

Radionuclide Pathways

4/22/2010

Introduction

Introduction

General

Radionuclides released into the environment by a nuclear facility, as well as the radiation emitted by that facility, result in a dose to the public.

The NRC limits on the exposure to the public are found in 10 CFR 20:

§ 20.1301 Dose limits for individual members of the public.

(a) Each licensee shall conduct operations so that—

(1) The total effective dose equivalent to individual members of the public from the licensed operation does not exceed 0.1 rem (1 mSv) in a year, exclusive of the dose contributions from background radiation . . .

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Measurements must be made “as appropriate” in the environment and effluents:

§ 20.1302 Compliance with dose limits for individual members of the public.

(a) The licensee shall make or cause to be made, as appropriate, surveys of radiation levels in unrestricted and controlled areas and radioactive materials in effluents released to unrestricted and controlled areas to demonstrate compliance with the dose limits for individual members of the public in § 20.1301.

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General

There are different ways to show compliance. One is to determine the highest TEDE to a member of the public via measurement or calculation:

§ 20.1302 Compliance with dose limits for individual members of the public.

(b) A licensee shall show compliance with the annual dose limit in § 20.1301 by—

(1) Demonstrating by measurement or calculation that the total effective dose equivalent to the individual likely to receive the highest dose from the licensed operation does not exceed the annual dose limit; or

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Another method to show compliance is to compare concentrations in the effluent at the facility boundary to limits in Appendix B:

(2) Demonstrating that—

(i) The annual average concentrations of radioactive material released in gaseous and liquid effluents at the boundary of the unrestricted area do not exceed the values specified in table 2 of appendix B to part 20; and

(ii) If an individual were continuously present in an unrestricted area, the dose from external sources would not exceed 0.002 rem (0.02 mSv) in an hour and 0.05 rem (0.5 mSv) in a year.

Introduction

General

Atomic No.	Radionuclide	Class	Table 1 Occupational Values			Table 2 Effluent Concentrations		Table 3 Releases to Sewers
			Col. 1 Oral Ingestion ALI (μCi)	Inhalation		Col. 1 Air ($\mu\text{Ci}/\text{m}^3$)	Col. 2 Water ($\mu\text{Ci}/\text{m}^3$)	Monthly Average Concentration ($\mu\text{Ci}/\text{m}^3$)
				Col. 2 ALI (μCi)	Col. 3 DAC ($\mu\text{Ci}/\text{m}^3$)			
53	Iodine-130	D, all compounds	4E+2 Thyroid (1E+3)	7E+2 Thyroid (2E+3)	3E-7 - -	- 3E-9	- 2E-5	- 2E-4
53	Iodine-131	D, all compounds	3E+1 Thyroid (9E+1)	5E+1 Thyroid (2E+2)	2E-8 - -	- 2E-10	- 1E-6	- 1E-5

Introduction

General

When demonstrating compliance by determining the highest likely dose to an individual, one or both of the following must be done. Each has advantages and disadvantages:

1. Collection and/or analysis of environmental media at the boundary of the unrestricted area and/or at the residence of the individual expected to receive the highest dose. (environmental monitoring/surveillance)
2. Pathways analysis
(mathematical calculation)

Introduction

General

1. Collection and/or Analysis of Environmental Media

Advantages:

- If the radionuclides are at high enough levels to be measured, a direct measurement eliminates the large degree of uncertainty associated with a mathematical pathways analysis.

In extreme cases, the radionuclide concentration in an exposed individual (s) might be measured directly (e.g., I-131 in thyroid), or the dose might be estimated by chromosomal analysis.

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General

1. Collection and/or Analysis of Environmental Media

Disadvantages:

- Radionuclide concentrations in the air, water, soil and food samples might be too low to be measured.
- The concentrations exhibit considerable variation from one location to another. Even if the radioactive material could be measured, an excessively large number of samples might have to be collected to permit a reasonable estimate of the dose.

Introduction

General

2. Pathways Analysis

Advantages:

- A pathways analysis can predict concentrations in the environment that are below our ability to measure in a collected sample.
- The analysis can predict the concentration in any location, not just a few locations.

Introduction

General

2. Pathways Analysis

Disadvantages:

- There can be substantial uncertainty associated with a mathematical analysis even when the source term is well known precisely:
 - There are uncertainties in how closely the mathematical equations reflect the actual radionuclide pathways.
 - There are uncertainties in the input parameters to the equations.

Introduction

Purpose of the Presentation

The purpose of this presentation is to provide some insight into how a pathways analysis might be performed. In other words, to show how mathematical models can be used to estimate the concentration of radionuclides in the environment and thereby calculate the dose to the public.

The methodology of Regulatory Guide 1.109 will be considered and some example calculations will be performed “by hand.”

In the “real world”, these calculations would be performed by computers.

Environmental Inventory

Environmental Inventory

General

The environmental inventory is the total activity of a radionuclide in the environment as a result of releases from a facility (e.g., Bq of Cs-137).

Although it doesn't assist in estimating the dose to the public, the environmental inventory concept can provide insight into the levels of radionuclides in the environment.

Environmental Inventory

General

The environmental inventory is calculated as follows:

$$A = \frac{Q}{\lambda}(1 - e^{-\lambda t})$$

A is the environmental inventory (e.g., Bq)

Q is the release rate (e.g., Bq/s)

λ is the decay constant of the radionuclide (e.g., s⁻¹)

t is the duration of the release (e.g., s)

Environmental Inventory

Example 1.

A facility releases 0.01 GBq/day of I-131.

Calculate the environmental inventory after 365 days of continuous release.

The decay constant for I-131 is:

$$\lambda = \frac{0.693}{T} = \frac{0.693}{8d} = 0.0866 d^{-1}$$

Environmental Inventory

Example 1.

$$\begin{aligned} A &= \frac{Q}{\lambda}(1 - e^{-\lambda t}) \\ &= \frac{0.01}{0.0866}(1 - e^{-0.0866 \times 365}) \\ &= 0.115(1 - e^{-31.6}) \\ &= 0.115 \text{GBq} \end{aligned}$$

The half life of I-131 is sufficiently short that the equilibrium (maximum) activity has been achieved. Extending the duration of the release beyond 365 days will not increase the environmental inventory.

Environmental Inventory

Example 2.

A facility releases 0.01 GBq/day of Cs-137. Calculate the environmental inventory after 365 days of continuous release.

The decay constant for Cs-137 is:

$$\lambda = \frac{0.693}{T} = \frac{0.693}{10,983 d} = 6.31 \times 10^{-5} d^{-1}$$

Environmental Inventory

Example 2.

$$\begin{aligned} A &= \frac{Q}{\lambda}(1 - e^{-\lambda t}) \\ &= \frac{0.01}{6.31 \times 10^{-5}}(1 - e^{-6.31 \times 10^{-5} \times 365}) \\ &= 158(1 - 0.977) \\ &= 3.6 \text{GBq} \end{aligned}$$

Even though they have the same release rates (GBq/d) and duration of release, the Cs-137 environmental inventory is much greater than that of I-131. Furthermore, the Cs-137 inventory continues to increase for approximately 150 years before reaching its maximum activity.

Conceptual Site Model

Conceptual Site Model

General

The conceptual site model (CSM) is a “picture” of the site. Producing this picture involves identifying the:

- Source term
- Exposed population of concern
- Exposure pathways

Whether or not it is considered part of the CSM, site-specific information will eventually be needed about wind direction, wind speed, atmospheric stability, soil characteristics, surface and groundwater flow, etc.

Conceptual Site Model

General

The conceptual site model can vary dramatically from one type of facility to another, e.g.:

nuclear power plant

accelerator

low level waste site

uranium recovery facility

decommissioned property

Conceptual Site Model

Source Term – Nuclear Power Plant

The primary source terms are the release rates (e.g., Ci/s) of the radionuclides in the gaseous and liquid effluents.

These release rates are usually known fairly accurately because the effluents are monitored closely.

The source term might include more than a dozen fission products and activation products.

Conceptual Site Model

Source Term – Accelerator

The primary source term might be the release rate of short-lived radionuclides (e.g., C-11, N-13, O-15) in the stack gases.

Another important source term might be neutron and gamma shine, i.e., exposure of the public to scattered neutrons and gamma rays from the facility.

These release rates are usually known fairly accurately due to monitoring.

Conceptual Site Model

Source Term – Low Level Waste Site

The primary source term might be the total activities of the buried radionuclides.

Since there are no stack or liquid effluent discharge points to monitor, considerable uncertainty can exist regarding the rate at which the material is released to the environment.

Radionuclides get into the air via evaporation and suspension. The buried material can get into the groundwater via leaching.

Conceptual Site Model

Source Term – Uranium Recovery Facility

The source term would typically be the activity of the material processed each year. If there are mill tailings impoundments, the concentration in the impoundments would be needed.

Radon releases are a major concern at both conventional uranium mills and in-situ leach facilities.

Surface runoff into offsite lakes or streams and the release of airborne particulate uranium and is much more of an issue at conventional mills than in-situ operations

Contamination of groundwater is a concern at all uranium recovery facilities.

These releases can be difficult to quantify.

Conceptual Site Model

Source Term – Decommissioned Property

The principal source term is usually the concentration of the radionuclides in the surface soil.

Conceptual Site Model

Exposed Population of Concern

In most cases, the population of concern is the maximally exposed individual. This is usually the individual living at the nearest downwind residence. In the case of decommissioned property, it would likely be a residential farmer living on the contaminated land.

In other cases, the concern might be the dose to the nearest downwind community.

Conceptual Site Model

Exposure Pathways - Nuclear Power Plant

Exposure pathways are often divided into those of the:

- aquatic ecosystem
- terrestrial ecosystem

The aquatic and terrestrial exposure pathways on the next two slides are identified in Regulatory Guide 1.109.

Other significant pathways identified at a facility must be accounted for in the dose calculations.

Conceptual Site Model

Exposure Pathways - Nuclear Power Plant

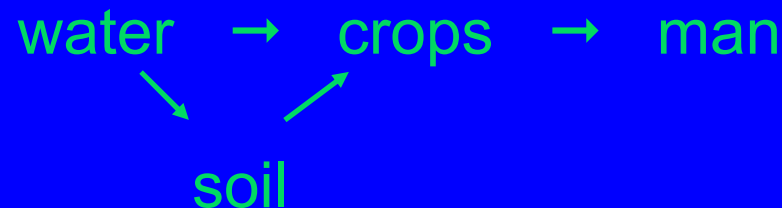
Important pathways for the aquatic ecosystem:

Potable Water: water → man

Aquatic Foods: water → fish → man

Shoreline Deposits: water → sediment → shore → man

Crops irrigated with contaminated water:



Conceptual Site Model

Exposure Pathways - Nuclear Power Plant

Important pathways for the terrestrial ecosystem:

Submersion: air → man (noble gases only)

Inhalation: air → man

External Gamma: air → ground → man

Food: air → vegetables/produce → man

soil

air → forage → milk → man

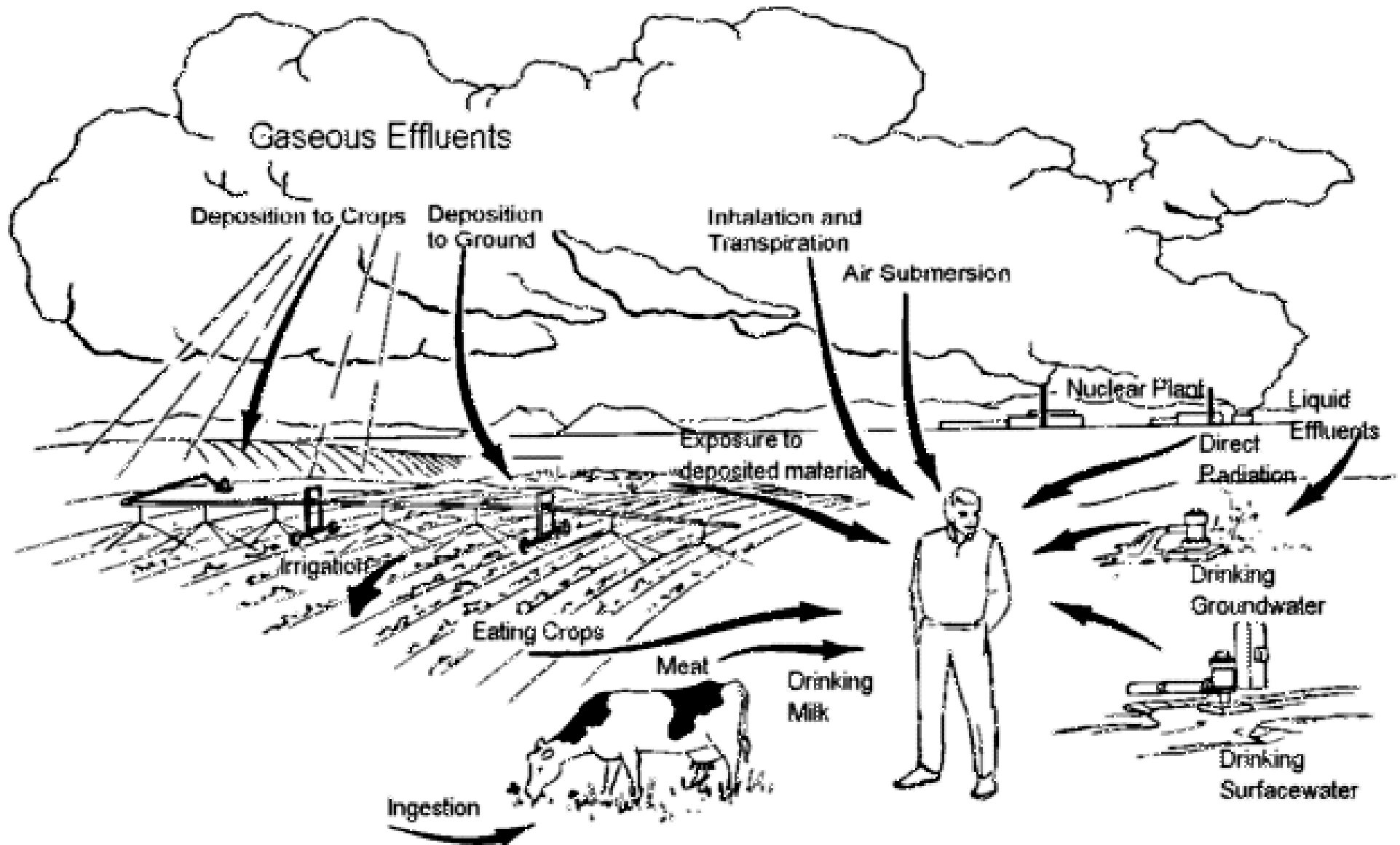
soil

air → forage → meat → man

soil

Conceptual Site Model

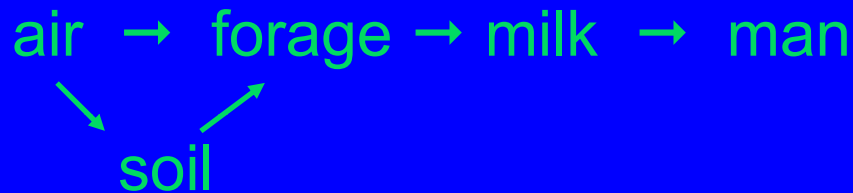
Exposure Pathways - Nuclear Power Plant



Conceptual Site Model

Exposure Pathways - Nuclear Power Plant

At a nuclear power plant, one of the more important pathways involves the deposition of radionuclides on pasture grass and the consumption of milk.



Since cows consume large areas of pasture grass (and soil), high levels of deposited radionuclides can be found in milk.

I-131 is particularly important because it has a short half-life and milk is one of the few foods consumed immediately after production.

Mathematical Models of Environmental Transport

Mathematical Models of Environmental Transport

General

Once the conceptual site model has been developed, it is necessary to generate the mathematical equations that:

- Describe the rate and direction of the radionuclides through the environment
- Calculate the concentration of the radionuclides in different components of the environment
- Estimate the dose to the public

Mathematical Models of Environmental Transport

General

There are two approaches to the mathematical modeling:

Systems Analysis Approach

- Dynamic, calculates concentrations and exposures at any specified time.
- Requires considerable amount of input data.
- Too complicated for routine use.

Concentration Factor Approach

- Only calculates annual average concentrations and exposures.
- Limited input data required.
- Simple, appropriate for routine use.

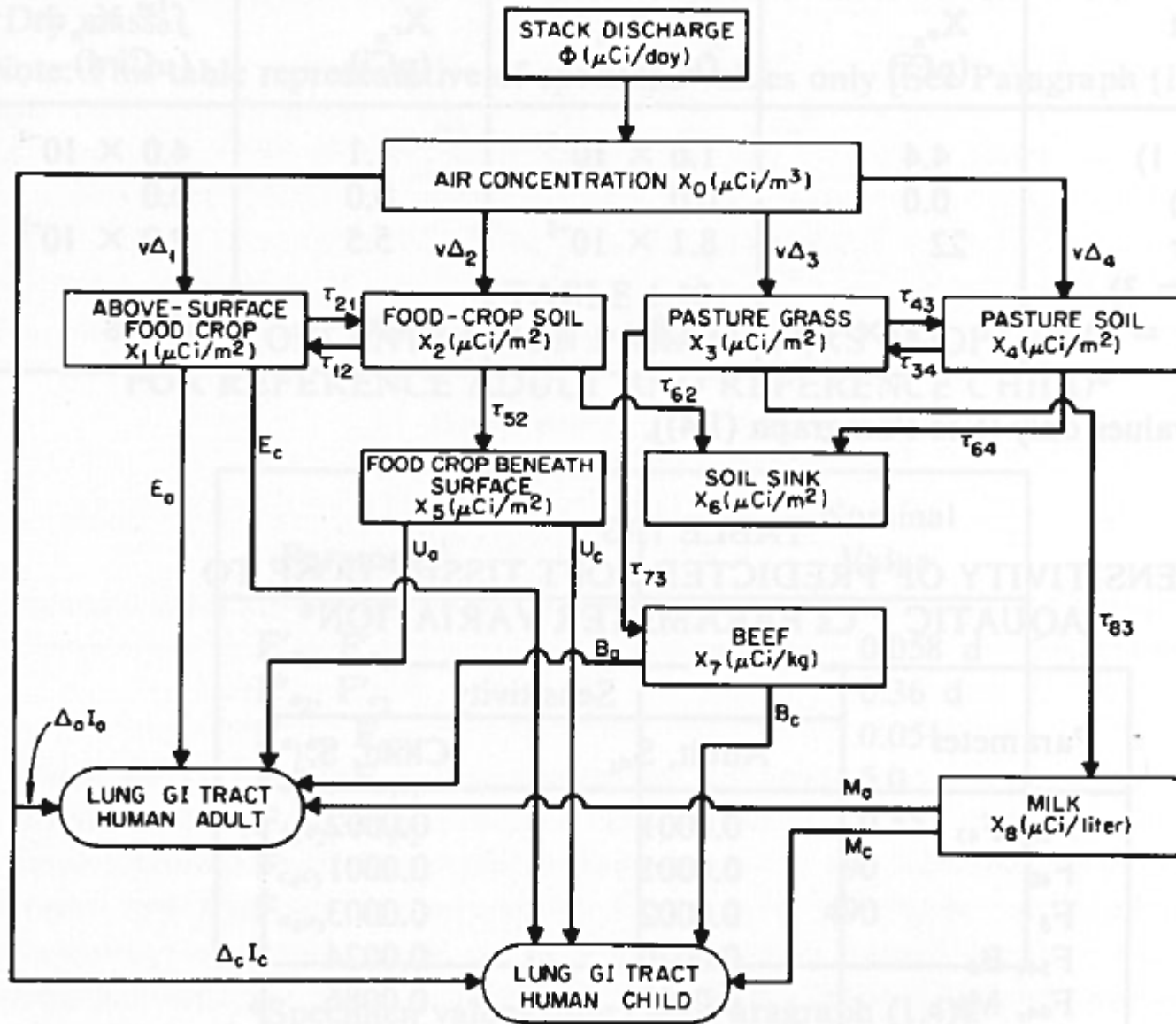
Mathematical Models of Environmental Transport

Systems Analysis Approach

- The following slide shows an SA conceptual model of a compartmentalized terrestrial environment.
- The compartmental concentrations are symbolized by the Greek letter χ
- The transfer coefficients (τ) indicate the rate of movement of the radionuclides between compartments.
- The arrows indicate the direction of movement between compartments. Note that arrows sometimes go in both directions between two compartments.

Mathematical Models of Environmental Transport

Systems Analysis Model of Terrestrial Ecosystem (ICRP 29)



Mathematical Models of Environmental Transport

Systems Analysis Approach

- Differential equations showing the rate of change of the radionuclide concentrations in the various environmental compartments are set up and solved.
- As an example, we will set up the differential equation for compartment three (pasture grass):

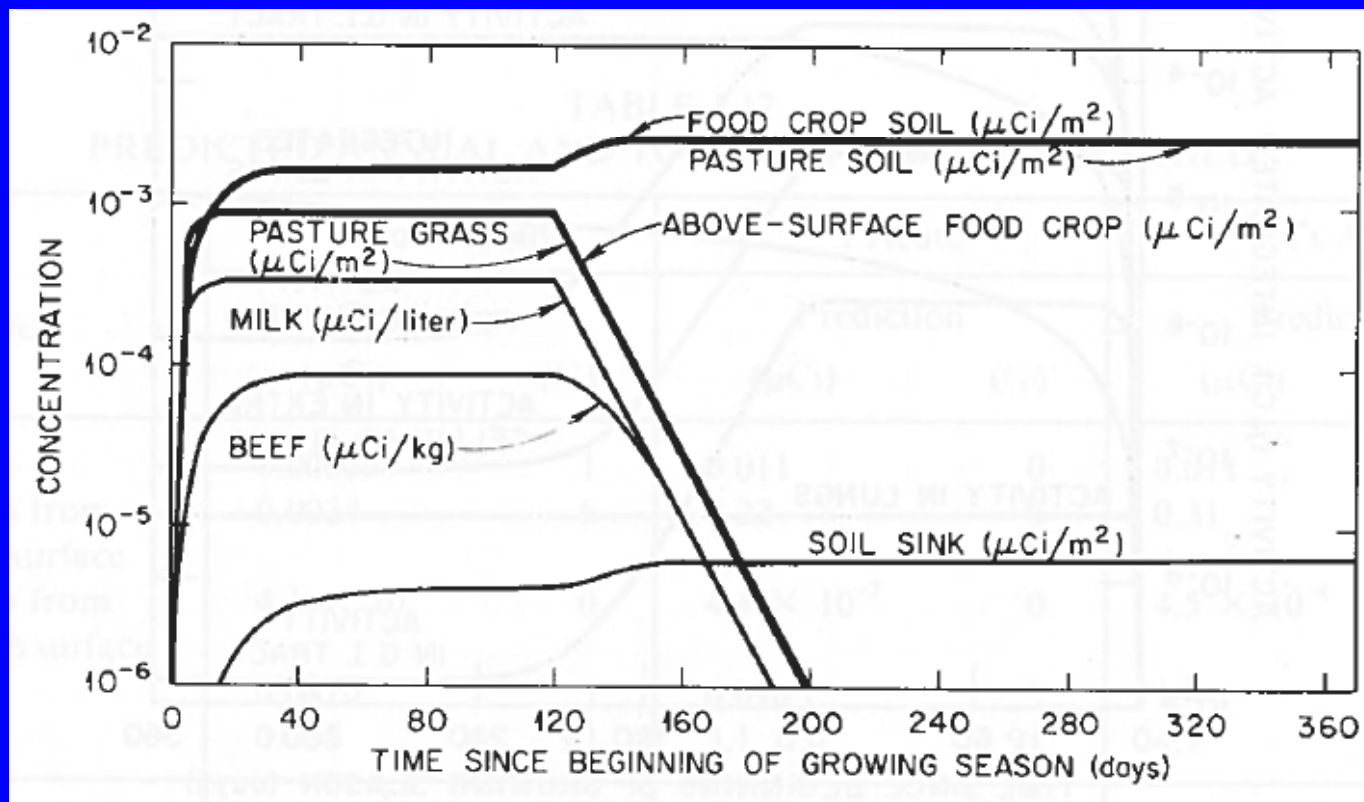
$$\begin{aligned}\frac{\partial \chi_3}{\partial t} &= \text{Input} - \text{Output} \\ &= (\chi_0 v \Delta_3 + \chi_4 \tau_{34}) - (\chi_3 \tau_{43} + \chi_3 \tau_{73} + \chi_3 \tau_{83} + \lambda \chi_3)\end{aligned}$$

- The solution to this equation, which gives the concentration in pasture grass (χ_3) at a specified time, is rather complicated.

Mathematical Models of Environmental Transport

Systems Analysis Approach

The following figure illustrates the ability of the SA approach to model the environment as a function of time. In this case I-131, a short-lived nuclide, is modeled.



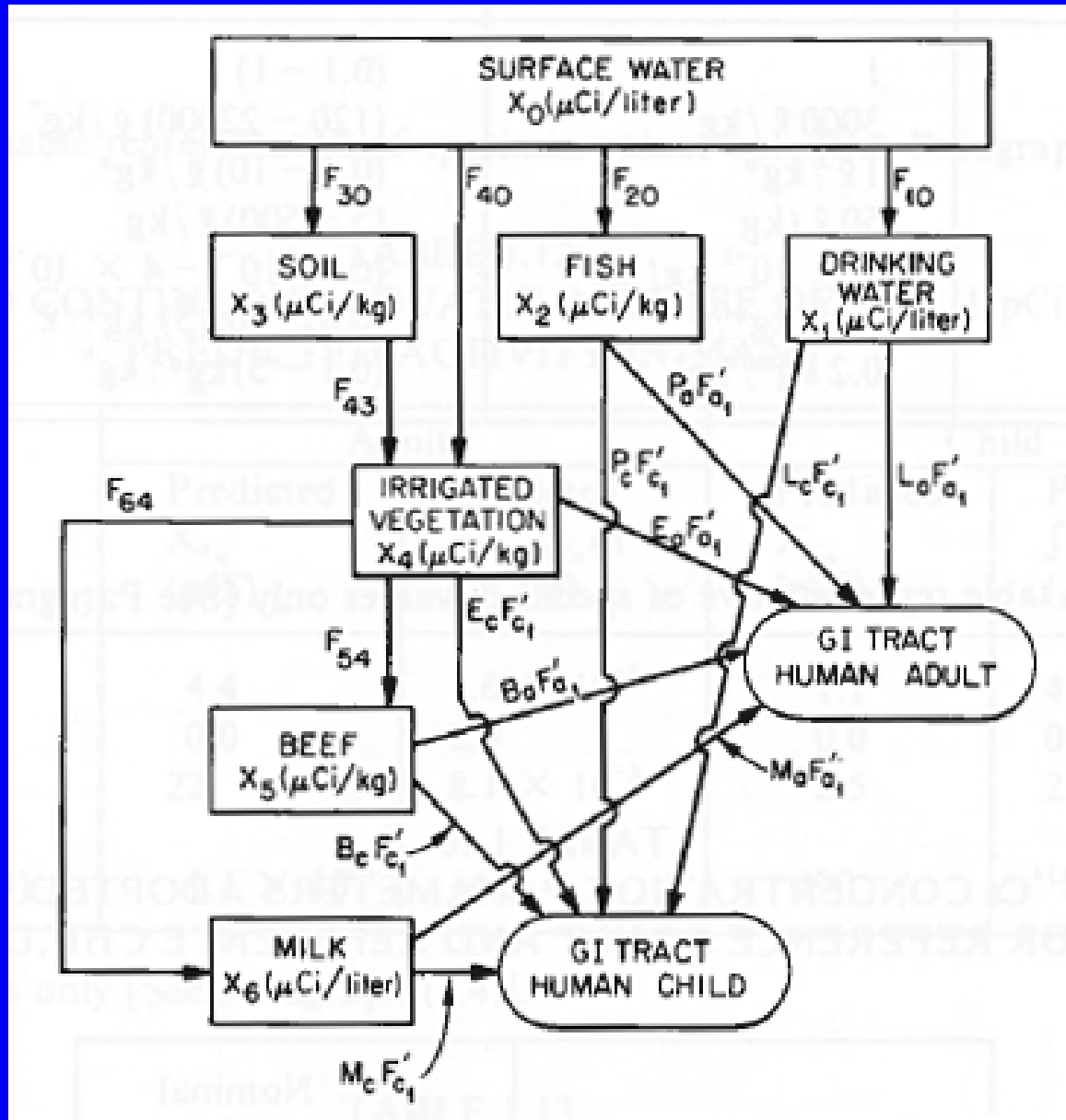
Mathematical Models of Environmental Transport

Concentration Factor Approach

- The following slide shows a CF conceptual model of a compartmentalized aquatic environment.
- The compartmental concentrations are symbolized by the letter X.
- The arrows indicate the direction of movement between compartments. Note that arrows only go in one direction. Averaged over a year, the net movement of radioactive material is in one direction only.
- The concentration factors (F) next to the arrows indicate the ratio of the concentrations in the two compartments.

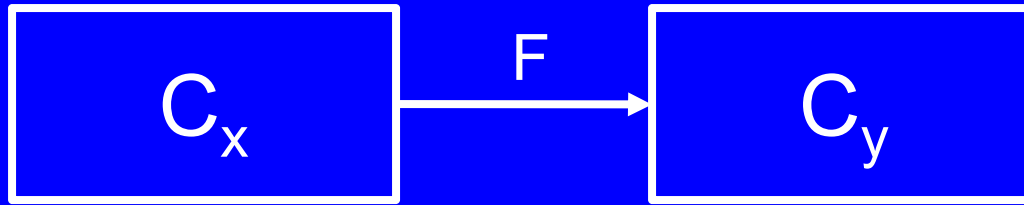
Mathematical Models of Environmental Transport

Concentration
Factor Model of
Aquatic Ecosystem
(ICRP 29)



Mathematical Models of Environmental Transport

Concentration Factor Approach



The general form of the equation that estimates the concentration in compartment y is:

$$C_y = C_x \times F$$

Example: using the aquatic ecosystem model in the previous slide, the concentration in fish (X_2) is the concentration in the water (X_1) multiplied by the bioaccumulation factor (F_{20}):

$$X_2 = X_0 \times F_{20}$$

Mathematical Models of Environmental Transport

Concentration Factor Approach

General form of the equation estimating the dose to man:

$$D = C \times U \times DF$$

D is the annual dose (e.g., mSv)

C is the concentration in the product being consumed or inhaled (e.g., Bq/kg)

U is the rate of consumption or inhalation (e.g., kg/year)

DF is the dose conversion factor (e.g., mSv/kg)

Mathematical Models of Environmental Transport

Calculating the Concentrations in Air and Water

The starting point (first compartment) in the terrestrial environment is the air.

The first compartment in the aquatic environment is the water.

Calculating the concentrations in air and water based on a discharge rate requires environmental transport equations that model the dilution of the effluent in the atmosphere and/or surface water (e.g., river, lake).

These can be complicated.

Mathematical Models of Environmental Transport

Calculating the Concentrations in Air and Water

Regulatory Guide 1.111 *Methods for Estimating Atmospheric Transport and Dispersion of Gaseous Effluents in Routine Releases from Light-Water-Cooled Reactors* and provides an acceptable means to estimate the concentrations in air due to gaseous effluents.

The equations in this Regulatory Guide are those of the Gaussian plume model.

The meteorological input parameters typically consist of “real,” rather than worst case, meteorological data.

Mathematical Models of Environmental Transport

Calculating the Concentrations in Air and Water

Regulatory Guide 1.113 *Estimating Aquatic Dispersion of Effluents from Accidental and Routine Reactor Releases for the Purpose of Implementing Appendix I* describes an acceptable method to estimate the radionuclide concentrations in water due to liquid effluent releases.

An excellent discussion of these types of calculations, including examples, is provided in Till and Grogan's *Radiological Risk Assessment and Environmental Analysis* (2008).

Mathematical Models of Environmental Transport

Computer Codes for Estimating the Dose to the Public

The Environmental Protection Agency has developed a computer code called CAP88-PC which can be used for demonstrating compliance with 40 CFR 61 Subpart H, the Clean Air Act standard (NESHAPS) that applies to DOE facilities emitting radionuclides to air. This code incorporates parts of NRC Reg Guide 1.109.

A similar code, COMPLY, is used by NRC licensees and non-DOE federal facilities to demonstrate compliance with NESHAPS.

Mathematical Models of Environmental Transport

Computer Codes for Estimating the Dose to the Public

The EPA's PRESTO computer codes estimate doses to the public as a result of releases from the land disposal of low level radioactive waste. One example is PRESTO-EPA-CPG which calculates the maximum annual whole body dose to a critical population group (CPG). Others include PRESTO-EPA-POP, PRESTO-EPA-DEEP, PRESTO-EPA-BRC and PATHRAE-EPA.

The MILDOS-AREA computer code can be used to calculate the radiation doses received by individuals and the general population within an 80-km radius of an operating uranium recovery facility (uranium mill or in situ leach).

Mathematical Models of Environmental Transport

Computer Codes for Estimating the Dose to the Public

The primary computer code used to calculate the dose to the public from decommissioned property is the RESRAD (produced at Argonne National Laboratory and supported by the NRC). A similar but less complex code, DandD, might also be used.

Regulatory Guide 1.109

*Calculation of Annual Doses to Man from
Routine Releases of Reactor Effluents for
the Purpose of Evaluating Compliance with
10 CFR Part 50, Appendix I*

Regulatory Guide 1.109

General

NRC Regulatory Guide 1.109 provides an acceptable method for calculating the annual doses to the public as a result of routine releases from a nuclear power plant.

Once radioactive material is in the environment, the type of facility that released it is irrelevant. As such the equations in Regulatory Guide 1.109 can be used to estimate the doses due to the releases from other types of facilities.

Regulatory Guide 1.109

Appendix A

Estimating the annual dose due to four aquatic pathways:

1. Potable Water
2. Aquatic Foods
3. Dose from Shoreline Deposits
4. Dose from Foods Irrigated with Contaminated Water:
 - Vegetation (crops)
 - Milk
 - Meat

Regulatory Guide 1.109

Appendix B

Estimating the following doses from noble gases discharged to the atmosphere:

1. Annual Gamma Air Dose from Noble Gas Releases from Free-Standing Stacks More than 80 Meters High
2. Annual Gamma Air Dose from All Other Noble Gas Releases and Annual Beta Air Dose from All Noble Gas Releases
3. Annual Total Body and Skin Doses from Noble Gas Effluents

Regulatory Guide 1.109

Appendix C

Estimating the doses via additional pathways from radioiodines and other radionuclides discharged to the atmosphere:

1. Annual external dose from Direct Exposure to Activity Deposited on the Ground Plane.
2. Annual Dose from Inhalation of Radionuclides in Air
3. Concentrations of Airborne Radionuclides in Foods
 - Forage, Produce and Leafy Vegetables
 - Milk
 - Meat
4. Annual Dose from Atmospherically Released Radionuclides in Foods

Regulatory Guide 1.109

Generalized Equation

The annual dose calculations in Regulatory Guide 1.109 are performed via equations that take following generalized form:

$$R_{aipj} = C_{ip} \times U_{ap} \times D_{aipj}$$

R is the annual dose equivalent (e.g., mrem/y)

C is the concentration (e.g., pCi/liter)

U is the usage factor (e.g., liters/year ingested)

D is the dose factor (e.g., mrem/pCi ingested)

Subscripts:

- i radionuclide for which the calculation is performed
- p pathway for which the calculation is performed
- j organ for which the calculation is performed
- a age group for which the calculation is performed
(0-1, 1-11, 11-17, 17+)

Regulatory Guide 1.109

Conservatism in Calculations

To demonstrate compliance with the regulations, the dose from submersion and inhalation might be calculated at the location with the highest ground-level concentrations in air.

Similarly, the external exposures due to contamination deposited on the ground might be calculated for the location where the highest ground level deposition is assumed to occur. The same location might be chosen to estimate the doses due to the ingestion of food.

Regulatory Guide 1.109

Conservatism in Calculations

The total dose to a tissue is the sum of the doses to that tissue from all the pathways (e.g., inhalation, external exposure, milk, etc.).

For a given pathway, a dose could be calculated for each of the four age groups and the highest of these could be used for the summation. For example, the reported thyroid dose might be that for the baby's thyroid from drinking milk, plus the dose to the child's thyroid due to inhalation, plus the dose to the adult's thyroid from ingesting contaminated food.

A less conservative approach is to calculate the dose for each pathway to a maximally exposed “real” person (e.g., a person at the nearest residence within 5 miles).

Regulatory Guide 1.109

Computer Codes to Perform Reg Guide 1.109 Calculations

- Some NRC power plant licensees use in-house software or spreadsheets.
- Some use commercially available software (e.g., MIDAS, RETDAS from Vertech Software).
- Some use a combination of three NRC codes:
 - LADTAP II - dose assessments for liquid effluent pathways
 - GASPAR II - dose assessments for gaseous effluent pathways.
 - XOQDOQ - atmospheric dispersion and deposition calculations.

Regulatory Guide 1.109

Computer Codes to Perform Reg Guide 1.109 Calculations

The NRC staff use the code NRCDOSE to confirm the licensee's calculations.

NRCDOSE incorporates the three codes LADTAP II, GASPAR II, and XOQDOQ. The earlier version of the code, PCDOSE operated as a spreadsheet

Regulatory Guide 1.109

Dose Factor Issues

The dose factors for the various organs calculate the dose out to 50 years after the ingestion/inhalation, i.e., a CDE

Regulatory Guide 1.109 does not use tissue weighting factors or calculate an effective dose equivalent. The total body dose of Reg Guide 1.109 is the total energy deposited in the body divided by the body mass.

When a radionuclide is uniformly distributed in the body, the Regulatory Guide 1.109 total body dose factors approximate the effective dose equivalent factors in Federal Guidance Report 11. Otherwise, their dose factors can be quite different.

Most codes (e.g., GASPAR, LADTAP) do not use the dose factors in Regulatory Guide 1.109.

Example Calculations for Regulatory Guide 1.109

Example Calculations for Regulatory Guide 1.109

Introduction

We will perform example dose calculations for members of the public exposed to releases from a hypothetical nuclear power plant. The methodology is that of Regulatory Guide 1.109.

The pathways, radionuclide, organ, and age group for which we perform the example calculations are:

Pathways (p): each of the four aquatic pathways described in Appendix A.

Radionuclide (i): I-131 ($\lambda = 0.0036 \text{ hr}^{-1}$)

Organ (j): thyroid

Age Group (a): adult, 17+ years

Example Calculations for Regulatory Guide 1.109

Basic Site Specific Data

Discharge rate (Q): 4 Ci of I-131/year in liquid effluents

Volumetric flow rate of liquid effluents (F): 2000 ft³/s

Example Calculations for Regulatory Guide 1.109

1. Potable Water Pathway

Calculation of the dose to an adult's thyroid due to drinking water contaminated with I-131. The I-131 was released in liquid effluents into a body of water (e.g., river) from which the drinking water was obtained.

$$\text{General Equation: } R_{\text{aipj}} = C_{\text{ip}} U_{\text{ap}} D_{\text{aipj}}$$

U_{ap} = usage factor or intake rate of potable water = 370 l/yr
(see Table E-4 on page 39)

D_{aipj} = ingestion dose factor = 1.95×10^{-3} mrem/pCi
(see Table E-11 on page 57)

Example Calculations for Regulatory Guide 1.109

1. Potable Water Pathway

The equation to calculate the concentration (C) in the drinking water can be derived from the following equation:

$$R_{apj} = C_{ip} U_{ap} D_{aipj} = 1100 \frac{M_p U_{ap}}{F} \sum Q_i D_{aipj} e^{-\lambda t} \quad \text{Equation A-2 (p. 12)}$$

Dividing both sides of the equation by U and D and dropping the summation symbol (the latter is not necessary since single values are specified for a, i, j and p) gives the following equation for the concentration.

$$C_{ip} = 1100 \frac{M_p Q_i}{F} e^{-\lambda t}$$

Example Calculations for Regulatory Guide 1.109

1. Potable Water Pathway

$$C_{ip} = 1100 \frac{M_p Q_i}{F} e^{-\lambda t}$$

Symbol	Meaning	Value	Source
1100	converts (Ci/y) (ft ³ /s) to pCi/l	1100	
Q	release rate of nuclide in the liquid effluents	4 Ci/y	site-specific
M	mixing ratio (the reciprocal of the dilution factor) - the average concentration in the drinking water divided by the average concentration in the liquid effluents - must be measure or calculated	10 ⁻³	site-specific
F	volumetric discharge rate of the liquid effluent	2000 ft ³ /s	site-specific
λ	radionuclide decay constant	0.0036 hr ⁻¹	nuclide-specific
t	average transit time - from the time of discharge to the time of consumption	24 hrs	Table E-15 (page 69)

Example Calculations for Regulatory Guide 1.109

1. Potable Water Pathway

The concentration of I-131 in the drinking water is:

$$\begin{aligned}C_{ip} &= 1100 \frac{M_p Q_i}{F} e^{-\lambda t} \\&= 1100 \left(\frac{10^{-3} \times 4}{2000} \right) e^{-0.0036 \times 24} \\&= 2.02 \times 10^{-3} \text{ pCi/l}\end{aligned}$$

And, the annual dose to the adult thyroid is:

$$\begin{aligned}R_{aipj} &= C_{ip} U_{ap} D_{aipj} \\&= 2.02 \times 10^{-3} \text{ pCi/l} \times 370 \text{ l/y} \times 1.95 \times 10^{-3} \text{ mrem/pCi} \\&= 1.46 \times 10^{-3} \text{ mrem/year}\end{aligned}$$

Example Calculations for Regulatory Guide 1.109

2. Aquatic Foods (fish) Pathway

Calculating the dose to an adult's thyroid from ingesting fish.

General Equation: $R_{aipj} = C_{ip} U_{ap} D_{aipj}$

U_{ap} = usage factor or intake rate of potable water = 6.9 kg/yr
(see Table E-4 on page 39)

D_{aipj} = ingestion dose factor = 1.95×10^{-3} mrem/pCi
(see Table E-11 on page 57)

Example Calculations for Regulatory Guide 1.109

2. Aquatic Foods (fish) Pathway

The equation to calculate the concentration (C) in fish can be derived from the following equation:

$$R_{apj} = C_{ip} U_{ap} D_{aipj} = 1100 \frac{M_p U_{ap}}{F} \sum Q_i B_{ip} D_{aipj} e^{-\lambda t} \quad \text{Equation A-3 (p. 12)}$$

Dividing both sides of the equation by U and D and dropping the summation symbol (the latter is not necessary since single values are specified for a, i, j and p) gives the following equation for the concentration.

$$C_{ip} = 1100 \frac{M_p Q_i B_{ip}}{F} e^{-\lambda t}$$

Example Calculations for Regulatory Guide 1.109

2. Aquatic Foods (fish) Pathway

$$C_{ip} = 1100 \frac{M_p Q_i B_{ip}}{F} e^{-\lambda t}$$

Symbol	Meaning	Value	Source
B	bioaccumulation factor - the ratio of the concentration in the aquatic food to the concentration in water - the value of 15 l/kg indicates that there are 15 pCi of I-131 / kg of fish for every pCi/l in water.	15 l/kg	Table A-1 (page 13)
t	average transit time - from the time of discharge to the time of consumption	240 hrs	Table E-15 (page 69)

Example Calculations for Regulatory Guide 1.109

2. Aquatic Foods (fish) Pathway

The concentration of I-131 in the fish is:

$$\begin{aligned} C_{ip} &= 1100 \frac{M_p Q_i B_{ip}}{F} e^{-\lambda t} \\ &= 1100 \left(\frac{10^{-3} \times 4 \times 15}{2000} \right) e^{-0.0036 \times 240} \\ &= 1.39 \times 10^{-2} \text{ pCi/kg} \end{aligned}$$

And, the annual dose to the adult thyroid is:

$$\begin{aligned} R_{aipj} &= C_{ip} U_{ap} D_{aipj} \\ &= 1.39 \times 10^{-3} \text{ pCi/l} \times 6.9 \text{ kg/y} \times 1.95 \times 10^{-3} \text{ mrem/pCi} \\ &= 1.87 \times 10^{-4} \text{ mrem/year} \end{aligned}$$

Example Calculations for Regulatory Guide 1.109

3. Shoreline Deposits Pathway

Calculation of the external dose to an adult's thyroid from contaminated shoreline deposits.

General Equation: $R_{aipj} = S_{ip} U_{ap} D_{aipj}$

U_{ap} = exposure time for shoreline activity = 8.3 hr/yr
(see Table E-4 on page 39)

D_{aipj} = external dose factor = 2.80×10^{-9} mrem/h per pCi/m²
(see Table E-6 on page 41)

Example Calculations for Regulatory Guide 1.109

3. Shoreline Deposits Pathway

Equation A-5 (p.14) calculates the radionuclide concentration (S) in shoreline deposits:

$$S_{ip} = 100 T_i C_{iw} W \left(1 - e^{-\lambda t}\right)$$

Symbol	Meaning	Value	Source
T	radiological half life (days)	8.02 d	nuclide-specific
C	radionuclide concentration in water adjacent to sediment	2.02×10^{-3} pCi/l	use that in potable water
W	shore width factor	0.2	Table A-2 (page 15)
t	The length of time the sediment is exposed to the contaminated water - set at 15 years, the midpoint of facility operating life	1.31×10^5 hrs	Table E-15 (page 68)

Example Calculations for Regulatory Guide 1.109

3. Shoreline Deposits Pathway

The radionuclide concentration (S) in shoreline deposits:

$$\begin{aligned} S_{ip} &= 100 T_i C_{iw} W \left(1 - e^{-\lambda t}\right) \\ &= 100 \times 8.02 \times 2.02 \times 10^{-3} \times 0.2 \left(1 - e^{-0.0036 \times 1.31 \times 10^5}\right) \\ &= 0.324 \text{ pCi} / \text{m}^2 \end{aligned}$$

Calculation of the external dose to an adult's thyroid from contaminated shoreline deposits:

$$\begin{aligned} R_{aipj} &= S \quad U \quad D \\ &= 0.324 \text{ pCi/m}^2 \times 8.3 \text{ h/y} \times 2.80 \times 10^{-9} \text{ mrem/h per pCi/m}^2 \\ &= 7.53 \times 10^{-9} \text{ mrem/y} \end{aligned}$$

Example Calculations for Regulatory Guide 1.109

4. Food Crop Pathway

Calculation of the dose due to ingesting food crops irrigated with contaminated water.

General Equation: $R_{aipj} = C_{ip} U_{ap} D_{aipj}$

U_{ap} = usage factor or intake rate of food crops = 190 kg/yr
(see Table E-4 on page 39)

D_{aipj} = ingestion dose factor = 1.95×10^{-3} mrem/pCi
(see Table E-11 on page 57)

Example Calculations for Regulatory Guide 1.109

4. Food Crop Pathway

Radionuclide concentration in irrigated crops (Equation A-8):

$$C_{iv} = d_i \left[\frac{r(1 - e^{-\lambda_{Ei} t_e})}{Y_v \lambda_{Ei}} + \frac{f_I B_{iv} (1 - e^{-\lambda_i t_b})}{P \lambda_i} \right] e^{-\lambda_i t_h}$$

Deposition rate (d_i) of irrigation water (Equation A-9):

$$d_i = C_{iw} I$$

C_{iw} , the concentration in the irrigation water (site-specific), is set at the same concentration as in potable water.

I , the irrigation rate (site-specific), is set at 0.1 l/m²/hr

$$d_i = 2.02 \times 10^{-3} \text{ pCi/l} \times 0.1 \text{ l/m}^2\text{/hr} = 2.02 \times 10^{-4} \text{ pCi/m}^2\text{/hr}$$

Example Calculations for Regulatory Guide 1.109

4. Food Crop Pathway

Symbol	Meaning	Value	Source
r	The fraction of the deposited activity that is retained on the vegetation	1.0	Table E-15 (p. 68)
λ_{Ei}	The effective removal rate constant from the vegetation. $\lambda_{Ei} = \lambda_i + \lambda_w$ (see p. 4) where λ_w is the removal rate constant due to weathering. The latter is set at 0.0021 h^{-1} (Table E-15, p. 69), hence $\lambda_{Ei} = 0.0036 + 0.0021$	0.0057 h^{-1}	nuclide-specific
t_e	The time crops are exposed during the growing season	1440 h	Table E-15 (p. 68)
Y_v	The agricultural productivity or yield (wet weight)	2.0 kg/m^2	Table E-15 (p. 69)
f_I	The fraction of the year that crops are irrigated	1.0	site-specific
B_{iv}	Concentration (bioaccumulation) factor from soil in pCi/kg wet weight in crops per pCi/kg in dry soil	0.02	Table E-1 (p. 37)
t_b	Time the soil is exposed to contaminated water - set at 15 years, the midpoint of the facility operating life	$1.31 \times 10^5 \text{ h}$	Table E-15 (p. 68)
P	Surface density of dry soil	240 kg/m^2	Table E-15 (p. 68)
t_h	Holdup time between harvest and consumption of food	336 h	Table E-15 (p. 69)

Example Calculations for Regulatory Guide 1.109

4. Food Crop Pathway

Radionuclide concentration in irrigated crops (Equation A-8):

$$\begin{aligned} C_{iv} &= d_i \left[\frac{r(1 - e^{-\lambda_{Ei} t_e})}{Y_v \lambda_{Ei}} + \frac{f_I B_{iv}(1 - e^{-\lambda_i t_b})}{P \lambda_i} \right] e^{-\lambda_i t_h} \\ &= 2.02 \times 10^{-4} \left[\frac{1.0(1 - e^{-0.0057 \times 1440})}{2.0 \times 0.0057} + \frac{1.0 \times 0.02(1 - e^{-0.0036 \times 1.31 \times 10^5})}{240 \times 0.0036} \right] e^{-0.0036 \times 336} \\ &= 2.02 \times 10^{-4} \left[\frac{1.0}{0.0114} + \frac{0.02}{0.864} \right] 0.298 \\ &= 5.28 \times 10^{-3} \text{ pCi / kg} \end{aligned}$$

Example Calculations for Regulatory Guide 1.109

4. Food Crop Pathway

The annual dose to the thyroid of an adult due to the ingestion of vegetation is calculated using the generalized equation:

$$R = C \times U \times D$$

$$= 5.28 \times 10^{-3} \text{ pCi/kg} \times 190 \text{ kg/y} \times 1.95 \times 10^{-3} \text{ mrem/pCi}$$

$$= 1.96 \times 10^{-3} \text{ mrem/y}$$

$$= 1.96 \times 10^{-5} \text{ mSv/y}$$

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

Calculation of the dose due to drinking milk from animals that drank contaminated water and grazed on pasture irrigated with contaminated water.

General Equation: $R_{aipj} = C_{ip} U_{ap} D_{aipj}$

U_{ap} = usage factor or intake rate of milk = 110 l/yr
(see Table E-4 on page 39)

D_{aipj} = ingestion dose factor = 1.95×10^{-3} mrem/pCi
(see Table E-11 on page 57)

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

Equation A-11 (p. 16) calculates the concentration (C_{iA}) in the milk:

$$C_{iA} = F_{iA} (C_{iF} Q_F + C_{iAw} Q_{aw})$$

The equation calculating C_{iF} , the concentration in the forage or feed, can be derived from Equation A-13. It is essentially the same as Equation A-8 used to calculate the concentration in vegetation but some input parameters will differ (e.g., Y_v).

$$C_{iF} = d_i \left[\frac{r (1 - e^{-\lambda_{Ei} t_e})}{Y_v \lambda_{Ei}} + \frac{f_I B_{iv} (1 - e^{-\lambda_i t_b})}{P \lambda_i} \right] e^{-\lambda_i t_h}$$

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

Symbol	Meaning	Value	Source
F_{iA}	Stable element transfer coefficient - ratio of radionuclide concentration in milk to daily intake rate	0.06 d	Table E-1 (p. 37)
Q_F	Consumption rate of contaminated forage/feed by animal	50 kg/d	Table E-3 (p. 38)
C_{iAw}	Concentration in animal's drinking water	2.02×10^{-3} pCi/l	Value calculated in previous example for potable water
Q_{Aw}	Animal's consumption rate of contaminated water	60 l/d	Table E-3 (p. 38)
d_i	Deposition rate from irrigated water	2.02×10^{-4} pCi/m ² /h	Value calculated in previous example
r	The fraction of the activity deposited on the vegetation that is retained on the vegetation	1.0	Table E-15 (p. 68)
λ_{Ei}	The effective removal rate constant from the vegetation. $\lambda_{Ei} = \lambda_i + \lambda_w$ (see p. 4) where λ_w is the removal rate constant due to weathering. The latter is set at 0.0021 h^{-1} (Table E-15, p. 69), hence $\lambda_{Ei} = 0.0036 + 0.0021$	0.0057 h^{-1}	nuclide-specific

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

Symbol	Meaning	Value	Source
t_e	The time crops are exposed during the growing season	1440 h	Table E-15 (p. 68)
Y_v	The agricultural productivity or yield (wet weight)	0.7 kg/m ²	Table E-15 (p. 69)
f_I	The fraction of the year that crops are irrigated	1.0	site-specific
B_{iv}	Concentration (bioaccumulation) factor from soil in pCi/kg wet weight in crops per pCi/kg in dry soil	0.02	Table E-1 (p. 37)
t_b	Time the soil is exposed to contaminated water - set at 15 years, the midpoint of the facility operating life	1.31×10^5 h	Table E-15 (p. 68)
P	Surface density of dry soil	240 kg/m ²	Table E-15 (p. 68)
t_h	Holdup time between harvest and consumption of food/forage/feed	0 for pasture grass (2160 h for stored feed)	Table E-15 (p. 69)

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

The I-131 concentration in the forage is:

$$\begin{aligned} C_{iF} &= d_i \left[\frac{r(1 - e^{-\lambda_{Ei} t_e})}{Y_v \lambda_{Ei}} + \frac{f_I B_{iv}(1 - e^{-\lambda_i t_b})}{P \lambda_i} \right] e^{-\lambda_i t_h} \\ &= 2.02 \times 10^{-4} \left[\frac{1.0(1 - e^{-0.0057 \times 1440})}{0.7 \times 0.0057} + \frac{1.0 \times 0.02(1 - e^{-0.0036 \times 1.31 \times 10^5})}{240 \times 0.0036} \right] e^{-0.0036 \times 0} \\ &= 2.02 \times 10^{-4} \left[\frac{1.0}{0.004} + \frac{0.02}{0.864} \right] 1.0 \\ &= 5.05 \times 10^{-2} \text{ pCi / kg} \end{aligned}$$

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

The I-131 concentration in milk is:

$$\begin{aligned}C_{iA} &= F_{iA} (C_{iF} Q_F + C_{iAw} Q_{aw}) \\ &= 0.06 (5.05 \times 10^{-2} \times 50 + 2.02 \times 10^{-3} \times 60) \\ &= 0.159 \text{ pCi/l}\end{aligned}$$

Example Calculations for Regulatory Guide 1.109

5. Milk Pathway

The annual dose to the thyroid of an adult due to the ingestion of milk is calculated using the generalized equation:

$$R = C \times U \times D$$

$$= 0.159 \text{ pCi/l} \times 110 \text{ l/y} \times 1.95 \times 10^{-3} \text{ mrem/pCi}$$

$$= 3.41 \times 10^{-2} \text{ mrem/y}$$

$$= 3.41 \times 10^{-4} \text{ mSv/y}$$

Example Calculations for Regulatory Guide 1.109

6. Meat Pathway

Calculation of the dose due to ingesting meat from animals that drank contaminated water and grazed on pasture irrigated with contaminated water.

General Equation: $R_{aipj} = C_{ip} U_{ap} D_{aipj}$

U_{ap} = usage factor or intake rate of meat = 95 kg/yr
(see Table E-4 on page 39)

D_{aipj} = ingestion dose factor = 1.95×10^{-3} mrem/pCi
(see Table E-11 on page 57)

Example Calculations for Regulatory Guide 1.109

6. Meat Pathway

The only difference between the following equation to calculate the I-131 concentration in meat and that used to calculate the concentration in milk is that the transfer coefficient, F_{iA} , is for meat. According to Table E-1 (p. 37), an acceptable value for this transfer factor is 2.9×10^{-3} pCi/kg (per pCi ingested by the cattle per day).

$$\begin{aligned}C_{iA} &= F_{iA} (C_{iF} Q_F + C_{iAw} Q_{aw}) \\ &= 0.0029 (5.05 \times 10^{-2} \times 50 + 2.02 \times 10^{-3} \times 60) \\ &= 7.67 \times 10^{-3} \text{ pCi/kg}\end{aligned}$$

In this example we assume that the parameters used with the dairy cattle also apply to the cattle from which meat is obtained.

Example Calculations for Regulatory Guide 1.109

6. Meat Pathway

The annual dose to the thyroid of an adult due to the ingestion of milk is calculated using the generalized equation:

$$R = C \times U \times D$$

$$= 7.67 \times 10^{-3} \text{ pCi/kg} \times 95 \text{ kg/y} \times 1.95 \times 10^{-3} \text{ mrem/pCi}$$

$$= 3.41 \times 10^{-3} \text{ mrem/y}$$

$$= 1.42 \times 10^{-5} \text{ mSv/y}$$

Example Calculations for Regulatory Guide 1.109

7. Total Dose from All Aquatic Pathways

Potable water	1.46×10^{-3} mrem/yr
Aquatic Food (fish)	1.87×10^{-4} mrem/yr
Shoreline Deposits	7.53×10^{-9} mrem/yr
Vegetation (food crops)	1.96×10^{-3} mrem/yr
Milk	3.41×10^{-2} mrem/yr
Meat	1.42×10^{-3} mrem/yr
Total	3.91×10^{-2} mrem/yr

Selected References

Selected References

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