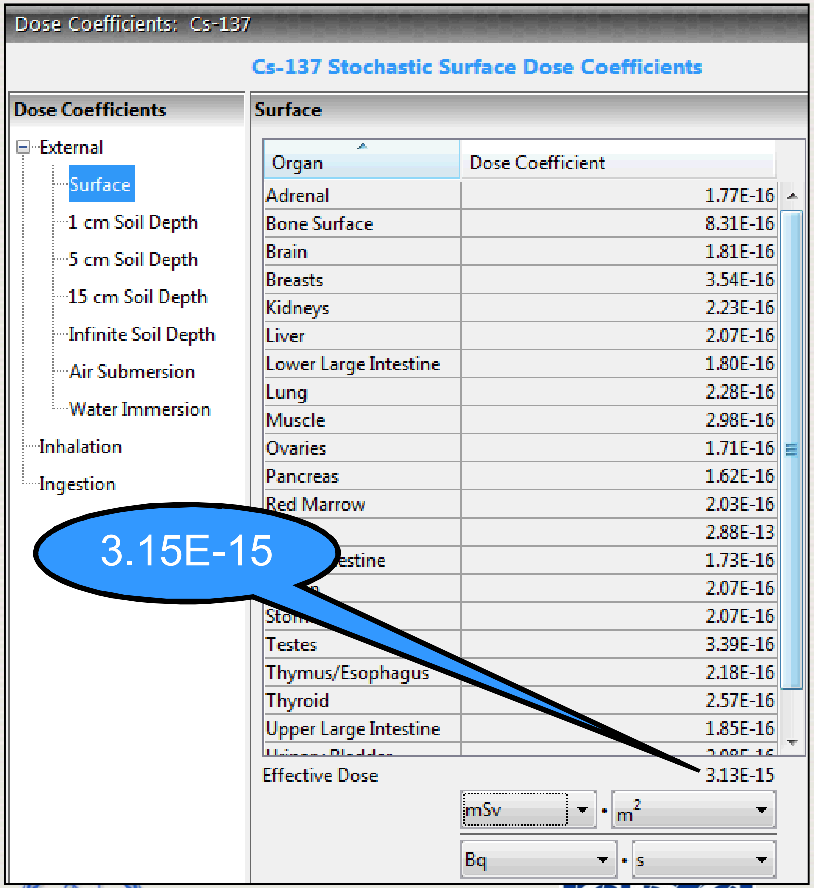
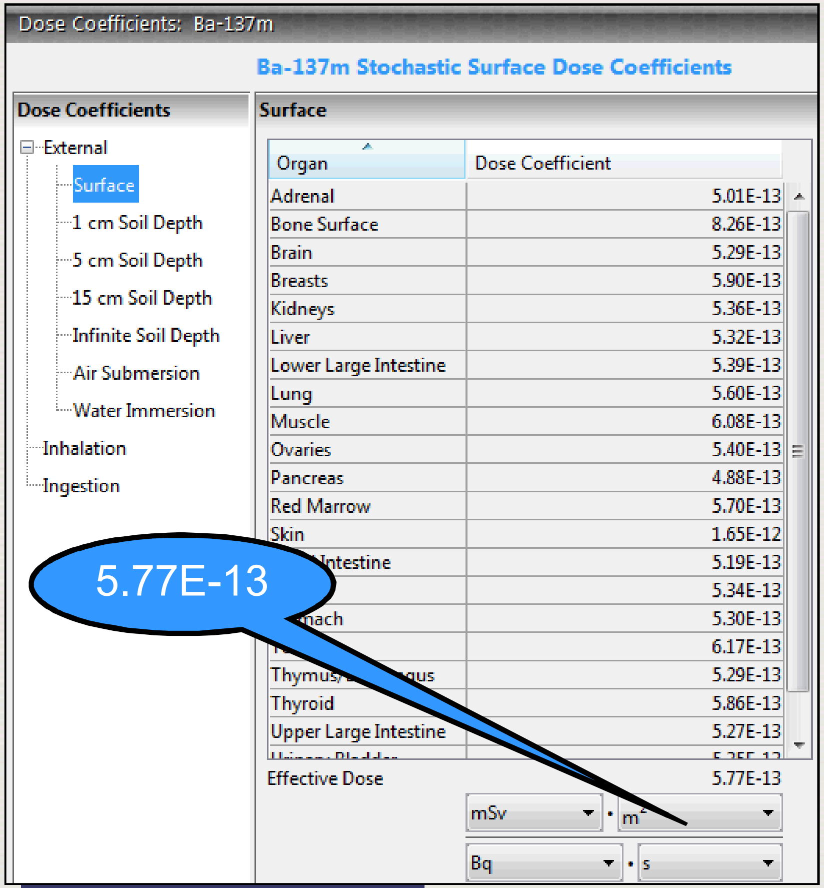
External Dose from Standing on Contaminated Ground

Note that the Air Submersion DC for the decay product, Ba-137m, is 184 times greater than that for Cs-137

- Always remember to consider radioactive decay products!





External Dose from Standing on Contaminated Ground

External dose calculation from standing on a contaminated surface:

$$Dp\_ExDP = \sum_{i}^{n} (Dp\_ExDC_i \times GRF \times WP_{i,TP})$$

$$mSv = \frac{mSv \times m^2}{Bq \times s} \times unitless \times \frac{Bq \times s}{m^2}$$

where:

- *Dp_ExDP* = Deposition External Dose Parameter, the external dose from all radionuclides over the time phase under consideration, Sv
- *GRF* = Ground Roughness Factor, 0.82 (dimensionless)
- Dp_ExDC_i = Deposition External Dose Coefficient, the external dose rate from radionuclide *i* per unit activity deposited on the ground, mSv•m²/Bq•s;
- WP_i = Weathering Parameter, the adjustment for radioactive decay and in-growth and the time-dependent weathering effects that change the amount of a radionuclide available to cause direct exposure over the time phase under consideration (*TP*), Bq•s/m².

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External Dose from Standing on Contaminated Ground

Example of surface contamination:

$$Dp\_ExDP = \sum_{i}^{n} (Dp\_ExDC_i \times GRF \times WP_{i,TP})$$

Radio-nuclide	Half-Life (y)	Branch Factor	Ground Con-centration (Bq/m²)	External Dose Coefficient (mSv•m²/Bq•s)	Ground Roughness Factor (dimensionless)	WP (Bq•s/m²)	Effective Dose (mSv)
Cs-137	30	N/A	1.0E+09	3.13E-15	0.82	3.60E+13	9.24E-02
Ba-137m	4.85E-06	0.946	9.46E+08	5.77E-13	0.82	3.40E+13	1.61E+01
						Total =	1.62E+01

Therefore, the effective dose to an adult standing on ground contaminated with 1.0E+09 Bq/m² from a time phase of 8 – 18 hours following deposition is 16.2 Sv

NOTE: > 99% of dose comes dose from the decay product, Ba-137m

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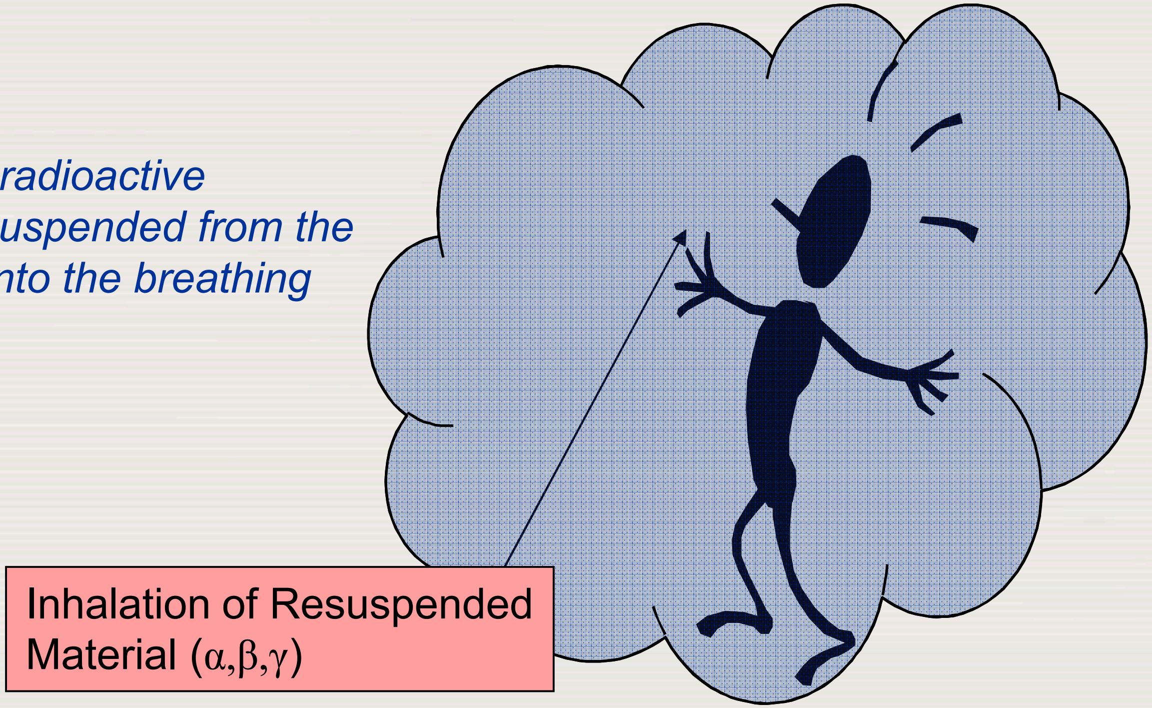
External Dose from Standing on Contaminated Ground

Example of external dose from surface contamination using the Turbo FRMAC © software tool (SNL, 2015a)

Dose from Inhalation of Resuspended Material while in Contaminated Area

A small fraction of the material deposited on surfaces (ground) is resuspended into the breathing zone

Inhalation of radioactive materials resuspended from the ground and into the breathing zone



Dose from Inhalation of Resuspended Material while in Contaminated Area

Additional Factors to Consider:

- Radioactive decay and in-growth modeling
- Are any radioactive decay products in equilibrium with parent radionuclides?
- Commitment periods
- Lung clearance (absorption) types
- Particle size distribution
- Chemical and physical forms
- Resuspension Factor and Resuspension Parameter modeling
- Age of receptor
- Breathing rate

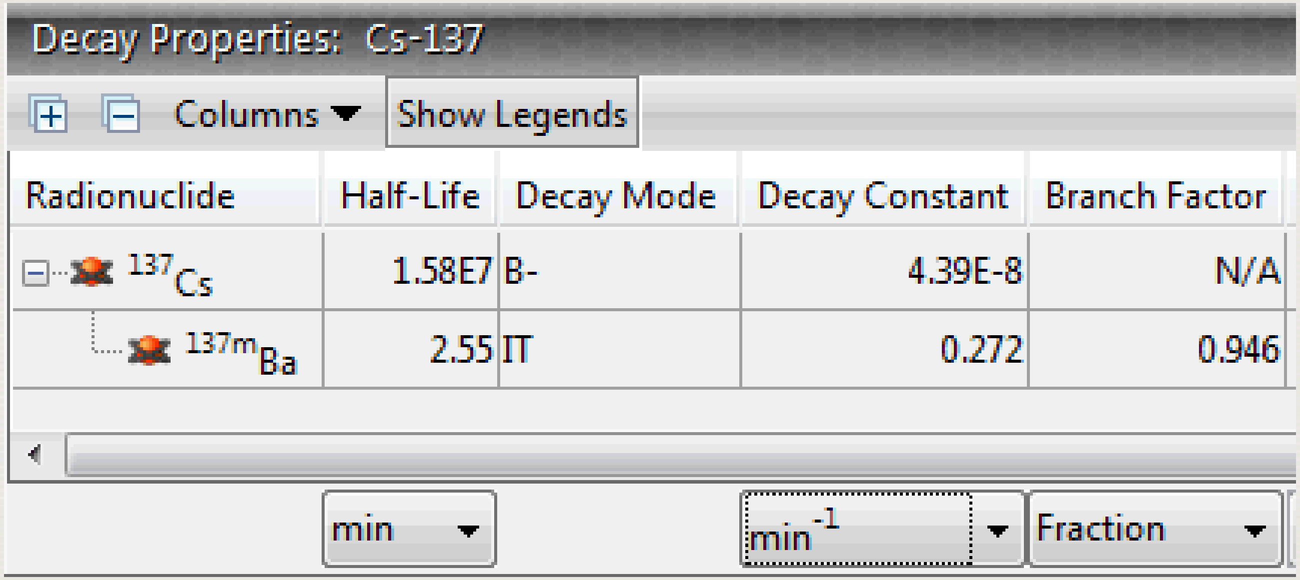
Dose from Inhalation of Resuspended Material while in Contaminated Area

Example of dose from inhalation of resuspended contamination:

- A large surface area is contaminated with Cs-137 at 1.0E9 Bq/m^2
- What is the Committed Effective dose to a receptor standing in the contaminated area for **10 hour, starting 8 hour after deposition**?

Do you expect the decay product (Ba-137m) to also be present if Cs-137 is present?

- Yes!



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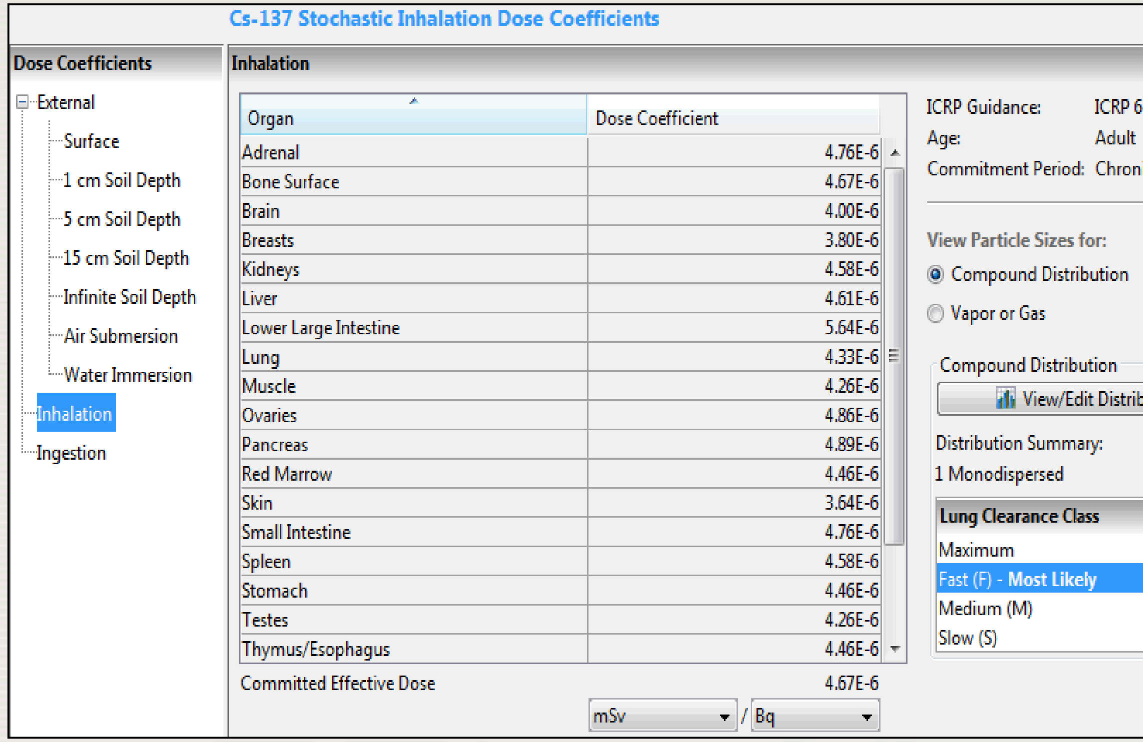
Dose from Inhalation of Resuspended Material while in Contaminated Area

Inhalation dose coefficients:

- What PSD and lung clearance type do you assume?
  - Assume the PSD is 1 µm AMAD
  - Assume lung clearance type for Cs-137 is class “F” per ICRP Report 72, Table 2



NOTES:

- Because Ba-137m has a half-life < 10 minutes (i.e., 2.55 minutes) it is not given an Inhalation DC.
- However, the Cs-137 DC does include the dose from Ba-137m that is formed inside the body after intake

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Dose from Inhalation of Resuspended Material while in Contaminated Area

Dose calculation for inhalation of resuspended material:

$$Dp\_InhDP = \sum_{i}^{n} (InhDC_i \times KP_{i,TP} \times BR_{AA})$$

$$mSv = \frac{mSv}{Bq} \times \frac{Bq \times s}{m^3} \times \frac{m^3}{s}$$

where:

Dp_InhDP = Deposition Inhalation Dose Parameter, the committed dose from the inhalation of plume-borne radionuclides over the time phase under consideration (*TP*), mSv;

$InhDC_i$ = Inhalation Dose Coefficient, the committed dose from inhalation of plume-borne radionuclide *i*, mSv/Bq,

$KP_{i,TP}$ = Resuspension Parameter, value that adjusts the airborne radioactivity level of radionuclide i over the time phase under consideration (TP) for radioactive decay and in-growth and the time-dependent resuspension factor (K_t), Bq•s/m^3; and

BR_{AA} = Activity-Averaged Breathing Rate, the volume of air breathed per unit time by an adult male during light exercise (ICRP, 1994, Table 6), 2.56E-04 m^3/s.

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Dose from Inhalation of Resuspended Material while in Contaminated Area

Example of external dose from plume submersion:

$$Dp\_InhDP = \sum_{i}^{n} (InhDC_i \times KP_{i,TP} \times BR_{AA})$$

Radio-nuclide	Half-Life (y)	Branch Factor	Inhalation Dose Coefficient (mSv/Bq)	Resupension Parameter (Bq•s/m^3)	Breathing rate (m^3/s)	Effective Dose (mSv)
Cs-137	30	N/A	4.67E-06	3.47E+08	2.56E-04	4.15E-01
Ba-137m	4.85E-06	0.946	NA	3.28E+08	2.56E-04	0
					Total =	4.15E-01

Therefore, the Committed Effective dose from inhalation of resuspended material to an adult standing on ground contaminated with Cs-137 and Ba-137m, in secular equilibrium, at a concentration of 1.0E+09 Bq/m^2 is 4.15E-01 mSv.

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Example Public Dose Problem

Example of projected dose from living/working in a contaminated area using the Turbo FRMAC © software tool (SNL, 2015a)

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Example Public Dose Problem

- A large surface area is contaminated with radioactive materials released from a nuclear power plant
- Based on preliminary models and monitoring results for an area occupied by members of the public, the estimated deposited radionuclides of concern are:

Radio-nuclide	Results (MBq/m^2)
Cs-134	3.26
Cs-136	0.112
Cs-137	3.25
I-131	1.25
I-132	1.110
La-140	0.655
Nb-95	0.195
Te-129m	1.23
Te-132	0.143

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Example Public Dose Problem

- You have been asked to estimate the:
  - Committed Effective dose and
  - Committed Equivalent$_{Thyroid}$ dose

  to adult members of the public that were exposed to the radioactive material over a period of 0 – 7 days
- Assume the receptor was outside (unprotected) for the entire exposure period
- Assume the "maximum" lung clearance type
- Include the dose from:
  - External dose from submersion in the air-borne plume,
  - Inhalation dose from submersion in the air-borne plume,
  - External dose from standing in the contaminated area, and
  - Inhalation dose from resuspended material while standing in the area

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Example Public Dose Problem

- How do the estimated Committed Effective dose and Committed Equivalent$_{Thyroid}$ compare to the IAEA's generic dose criteria?

Table A-1. Generic Criteria for Protective Actions and Other Response Actions in Emergency Exposure Situations to Reduce the Risk of Stochastic Effects (IAEA Pub. 1578, 2014)

Generic criteria		Examples of protective actions and other response actions
Projected dose that exceeds the following generic criteria: Take urgent protective actions and other response actions		
$H_{thyroid}$	50 mSv in the first 7 days	Iodine thyroid blocking
E	100 mSv in the first 7 days	Sheltering; evacuation; decontamination; restrictions on food, milk and drinking water; contamination control; reassurance of the public
H_{fetus}	100 mSv in the first 7 days	
Projected dose that exceeds the following generic criteria: Take early protective actions and other response actions		
E	100 mSv in the first year	Temporary relocation; decontamination; restrictions on food, milk and drinking water; reassurance of the public
H_{fetus}	100 mSv for the full period of in utero development	

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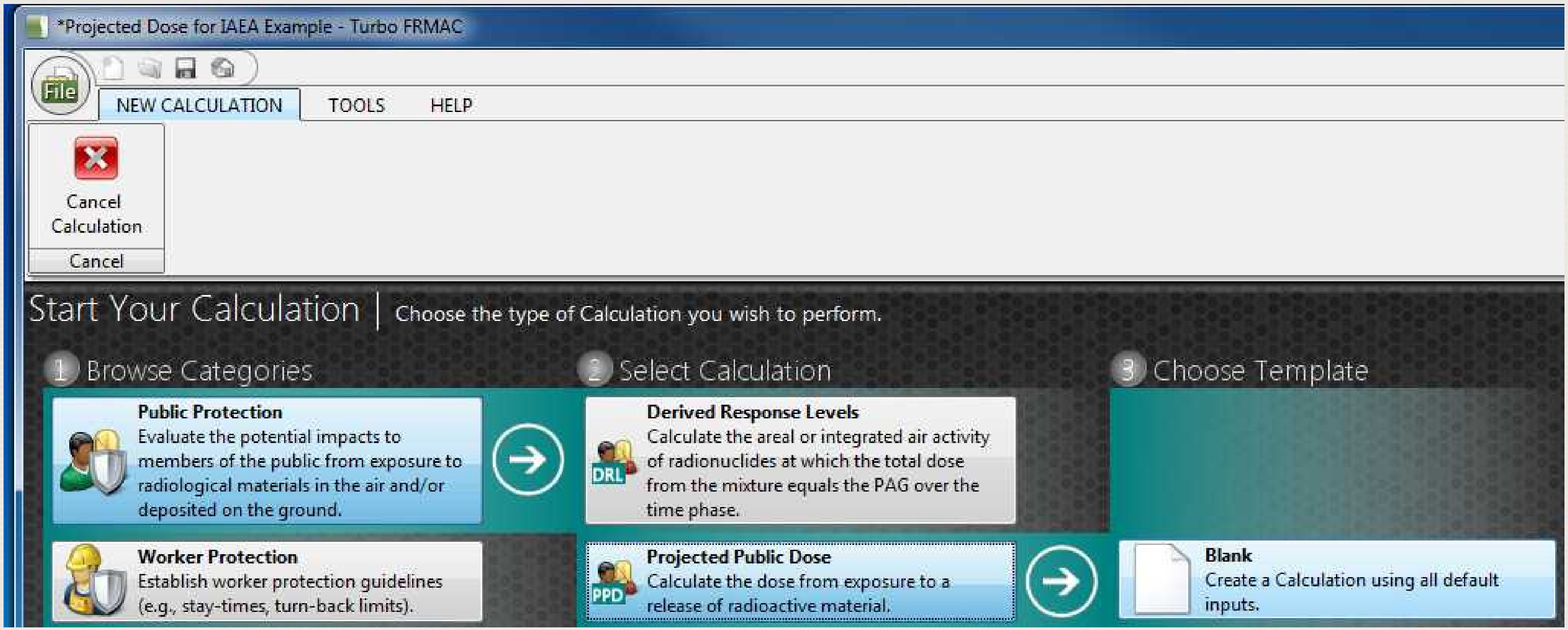
Example Public Dose Problem

- Start the Turbo FRMAC © software tool
- Open a blank projected public dose case



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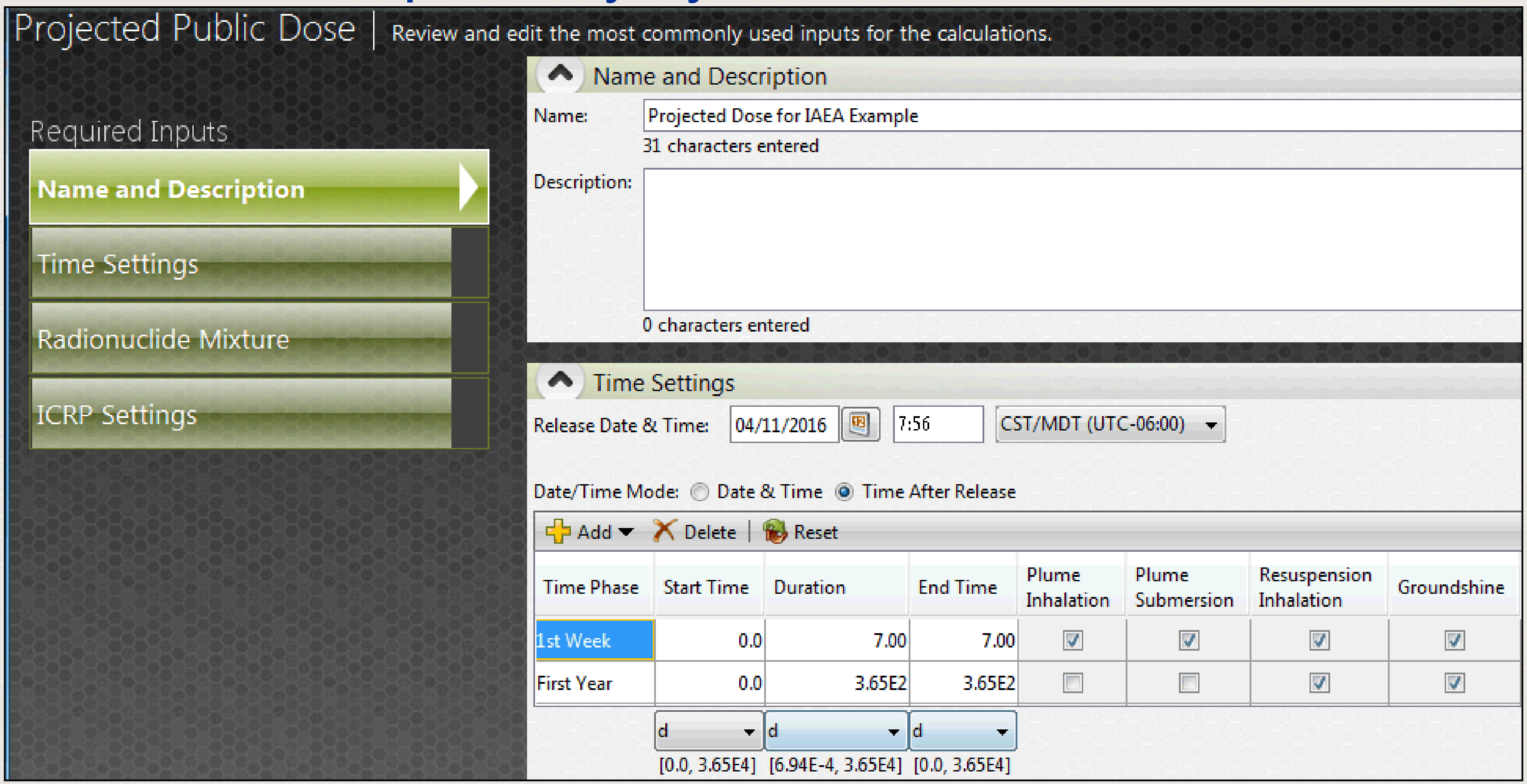
Example Public Dose Problem

- Set the time phases you want to consider
- Set the dose pathways you want to include



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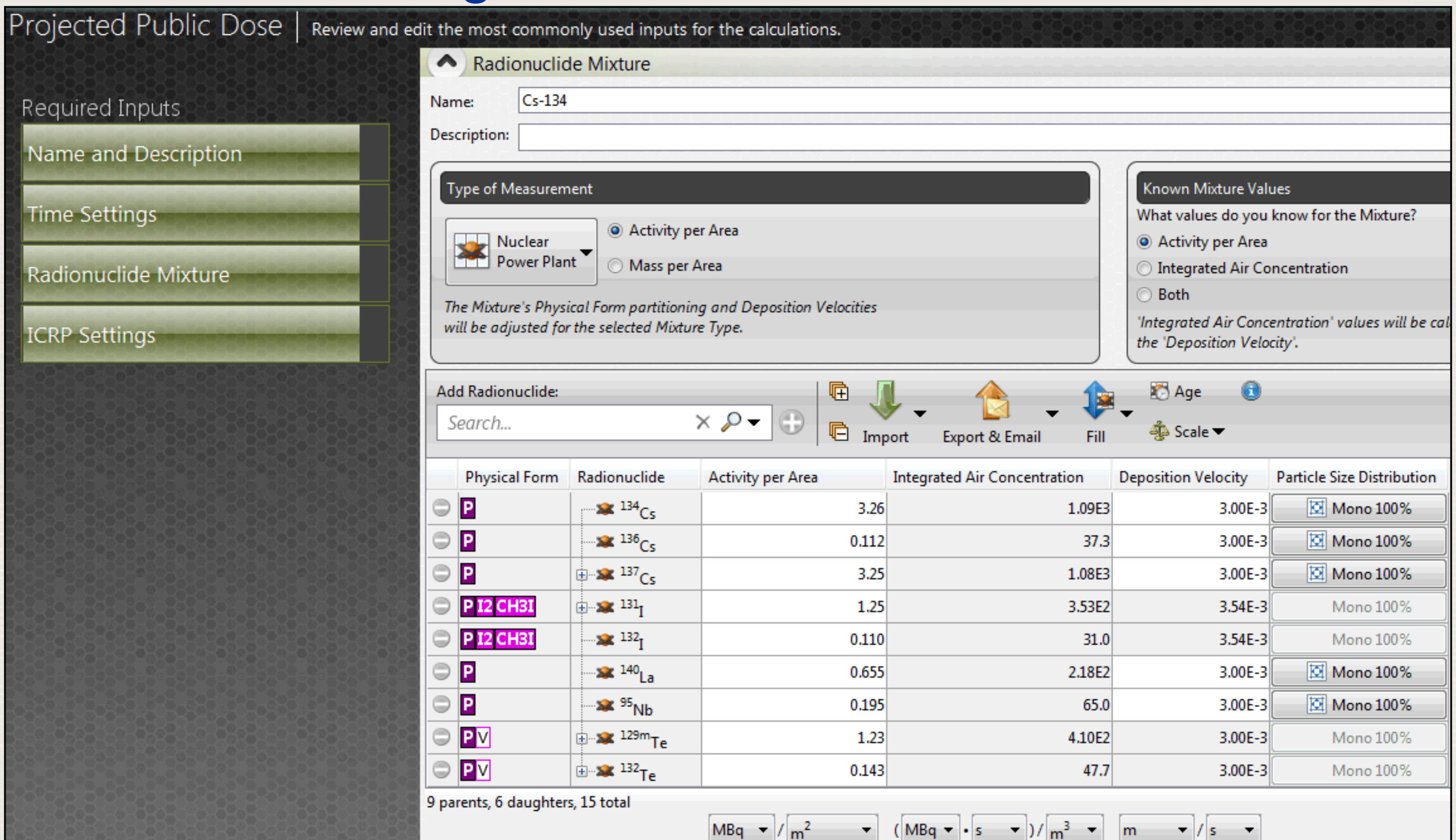
Example Public Dose Problem

- Enter the Nuclear Power Plant radionuclide mixture based on the estimated ground concentration data



Example Public Dose Problem

- Note that:
  - The integrated air activity is added based on the ground concentration
  - Decay products that are expected to be in equilibrium are automatically added

	Physical Form	Radionuclide	Activity per Area	Integrated Air Concentration	Deposition Velocity	Particle Size Distribution
	P	^{134}Cs	3.26	1.09E3	3.00E-3	Mono 100%
	P	^{136}Cs	0.112	37.3	3.00E-3	Mono 100%
	P	^{137}Cs	3.25	1.08E3	3.00E-3	Mono 100%
		^{137m}Ba	3.07	1.02E3	3.00E-3	Mono 100%
	P I2 CH3I	^{131}I	1.25	3.53E2	3.54E-3	Mono 100%
		^{131m}Xe	0.0	0.0	3.54E-3	N/A
	P I2 CH3I	^{132}I	0.110	31.0	3.54E-3	Mono 100%
	P	^{140}La	0.655	2.18E2	3.00E-3	Mono 100%
	P	^{95}Nb	0.195	65.0	3.00E-3	Mono 100%
	P V	^{129m}Te	1.23	4.10E2	3.00E-3	Mono 100%
	P V	^{132}Te	0.143	47.7	3.00E-3	Mono 100%

9 parents, 6 daughters, 15 total

MBq / m^2 (MBq · s) / m^3 m / s

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Example Public Dose Problem

- Also, note that the default physical forms for iodine released from a NPP are assumed

Physical Form	Radionuclide	Activity per Area	Integrated Air Concentration	Deposition Velocity	Particle Size Distribution
P	^{134}Cs	3.26	1.09E3	3.00E-3	Mono 100%
P	^{136}Cs	0.112	37.3	3.00E-3	Mono 100%
P	^{137}Cs	3.25	1.08E3	3.00E-3	Mono 100%
	^{137m}Ba	3.07	1.02E3	3.00E-3	Mono 100%
P I2 CH3I	^{131}I	1.25	3.53E2	3.54E-3	Mono 100%

Multiple Physical Forms

I-131

Set the Multiple Physical Forms for I-131.

Physical Form	Radionuclide	Airborne Partition	Activity per Area	Integrated Air Concentration	Deposition Velocity
P I2 CH3I	Sum	-	33.8	9.53E3	3.54E-3
Particulate	^{131}I	0.250	33.8	2.38E3	6.50E-3
Iodine Vapor	^{131}I	0.300	N/A	2.86E3	6.40E-3
Methyl Iodide	^{131}I	0.450	0.0	4.29E3	0.0

I-131 exists in 3 Physical Forms.

Fraction | µCi / m^2 | (µCi • s) / m^3 | m / s

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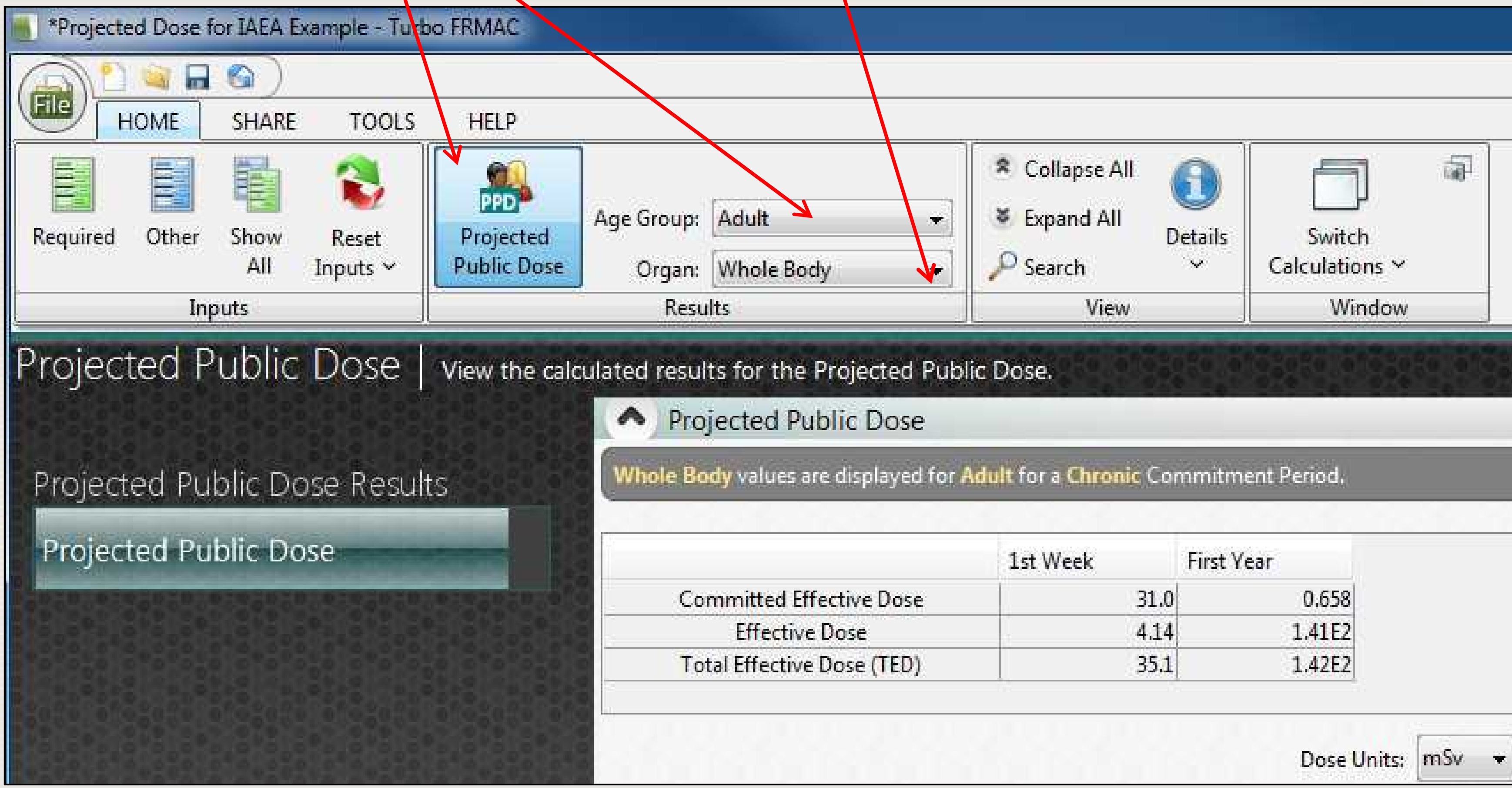
Example Public Dose Problem

- Click on Projected Public Dose to view the estimated dose results
- Select the desired Age Group and Organ



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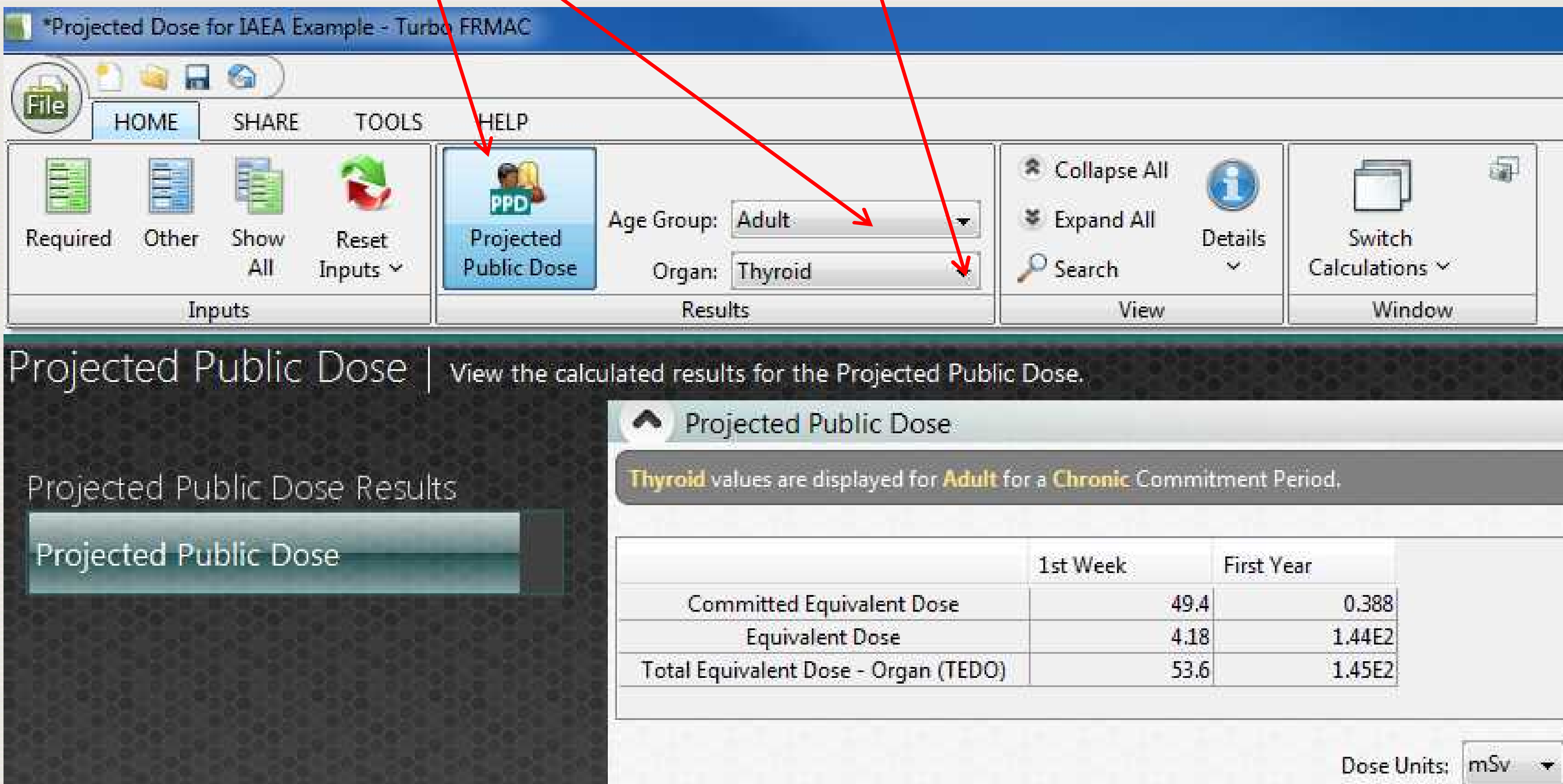
Example Public Dose Problem

- Click on Projected Public Dose to view the estimated dose results
- Select the desired Age Group and Organ



Example Public Dose Problem

Time Period	Committed Effective Dose (E) (mSv)	Effective Dose (E) (mSv)	Total Effective Dose (E) (mSv)	Generic Criteria, Total Effective Dose (mSv)
1st Week	31.0	4.14	35.1	100
1st Year	0.658	141	142	100

Time Period	Committed Equivalent Dose ($H_{thyroid}$) (mSv)	Equivalent Dose ($H_{thyroid}$) (mSv)	Total Equivalent Dose ($H_{thyroid}$) (mSv)	Generic Criteria, Total Effective Dose (mSv)
1st Week	49.4	4.18	53.6	100
1st Year	0.388	144	145	Not Applicable

Were any IAEA generic criteria exceeded?

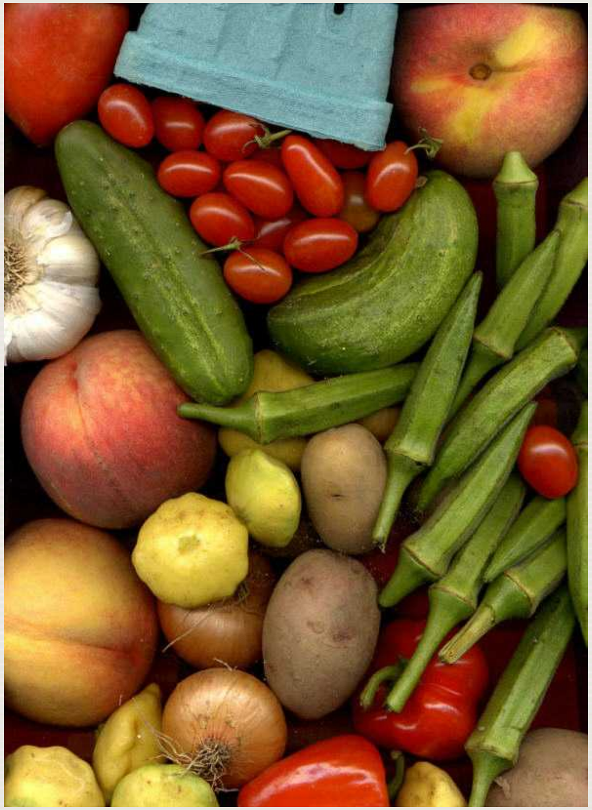
Yes, the 1st Year Total Effective Dose criteria was exceeded!

Lecture 4b.4

- Summary of Key Points:
  - Major environmental dose pathways include:
    - External (submersion) dose from radionuclides in the air-borne plume,
    - Inhalation dose from radionuclides in the air-borne plume,
    - External (groundshine) dose from radionuclides deposited on the ground,
    - Inhalation dose from the resuspension of radionuclides deposited on the ground
  - Environmental dose assessments are complex and difficult to do by hand
  - Use software to increase the speed and accuracy of environmental assessments

Lecture Module 4b

Lecture 4b.4: Environmental Dose Assessment, Contaminated Food



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Dose from Ingestion of Radiologically Contaminated Food

What are *safe* levels of contamination in food?

- OIL5 and OIL6 are measured values of concentrations in food, milk or water that warrant the consideration of restrictions on consumption so as to keep the effective dose to any person below **10 mSv per annum** (IAEA Publication 1467, 2011)

TABLE 9. DEFAULT SCREENING OILs FOR FOOD, MILK AND WATER CONCENTRATIONS FROM LABORATORY ANALYSIS

OIL	OIL value	Response action if the OIL is exceeded
OIL5	Gross beta (β): 100 Bq/kg or Gross alpha (α): 5 Bq/kg	Above OIL5: Assess using OIL6 Below OIL5: Safe for consumption during the emergency phase

TABLE 10. DEFAULT RADIONUCLIDE SPECIFIC OILs FOR FOOD, MILK AND WATER CONCENTRATIONS FROM LABORATORY ANALYSIS

Radionuclide		OIL6 (Bq/kg)	Radionuclide		OIL6 (Bq/kg)
H-3		2×10^5	Sc-44		1×10^7
Be-7		7×10^5	Sc-46		8×10^3
Be-10		3×10^3	Sc-47		4×10^5
C-11		2×10^9	Sc-48		3×10^5
C-14		1×10^4	Ti-44	+	6×10^2
F-18		2×10^8	V-48		3×10^4
Na-22		2×10^3	V-49		2×10^5
Na-24		4×10^6	Cr-51		8×10^5
Mg-28	+[a]	4×10^5	Mn-52		1×10^5
Al-26		1×10^3	Mn-53		9×10^4

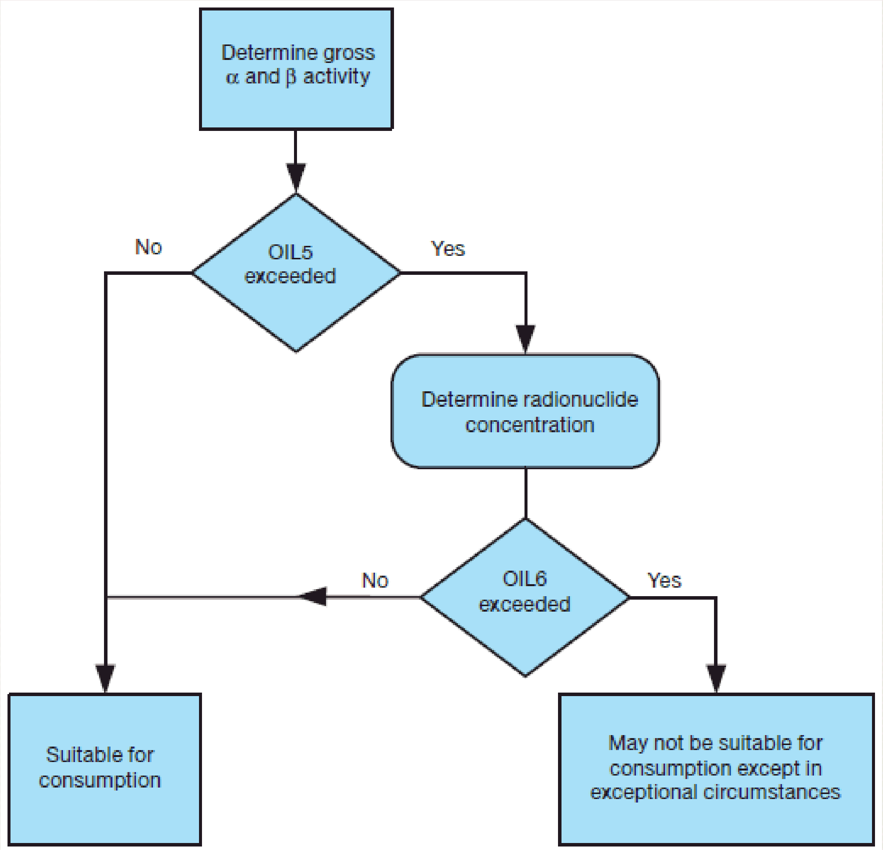
Default OILs (IAEA, 2011)

[a]'+' indicates radionuclides with progeny listed in Table 11 that are assumed to be in equilibrium with the parent radionuclide and therefore do not need to be considered independently when assessing compliance with OILs

Dose from Ingestion of Radiologically Contaminated Food

Accessing Food Safety:

- Survey to compare gross beta and alpha activity to OIL5 values
- If food contamination exceeds OIL5 values, food should be sampled and analyzed, and compared to the corresponding OIL6 value
- If the radionuclide concentrations is greater than the OIL6, consumption of non-essential food, milk or water should be stopped (IAEA, 2011)

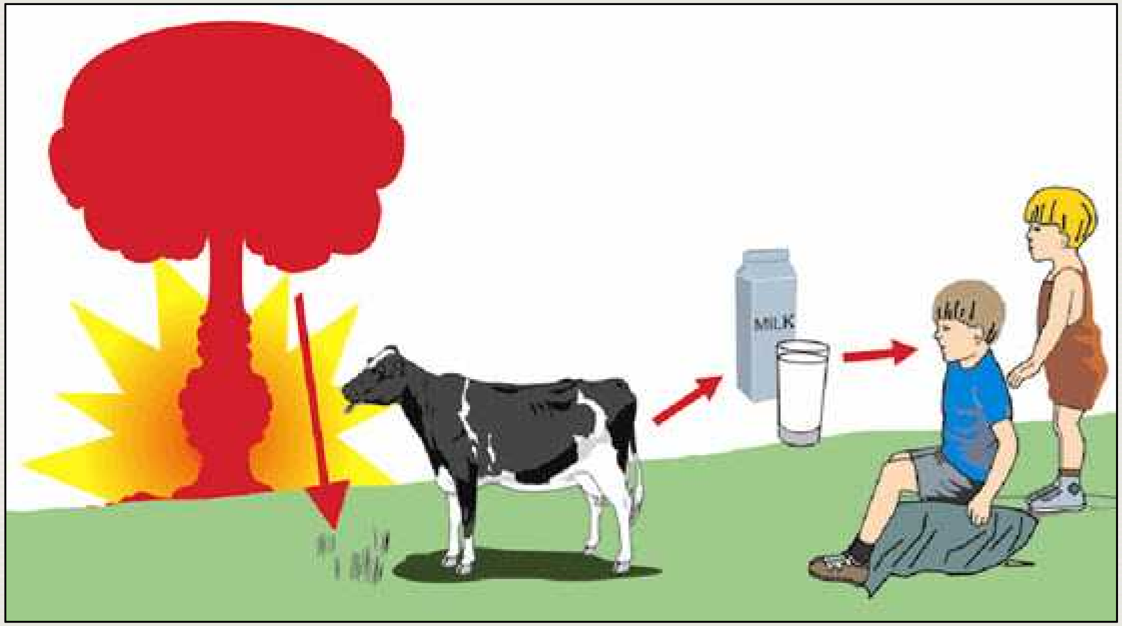


Process for assessing radionuclide concentrations in food (IAEA, 2011)

Dose from Ingestion of Radiologically Contaminated Food

Food can become contaminated by:

- Contamination directly depositing on the edible part of the plant
- Contamination being incorporated into the plant through root uptake
- Resuspended material being deposited on the edible portion of the plant
- Animals consuming contaminated feed and water and then incorporating the contamination into their flesh, milk, eggs, etc.



Dose from Ingestion of Radiologically Contaminated Food

Food contamination level projections:

- Methods are available to project contamination levels in food that have been contaminated by direct contamination, root uptake, and by incorporation into animal products (meat, milk, eggs, etc.)
- These methods can help farmers decide whether or not they should continue spending resources on the food resource.
- Food embargo decisions should always be based on laboratory analysis, not on model projections.

Dose from Ingestion of Radiologically Contaminated Food

Additional Factors to Consider:

- Age group that will consume the food
- How much food do they consume (e.g., kg/yr)
- How long will the contaminated food be eaten?
- Radioactive decay and in-growth modeling
- Are any radioactive decay products in equilibrium with parent radionuclides?

Dose from Ingestion of Radiologically Contaminated Food - IAEA

- IAEA-TECDOC-955 (1997) and IAEA-TECDOC-1162 (2000) specify ingestion dose assessment method
- IAEA General Safety Requirements Part 3 (IAEA Publication 1578, 2014) provides Ingestion dose coefficients for members of the public and workers

TABLE III.2D. MEMBERS OF THE PUBLIC: COMMITTED EFFECTIVE DOSE PER UNIT INTAKE $e(g)$ VIA INGESTION (Sv/Bq)

Radionuclide[a]	Physical half-life	Age ≤ 1 a		f_1 for $g > 1$ a	Age 1–2 a	2–7 a	7–12 a	12–17 a	>17 a
		f_1	$e(g)$		$e(g)$	$e(g)$	$e(g)$	$e(g)$	$e(g)$
Hydrogen									
Tritiated water	12.3 a	1.000	6.4×10^{-11}	1.000	4.8×10^{-11}	3.1×10^{-11}	2.3×10^{-11}	1.8×10^{-11}	1.8×10^{-11}
Organically bound tritium	12.3 a	1.000	1.2×10^{-10}	1.000	1.2×10^{-10}	7.3×10^{-11}	5.7×10^{-11}	4.2×10^{-11}	4.2×10^{-11}
Beryllium									
Be-7	53.3 d	0.020	1.8×10^{-10}	0.005	1.3×10^{-10}	7.7×10^{-11}	5.3×10^{-11}	3.5×10^{-11}	2.8×10^{-11}
Be-10	1.60×10^{6} a	0.020	1.4×10^{-8}	0.005	8.0×10^{-9}	4.1×10^{-9}	2.4×10^{-9}	1.4×10^{-9}	1.1×10^{-9}
Carbon									

Dose from Ingestion of Radiologically Contaminated Food - IAEA

$$E_{Ing} = \sum_{i}^{n} \left(C_{f,i} \times U_{f,i} \times DI_i \times CF_i \right) \times \prod_{j=1}^{n} RF_{i,j}$$

where:

E_{Ing} = Committed effective dose from ingestion, mSv;

$C_{f,i}$ = Activity concentration in food of radionuclide *i*, Bq/kg;

U_{fi} = The amount of food *f* consumed by the population of interest per day. For dirt ingestion maximum adult ingestion is about 100 mg/d with an average of about 25 mg/d; the maximum consumption for a child is 500 mg/d with an average of 100 mg/d, kg/d or L/d;

DI_i = Days of intake is the period food is assumed to be consumed. If $T_{1/2}$ is > 21 days use 30 days. If $T_{1/2}$ is < 21 days use the mean life T_m of the radionuclide, d;

T_m = Mean Life, d;

$$T_m = T_{1/2} \times 1.44$$

where:

$T_{1/2}$ = Radionuclide half-life, d.

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Dose from Ingestion of Radiologically Contaminated Food - IAEA

$$E_{Ing} = \sum_{i}^{n} \left(C_{f,i} \times U_{f,i} \times DI_i \times CF_i \right) \times \prod_{j=1}^{n} RF_{i,j}$$

where (continued):

CF_i = Ingestion dose conversion factor (Table IIIA of IAEA, 1997), mSv/Bq;

RF_j = Reduction Factor is the fraction of contamination remaining after the decay that occurs while the food is held up before consumption, dimensionless.

NOTE: RFs included in IAEA-TECDOC-955, but not included in IAEA-TECDOC-1162

where:

$RF_{i,j}$ = Reduction Factor for decay that occurs while the food is held up before consumption, dimensionless.

$$RF_i = 0.5^{\left(\frac{T_d}{T_{1/2}}\right)}$$

where:

T_d = Time food is held before consumption, d;

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Dose from Ingestion of Radiologically Contaminated Food - IAEA

$$E_{Ing} = \sum_{i}^{n} \left(C_{f,i} \times U_{f,i} \times DI_i \times CF_i \right) \times \prod_{j=1}^{n} RF_{i,j}$$

where (continued):

RF_j = Reduction Factor for some process j used to reduce the contamination before food is consumed, dimensionless. See Table F8 in Procedure F4 for RFs (IAEA, 1997);

Sample Analysis *Procedure F4 Pg. 4 of 8*

TABLE F8 REDUCTION FACTORS FOR PROCESSING OR FILTERING for FOOD

Discussion: Processing or filtering such as water filtration, washing produce or other preparation or culinary practice remove contamination. The reduction factor is based on measurements of contamination conducted before and after the process. The table below provides estimates of the effectiveness of various processes in removing contamination (IAEA94a).

Element	Food	Preparation	RF
Iodine	Spinach	washing	0.8
		washing and boiling	0.7
		rinsing	0.4
	Leaf lettuce	washing	0.5
		rinsing (15 minutes)*	0.2
		rinsing (20 hours)*	0.7
	Cabbage	washing	0.5
		outer leaves removing	0.4

Dose from Ingestion of Radiologically Contaminated Food - IAEA

Accessing Food Safety:

- OIL6 is exceeded when:

$$\sum_{i}^{n} \frac{C_{f,i}}{OIL6_i} > 1$$

where:

$C_{f,i}$ = is the concentration of radionuclide *i* in the food, milk or water, Bq/kg and

$OIL6_i$ = the concentration of radionuclide *i* from Table 10 of IAEA Publication 1467, Bq/kg.

Dose from Ingestion of Radiologically Contaminated Food - IAEA

Example of ingestion dose from contaminated food:

- A leaf lettuce crop is contaminated with I-131 at 3.0E3 Bq/kg
- The lettuce will be held 2 days before it is eaten
- The lettuce crop will be washed before it is eaten
- What is the Committed Effective dose to an adult eating the lettuce?
- How many kg of lettuce/day does the adult eat? Assume the adults eats 0.25 kg/d of lettuce

Decay Properties: I-131

Columns ▾ Show Legends

Radionuclide	Half-Life	Decay Mode	Decay Constant	Branch Factor
^{131}I	8.04	B-	8.62E-2	N/A
^{131m}Xe	11.9	IT	5.82E-2	1.11E-2
	d		d^{-1}	Fraction

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Dose from Ingestion of Radiologically Contaminated Food - IAEA

- Ingestion dose coefficients for members of the public from IAEA General Safety Requirements Part 3 (IAEA Publication 1578, 2014)

TABLE III.2D. MEMBERS OF THE PUBLIC: COMMITTED EFFECTIVE DOSE PER UNIT INTAKE $e(g)$ VIA INGESTION (Sv/Bq) (cont.)

Radionuclide[a]	Physical half-life	Age ≤1 a		f_1 for g > 1 a	Age 1–2 a	2–7 a	7–12 a	12–17 a	>17 a
		f_1	$e(g)$		$e(g)$	$e(g)$	$e(g)$	$e(g)$	$e(g)$
Iodine									
I-120	1.35 h	1.000	3.9×10^{-9}	1.000	2.8×10^{-9}	1.4×10^{-9}	7.2×10^{-10}	4.8×10^{-10}	3.4×10^{-10}
I-120m	0.883 h	1.000	2.3×10^{-9}	1.000	1.5×10^{-9}	7.8×10^{-10}	4.2×10^{-10}	2.9×10^{-10}	2.1×10^{-10}
I-121	2.12 h	1.000	6.2×10^{-10}	1.000	5.3×10^{-10}	3.1×10^{-10}	1.7×10^{-10}	1.2×10^{-10}	8.2×10^{-11}
I-123	13.2 h	1.000	2.2×10^{-9}	1.000	1.9×10^{-9}	1.1×10^{-9}	4.9×10^{-10}	3.3×10^{-10}	2.1×10^{-10}
I-124	4.18 d	1.000	1.2×10^{-7}	1.000	1.1×10^{-7}	6.3×10^{-8}	3.1×10^{-8}	2.0×10^{-8}	1.3×10^{-8}
I-125	60.1 d	1.000	5.2×10^{-8}	1.000	5.7×10^{-8}	4.1×10^{-8}	3.1×10^{-8}	2.2×10^{-8}	1.5×10^{-8}
I-126	13.0 d	1.000	2.1×10^{-7}	1.000	2.1×10^{-7}	1.3×10^{-7}	6.8×10^{-8}	4.5×10^{-8}	2.9×10^{-8}
I-128	0.416 h	1.000	5.7×10^{-10}	1.000	3.3×10^{-10}	1.6×10^{-10}	8.9×10^{-11}	6.0×10^{-11}	4.6×10^{-11}
I-129	1.57×10^{7} a	1.000	1.8×10^{-7}	1.000	2.2×10^{-7}	1.7×10^{-7}	1.9×10^{-7}	1.4×10^{-7}	1.1×10^{-7}
I-130	12.4 h	1.000	2.1×10^{-8}	1.000	1.8×10^{-8}	9.8×10^{-9}	4.6×10^{-9}	3.0×10^{-9}	2.0×10^{-9}
I-131	8.04 d	1.000	1.8×10^{-7}	1.000	1.8×10^{-7}	1.0×10^{-7}	5.2×10^{-8}	3.4×10^{-8}	2.2×10^{-8}
I-132	2.30 h	1.000	3.0×10^{-9}	1.000	2.4×10^{-9}	1.3×10^{-9}	6.2×10^{-10}	4.1×10^{-10}	2.9×10^{-10}
I-132m	1.39 h	1.000	2.4×10^{-9}	1.000	2.0×10^{-9}	1.1×10^{-9}	5.0×10^{-10}	3.3×10^{-10}	2.2×10^{-10}
I-133	20.8 h	1.000	4.9×10^{-8}	1.000	4.4×10^{-8}	2.3×10^{-8}	1.0×10^{-8}	6.8×10^{-9}	4.3×10^{-9}
I-134	0.876 h	1.000	1.1×10^{-9}	1.000	7.5×10^{-10}	3.9×10^{-10}	2.1×10^{-10}	1.4×10^{-10}	1.1×10^{-10}

Dose from Ingestion of Radiologically Contaminated Food - IAEA

$$E_{Ing} = \sum_{i}^{n} \left(C_{f,i} \times U_{f,i} \times DI_i \times CF_i \right) \times \prod_{j=1}^{n} RF_{i,j}$$

where:

- E_{Ing} = Adult Committed Effective dose from ingestion of I-131, mSv;
- $C_{f,i}$ = I-131 activity concentration in food of radionuclide *i*, 3E+03 Bq/kg;
- U_{fi} = Adult lettuce intake, 0.250 kg/d
- DI_i = I-131 days of intake, 11.6 d;

$$T_m = T_{1/2} \times 1.44 = 8.04\ d \times 1.44 = 11.6\ d$$

- CF_i = Adult Committed Effective Ingestion dose conversion factor, 2.2E-05 mSv/Bq;
- RF_j = Reduction Factor for decay over 2 day hold up period, 0.84, dimensionless; and

$$RF_i = 0.5^{\left(\frac{T_d}{T_{1/2}}\right)} = 0.5^{\left(\frac{2.0\,d}{8.04\,d}\right)} = 0.84$$

- RF_j = Reduction Factor for washing, 0.5, dimensionless;

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Dose from Ingestion of Radiologically Contaminated Food - IAEA

$$E_{Ing,I131} = \sum_{i}^{n}\left(\frac{3.0\text{+}03\ \mathrm{Bq}_{I131}}{\mathrm{Kg}} \times \frac{0.25\ \mathrm{kg}}{\mathrm{d}} \times 11.6\ \mathrm{d} \times \frac{2.2\mathrm{E\text{-}05\ mSv}}{\mathrm{Bq}_{I131}}\right)_i \times (0.84 \times 0.5)$$

$$= 0.080\ \mathrm{mSv}$$

Therefore, the adult's Committed Effective Dose from eating the contaminated leaf lettuce is 0.080 mSv.

Does this exceed the IAEA's generic dose criterion for ingestion?

NO!, because the generic dose limit criterion for ingestion is 10 mSv per annum

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Dose from Ingestion of Radiologically Contaminated Food – United States

- A similar method is used in the United States to assess the dose from contaminated food, milk, and water.
- Method 3.5 in the FRMAC Assessment Manual, Volume 1
- The main differences are:
  - 30% of the entire diet intake (kg/d) is assumed to be the contaminated food being assessed
  - Default intake period is 365 days (IAEA is ≤ 30 days)
  - Radioactive decay is accounted intake period

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Dose from Ingestion of Radiologically Contaminated Food – United States

$$E_{Ing,age} = \sum_{Subgroup} \left(DFIR_{subgroup,age} \times FFC_{subgroup} \times IngDP_{E,avg,age} \right)$$

$$mSv = \sum_{Subgroup} \left(\frac{kg_{wet}}{d} \times unitless \times \frac{mSv \cdot d}{kg_{wet}} \right)$$

where:

$E_{ing,age}$	=	Committed Effective Dose from ingestion, the dose to the whole body, received by a specific age group from ingestion of all radionuclides in all contaminated food types, mSv;
$DFIR_{subgroup,age}$	=	Daily Food Intake Rate for a food subgroup (as prepared for consumption, i.e. wet mass) for a specific age group, kg_{wet}/d;
$FFC_{subgroup,i}$	=	Fraction of Food Subgroup Contaminated, dimensionless;
$IngDP_{E, avg,age}$	=	Average Ingestion Dose Parameter for a food subgroup, the average of the individual $IngDP_{E,f,age}$ for each type of contaminated food in a subgroup for a specific age group, $mSv \cdot d/kg_{wet}$.;

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Dose from Ingestion of Radiologically Contaminated Food – United States

$$IngDP_{E,f,age} = \sum_i \left(C_{f,i} \times IngDC_{E,age,i} \times e^{-\lambda_i t_h} \times \frac{1 - e^{-\lambda_i t_c}}{\lambda_i} \right)$$

$$\frac{\text{mSv}\cdot\text{d}}{\text{kg}_{\text{wet}}} = \sum_i \left(\frac{\mu\text{Ci}}{\text{kg}_{\text{wet}}} \times \frac{\text{mSv}}{\text{Bq}} \times \text{unitless} \times \frac{\text{unitless}}{\text{d}^{-1}} \right)$$

where:

$IngDP_{E,f,age}$	=	Ingestion Dose Parameter, the committed effective dose received from ingestion of all radionuclides in a specific food type (*f*) by a specific age group, mSv·d/kg_{wet};
$C_{f,i}$	=	Food Contamination, the level of contamination of radionuclide *i* in a specific food type (*f*), Bq/kg_{wet} or Bq/l;
$IngDC_{E,age,i}$	=	Ingestion Dose Coefficient, the ingestion pathway dose coefficient for the whole body (*E*) for a specific age group for radionuclide *i*, mSv/Bq;
λ_i	=	Decay constant for radionuclide *i*, d^{-1};

Dose from Ingestion of Radiologically Contaminated Food – United States

$$IngDP_{E,f,age} = \sum_i \left(C_{f,i} \times IngDC_{E,age,i} \times e^{-\lambda_i t_h} \times \frac{1-e^{-\lambda_i t_c}}{\lambda_i} \right)$$

Where (continued):

t_h	=	Hold Time, the time elapsed from sample measurement to the beginning of the consumption period, d;
$e^{-\lambda_i t_h}$	=	Radioactive Decay adjustment for radionuclide *i* over time t_h, unitless;
t_h	=	Hold Time, the time elapsed from sample measurement to the beginning of the consumption period, d;
t_c	=	Consumption Time, the length of the consumption period (default 365 days), d; and
$\frac{1-e^{-\lambda_i t_c}}{\lambda_i}$	=	Integrated decay of radionuclide *i* over the length of consumption period, d.

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Example of Dose from Ingestion of Radiologically Contaminated Food

Example of projected dose from eating contaminated food using the Turbo FRMAC © software tool (SNL, 2015a)

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Example of Dose from Ingestion of Radiologically Contaminated Food

- A batch of fresh produce (fruit) was suspected of being contaminated after it was consumed over a 30 day period.
- Based on laboratory analyses, the radionuclide concentrations at the beginning of the 30 d consumption period were:

Radio-nuclide	Results (Bq/kg)
Am-241	40.1
Pu-238	125
Pu-239	520

Mmmmm! Mommy this watermelon tastes like Americium and Plutonium! Can I eat it without exceeding the IAEA's generic criteria?

Example of Dose from Ingestion of Radiologically Contaminated Food

- You have been asked to:
  - Estimate the Committed Effective dose to all age groups,
  - To identify the most restrictive age group,
  - Consider if it is appropriate to use the most conservative age group (e.g., does this age group eat significant amounts of fresh produce?), and
  - To estimate if the generic criteria has been exceeded.
- Assume that the receptor's entire dietary intake (kg/d) of fresh produce was the contaminated produce
- Assume the contaminated produce was consumed for 30 d

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Example of Dose from Ingestion of Radiologically Contaminated Food

- *IAEA Criteria for Use in Preparedness and Response for a Nuclear or Radiological Emergency*, General Safety Guide No. GSG-2, Publication 1467, International Atomic Energy Agency, 2011
- OIL5 and OIL6 are measured values of concentrations in food, milk or water that warrant the consideration of restrictions on consumption so as to keep the **effective dose** to any person **below 10 mSv per annum**.

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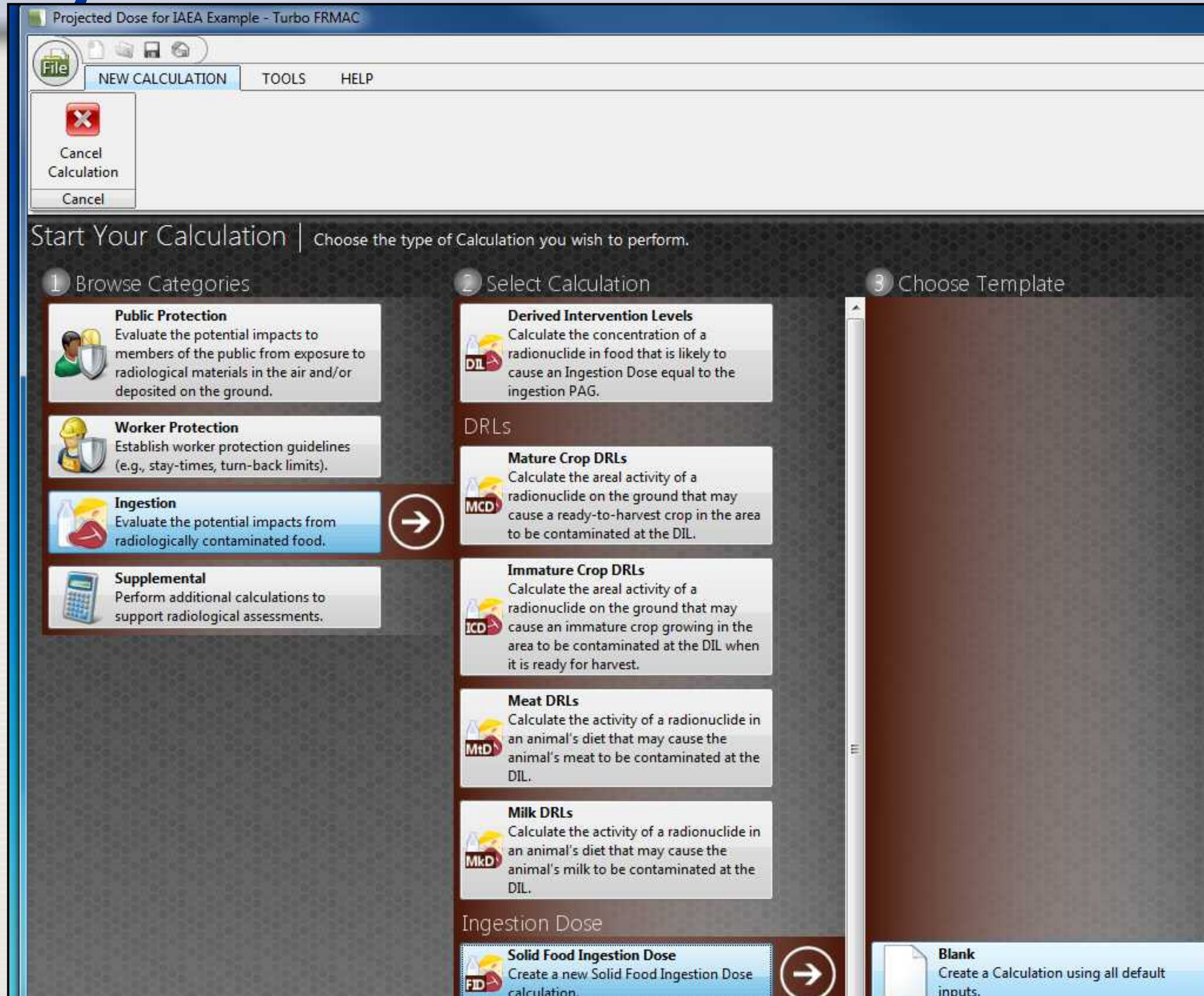
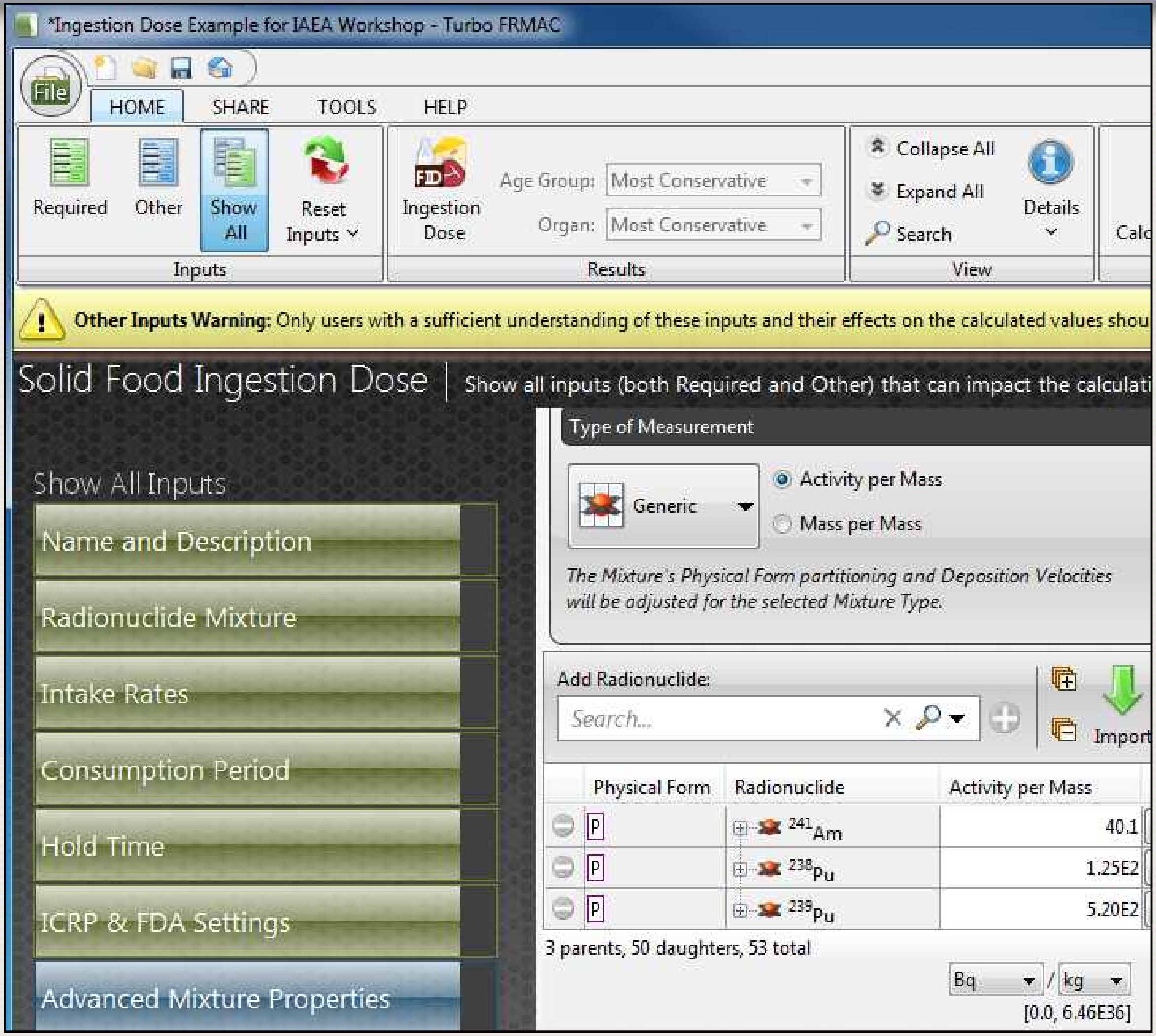
Example of Dose from Ingestion of Radiologically Contaminated Food

- Start the Turbo FRMAC © software tool (SNL, 2015a)
- Open a blank Solid Food Ingestion Dose case



Example of Dose from Ingestion of Radiologically Contaminated Food

- Enter the radionuclide contamination values of the fresh produce



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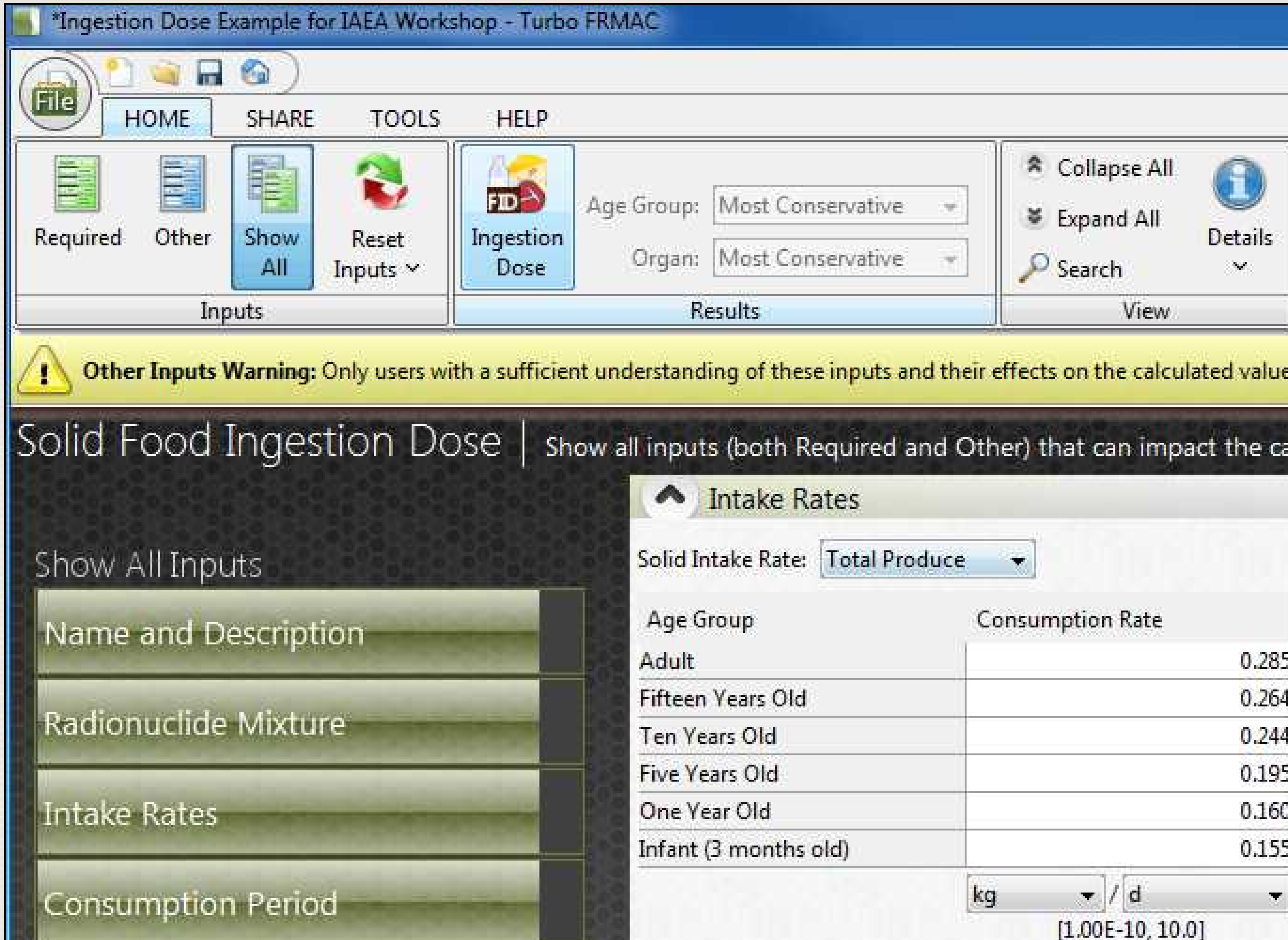
Example of Dose from Ingestion of Radiologically Contaminated Food

- Select the fresh produce intake rates



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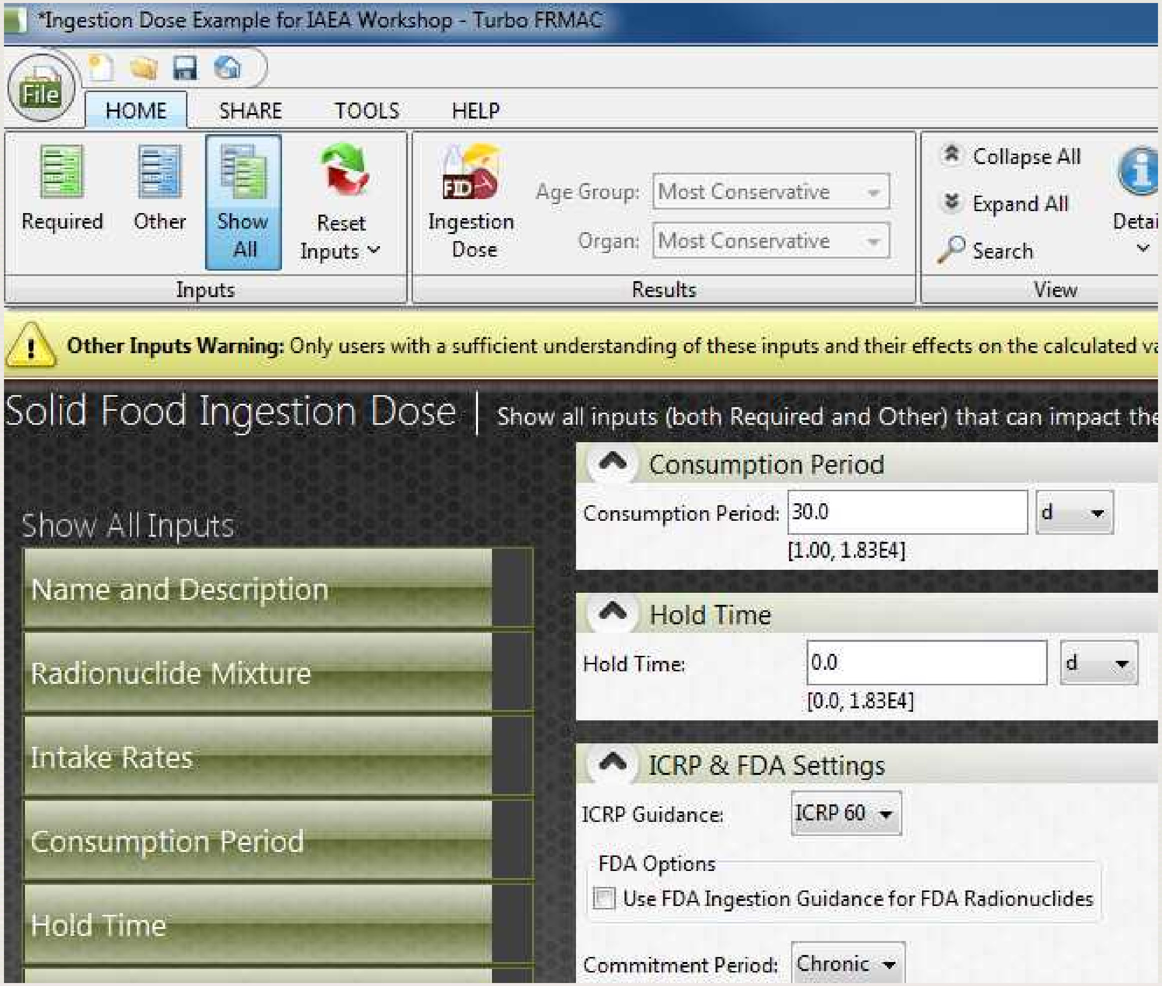
Example of Dose from Ingestion of Radiologically Contaminated Food

- Select the Consumption Period
- Select the Hold Time (assume no hold time because lab. results were set at the time consumption began)



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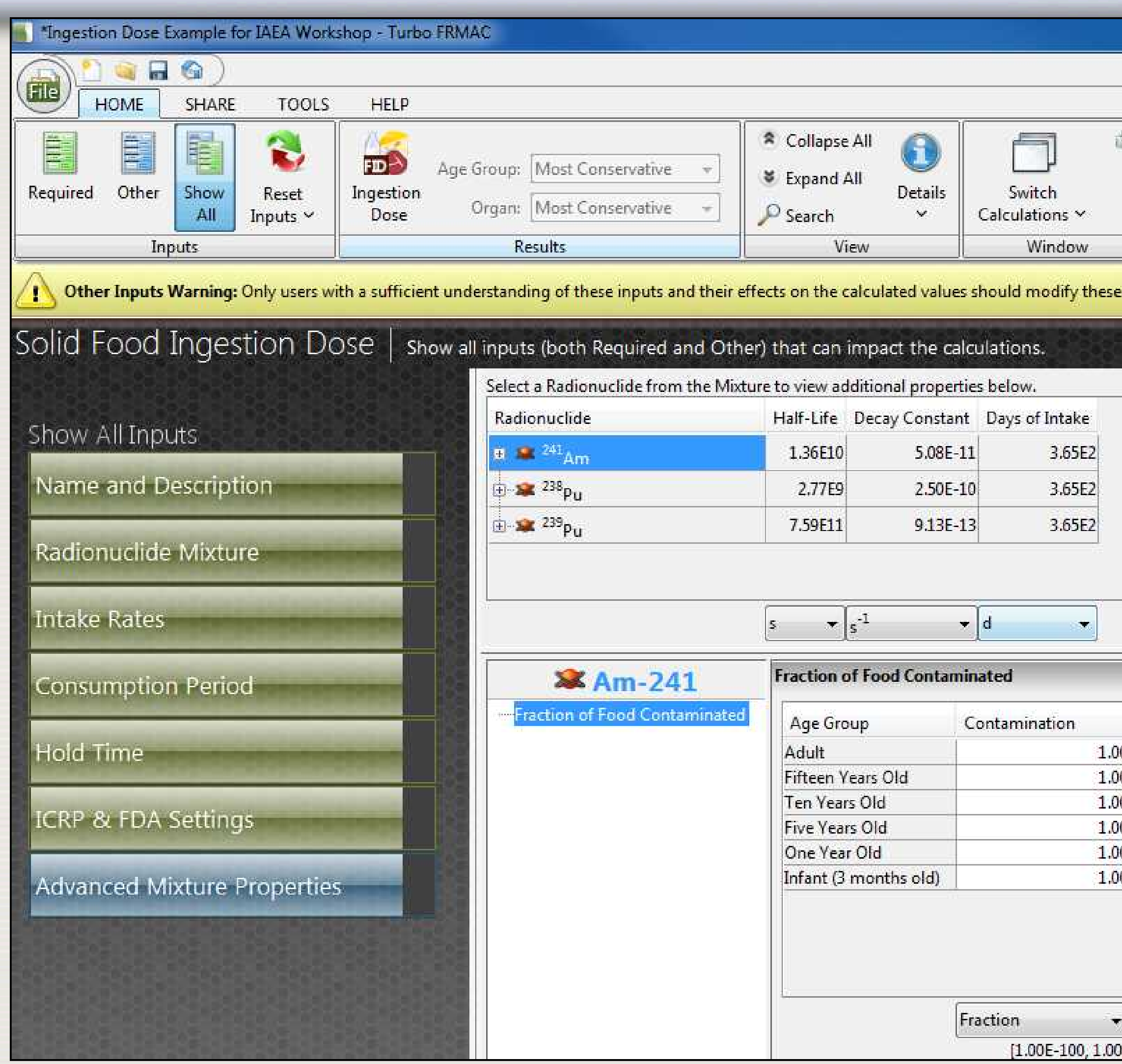
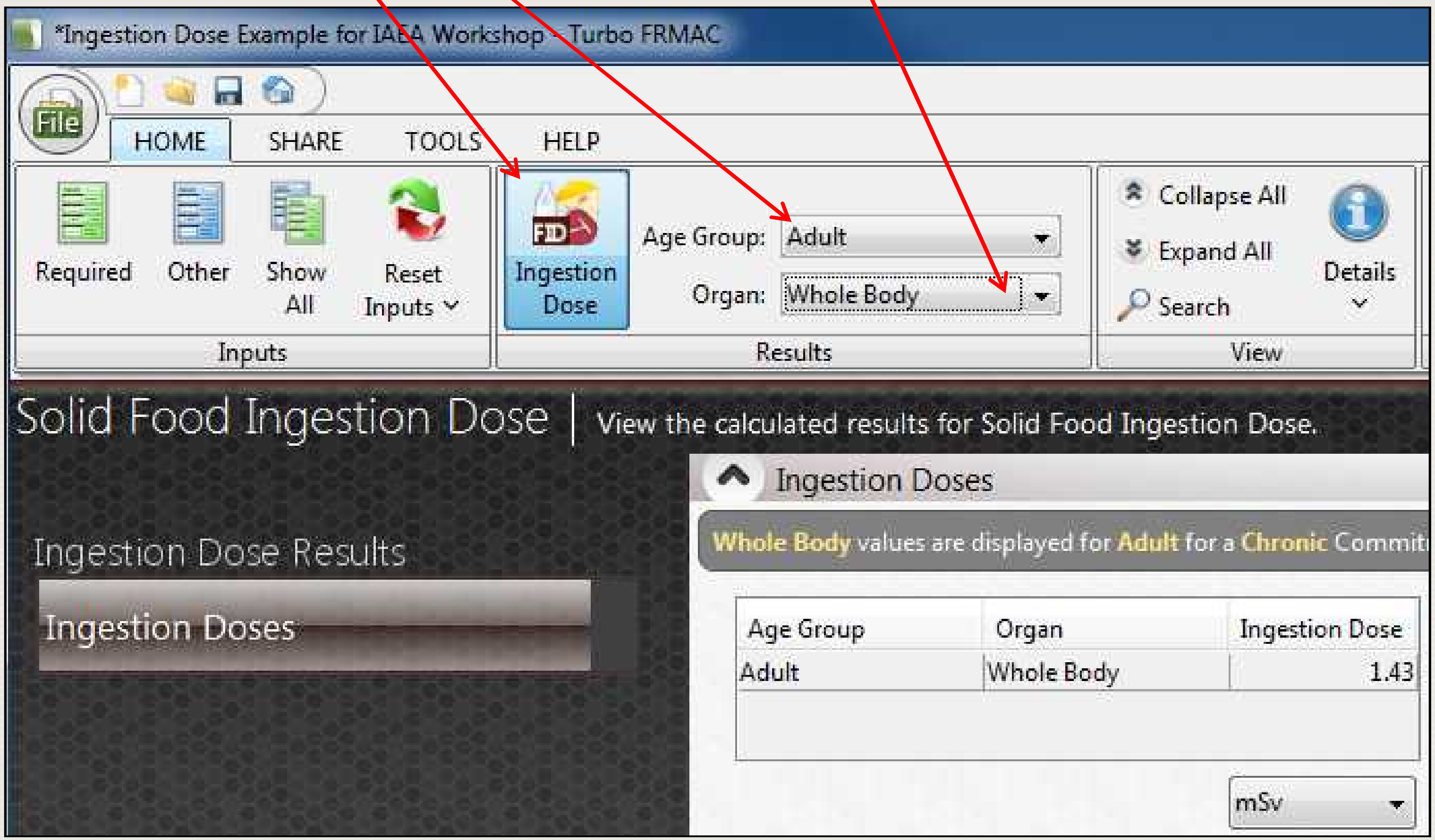
Example of Dose from Ingestion of Radiologically Contaminated Food

- Set the Fraction of Food Contaminated to 1.0 for all radionuclides and for all age groups



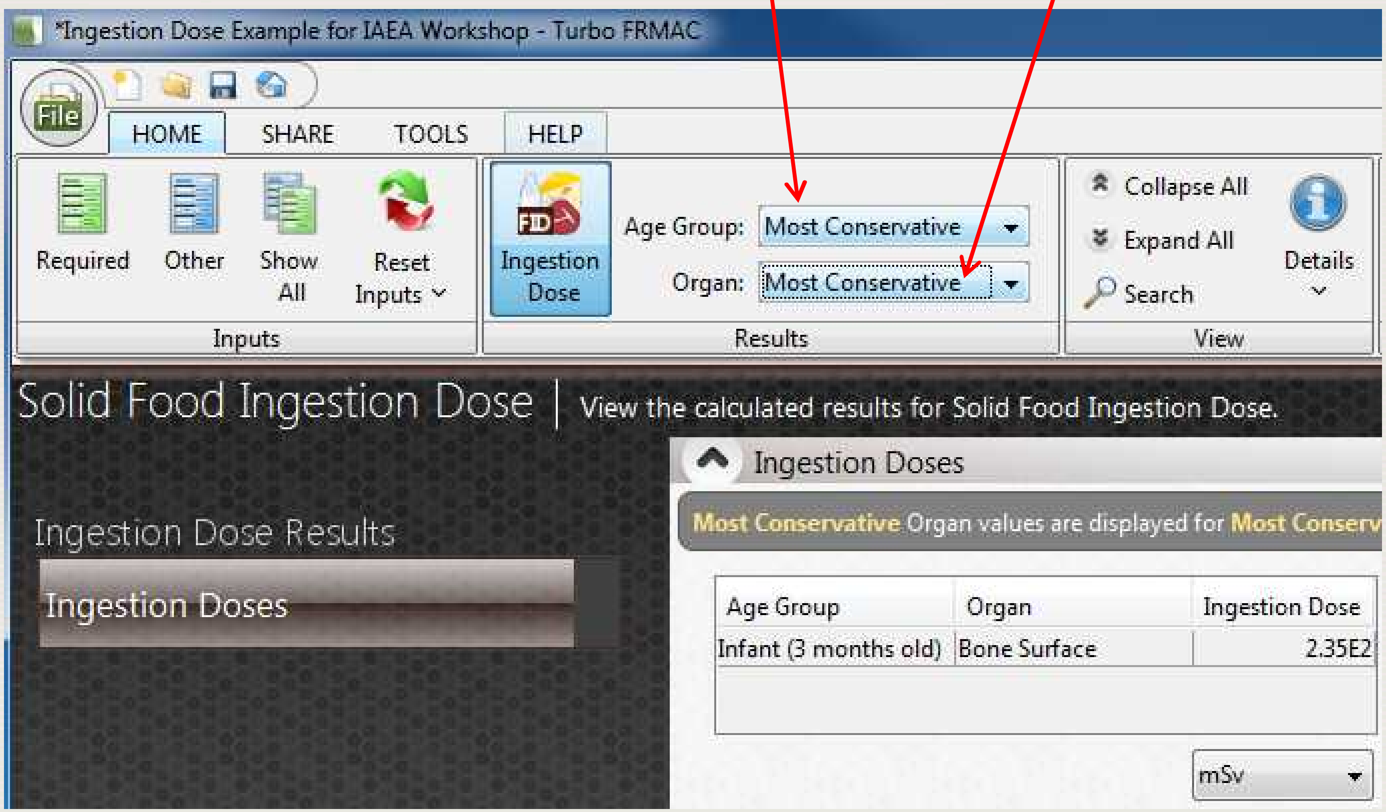
Example of Dose from Ingestion of Radiologically Contaminated Food

- Click on Ingestion Dose to view the estimated dose results
- Select the desired Age Group and Organ



Example of Dose from Ingestion of Radiologically Contaminated Food

- Select the Most Conservative Age Group and Organ
- Does this age group eat significant amounts of fresh produce?



Example of Dose from Ingestion of Radiologically Contaminated Food

- Is the Generic Criteria of 10 mSv (Effective Dose) met or exceeded?
- Does the 3 month old eat significant amounts of fresh produce?

Estimated Committed Effective and Committed Equivalent (Bone Surface) doses from eating contaminated fresh produce

Age Group	Committed Effective Dose (E) (mSv)	Most Conservative Equivalent Dose ($H_{Bone\ Surfaces}$) (mSv)
Adult	1.43	47.7
15 y old	1.30	38.8
10 y old	1.32	33.7
5 y old	1.30	27.8
1 y old	1.36	24.7
3 month old	13.1	235

Lecture 4b.5

- Summary of Key Points:
  - IAEA guidance provides operational intervention levels (OILs), emergency action levels (EALs), and generic dose criteria for ingestion assessments
  - Ingestion dose assessments can be relatively simple, but quickly become more complicated as the number of radionuclide contaminants increase
  - Use a software tool to speed up assessments and to minimize errors

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