Dust, Radon

Drinking Water

Fish, Meat, Milk, Plant Foods

Radioactively Contaminated Material in Soil

Infiltration, Ingestion, Leaching

External Surface Water, Groundwater
RESRAD Training Workshop

RESRAD Family of Risk Assessment Codes
Workshop Overview
- Dose Modeling/DCGL Overview
- RESRAD Overview
- Demonstration
- Methodology
- Putting it All Together
- Analysis Tools
- RESRAD Application
- Verification and Validation
- Workshop Review
- Closing Remarks
Why Perform a Dose Assessment?

- DOE Order 5400.5, Chapter IV

“DOE elements shall develop plans and protocols for the implementation of this guidance. FUSRAP sites shall be identified, characterized, and designated, as such, for remedial action and certified for release. Information on applications of the guidelines and requirements presented herein, including procedures for deriving specific property guidelines for allowable levels of residual radioactive material from basic dose limits, is contained in DOE/CH 8901, "A Manual for Implementing Residual Radioactive Material Guidelines, A Supplement to the U.S. Department of Energy Guidelines for Residual Radioactive Material at FUSRAP and SFMP Sites," June 1989.”

Why Perform a Dose Assessment?

- 10 CFR 20, Subpart E

“A site will be considered acceptable for unrestricted use if the residual radioactivity that is distinguishable from background radiation results in a TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 mSv) per year, including that from groundwater sources of drinking water, and that the residual radioactivity has been reduced to levels that are as low as reasonably achievable (ALARA).”
**Why Perform a Dose Assessment?**

- **Effective Dose Equivalent or Total Effective Dose Equivalent**
  - External dose + 50 year committed effective dose equivalent
  - External + Inhalation + Ingestion

- **External + Inhalation + Ingestion < 1 mSv/yr**
  - 0.25 mSv /yr DOE dose constraint

- **In Addition:**
  “When calculating TEDE to the average member of the critical group the licensee shall determine the peak annual TEDE dose expected within the first 1000 years after decommissioning

---

**Why Perform a Dose Assessment?**

- **There is not a “TEDE meter” available**
  - Time of decommissioning
  - 1,000 years after decommissioning

- **Requires the use of mathematical models to estimate TEDE**
Compliance Demonstration

- Soil Guideline or DCGL Development
  - Derive acceptable residual radioactive concentrations (DCGLs) for each radionuclide based on TEDE. Licensee must then prove the site meets the DCGLs. For multiple sources/radionuclides the “Sum of Fractions” must be less than 1

- Dose Modeling
  - Uses actual or expected radionuclide concentrations to estimate TEDE. Site must be below 0.25 mSv/yr

What is Dose Modeling?

- Dose modeling involves using radiological assessment models to determine the dose to an individual from residual radioactive material
- A licensee would input final residual radioactive material concentrations into the model to predict the dose to the individual.
- Often this is called the “forward” calculation

Radionuclides → Environmental Pathways → Dose
What is a Soil Guideline or DCGL?

- **Derived Concentration Guideline Level**
- Uses computer codes to estimate residual radioactive material concentrations so that the dose to an individual is below the dose limit
- Often this is called the “backward” calculation
  - Dose Limit → Environmental Pathways → Concentration
- Derived separately for each radionuclide based on its maximum dose
- Requires the use of the “Sum of Fractions” if multiple radionuclides or sources are present

RESRAD Overview
RESRAD, an internationally utilized model, successfully addresses the critical question "How clean is clean enough?"

Accepted for use by government regulatory agencies
- DOE (Designated by Order 5400.5)
- NRC (NUREG/CR-1757)
- EPA
- State agencies

In use for about 20 years
- Evaluation of more than 300 cleanup sites
- More than 100 training workshops
- International recognition

RESRAD Development Spans over Two Decades

[Flowchart showing the timeline and development stages of RESRAD from its inception in the early 1980s to its current status as of 2006]
The RESRAD Code

- Radiological Dose/Cancer Risk Calculation:
  - External radiation exposure
  - Internal radiation dose from inhalation (including radon)
  - Internal radiation dose from ingestion
    - drinking water (surface and/or groundwater)
    - produce, meat and milk
    - fish
    - soil

Exposure Pathways Considered in RESRAD: (Resident Farmer Scenario)
Exposure Pathways Considered in RESRAD:
(Industrial Use Scenario)

RESRAD Contains An Array of Parameters for Pathway Analysis in Performing Comprehensive Risk Assessment
Strong Track Record

- Federal Agency
  - Only code designated in DOE Order 5400.5 and the proposed 10 CFR Part 834 for the evaluation of radioactively contaminated sites
  - NRC has approved the use of RESRAD for dose evaluation by licensees involved in decommissioning, NRC staff evaluation of waste disposal requests, and dose evaluation of sites being reviewed by NRC staff
  - EPA used RESRAD in the analysis of radiation site cleanup regulations, and the EPA Science Advisory Board reviewed the RESRAD model
  - NRC supported the development of the probabilistic modules for demonstrating compliance with the license termination rule
  - EPA sponsored a benchmarking study

Documentation of the RESRAD Computer Code

- Chapters:
  - Pathway analysis,
  - Derivation of soil guidelines
  - User's guide for RESRAD
  - Verification & Validation
- Appendices include detailed discussions on
  - Pathway models
  - Source factors
  - Distribution coefficients
  - Estimation of off-site doses,
  - Special tritium and carbon-14 models,
  - Uncertainty analysis
Supporting Documentation

- Parameters
  - Development of Probabilistic RESRAD 6.0 and RESRAD-BUILD 3.0 Computer Codes [11/00]
  - A Compilation of Radionuclide Transfer Factors for the Plant, Meat, Milk and Aquatic Food Pathways and the Suggested Default Values for the RESRAD Code [8/93]

- Testing
  - Verification of RESRAD [6/94]
  - RESRAD Benchmarking Against Six Radiation Exposure Pathway Models [10/94]
  - Evaluation of Area Factor for Finite Area Sources for Inhalation Dose Calculations [7/98]
**Demonstration**

**Precipitation:** 1.3 m/y  
**Irrigation:** 0 m/y

**Current Scenario/Site History**
REsonant RADiological Industries is a former general manufacturer of small sources. Residues from plant operations were placed in a waste disposal pit until the plant ceased operations in 1969. Today, the site is vacant except for a single maintenance worker who checks the site 5 times weekly. This worker spends approximately 2 hours per visit at the site, and is indoors about 1 hour of that time. Drinking water is provided by a well located downgradient of the contaminated zone.

---

**Contaminated Zone**  
**Density:** 1.4 g/cm³  
**Am-241:** 50 pCi/g  
**Cs-137:** 40 pCi/g  
**Sr-90:** 45 pCi/g

**Total Porosity:** 0.45  
**Hydraulic Conductivity:** 7 m/yr

---

**Unsaturated Zone 1**  
**Density:** 1.6 g/cm³  
**Erosion Rate:** ???

**Hydraulic Conductivity:** 90 m/yr  
**Fraction of Contaminated Drinking Water:** ???

---

**Saturated Zone**  
**Am-241:** 4 pCi/L  
**Cs-137:** 3 pCi/L  
**Sr-90:** 2 pCi/L
Why Perform a Dose Assessment?

- Total Effective Dose Equivalent
  - External dose + 50 year committed effective dose equivalent
  - External + Inhalation + Ingestion

- External + Inhalation + Ingestion < 25 mrem/yr

* 25 mrem/yr is the dose constraint recommended for each DOE source or practice (Draft DOE G 441.1-XX)
Why Perform a Dose Assessment?

- 10 CFR 20, Subpart E
  - “…TEDE to an average member of the critical group that does not exceed 25 mrem (0.25 mSv) per year…”

- TEDE: Total Effective Dose Equivalent
  - External dose + 50 year committed effective dose equivalent
  - External + Inhalation + Ingestion

- External + Inhalation + Ingestion < 25 mrem/yr

- There is not a “TEDE meter” available
  - Time of decommissioning
  - 1,000 years after decommissioning

- Requires the use of mathematical models to estimate TEDE
Compliance Demonstration

- **Dose Modeling**
  - Uses actual or expected radionuclide concentrations to estimate TEDE. Site must be below 0.25 mSv/yr

- **DCGL Development**
  - Derive acceptable residual radioactive concentrations (DCGLs) for each radionuclide based on TEDE. Licensee must then prove the site meets the DCGLs.
  - For multiple sources/radionuclides the “Sum of Fractions” must be less than 1.

RESRAD Pathways

- Nine major environmental pathways are available in RESRAD
  - External (Ground)
  - Inhalation
    - Particulates
    - Radon
  - Ingestion
    - Soil
    - Water
    - Plant
    - Meat
    - Milk
    - Aquatic Foods
Demonstrating Compliance with 10CFR 20 Subpart E

- $H_E(t) \leq H_{EL}$

- $H_E(t)$ = dose from all pathways (mSv/year)

- $H_{EL}$ = basic dose limit
  = 0.25 mSv/year current or likely use

Demonstrating Compliance Using DCGLs

- RESRAD derives single radionuclide soil guidelines at the time of maximum total dose, and at the time of maximum dose for each individual radionuclide, as well as for each user specified time

\[ G_i(t)_{\text{pCi/g}} = \frac{H_{EL}}{DSR_i(t)} \frac{\text{mSv/yr}}{\text{Bq/g}} \]

- $DSR_i(t)$ is the dose to source ratio (mSv/yr per Bq/g)
Calculating the Dose to Source Ratio

\[ \text{DSR}_{ip}(t) = \frac{H_{E,ip}(t)}{S_i(0)} \]

\[ H_E(t) = \sum_i \sum_p H_{E,ip}(t) \]

\[ S_i(0) = \text{initial concentration of the } i\text{th principal radionuclide} \]

Illustrative Example

- A site is contaminated with Cs-137 and requires remediation activities to release the site for unrestricted use. A site-specific analysis was conducted using RESRAD. An initial concentration of 1 pCi/g Cs-137. The resultant peak dose to the receptor was 1.7 mrem/yr.

- What would the DCGL be for Cs-137 if the dose constraint was set to 25 mrem/yr?
**Illustrative Example Cont.**

\[
D\text{SR}_{\text{Cs-137}} = \frac{1.7 \text{ mrem/yr}}{1 \text{ pCi/g}} = 1.7 \frac{\text{mrem/yr}}{\text{pCi/g}}
\]

\[
D\text{CGL}_{\text{Cs-137}} = \frac{25 \text{ mrem/yr}}{1.7 \frac{\text{mrem/yr}}{\text{pCi/g}}} = 14.7 \text{ pCi/g}
\]

**Multiple Radionuclides/Sources**

- Use the Sum of Fractions to ensure the value is less than 1

\[
\sum_{i=1}^{n} \sum_{j=1}^{m} \frac{S_{i,j}(t=0)}{G_{i,j}(t)} \leq 1
\]

- \(S_{i,j}(t=0)\) is your initial source concentration for source \(i\) and radionuclide \(j\) at time \(t=0\)
**Calculation of the Dose to Source Ratio**

- \( \text{DSR}_{sp}(t) = \sum_j DCF_{j,p} \times BRF_{i,j} \times \sum_q \int_{t}^{t+\tau_{aq}} ETF_{j,pq}(\tau) \times SF(\tau) \, d\tau \)

- \( DCF_{jp} \) = dose conversion factor (mrem/yr per pCi/g or mrem/pCi)

- \( BRF \) = branching factor (dimensionless)

- \( ETF_{jp}(t) \) = environmental transport factor (dimensionless or g/yr)

- \( SF_{ij}(t) \) = source factor for ingrowth, decay and leaching (dimensionless)

---

**Dose Conversion Factors**

- **External exposure pathway:**
  - infinite depth volume factors (mrem/yr per pCi/g)

- **Inhalation pathway:**
  - inhalation factors (mrem/pCi)

- **Ingestion pathways:**
  - ingestion factors (mrem/pCi)

References:
- ICRP 60 (1990)
- Inhalation/Ingestion DCFs - FGR No.11 (1988)
  - ICRP 72 (1996) - Age-dependent DCFs
Dose Conversion Factor/Risk Factor Libraries

- Using the Dose Conversion Factor Editor
  - Users can modify Dose Conversion Factors
    - Select a more appropriate DCF from the standard library
    - Create a new DCF library with values that are appropriate to the site

- Users can modify Slope factors
  - HEAST 2001
  - FGR 13 Morbidity
  - FGR 13 Mortality
  - User Specified

Source Factors

- Ingrowth of principal radionuclide j from principal radionuclide i, assuming associate radionuclides are in secular equilibrium with their principal radionuclides

- Accounts for radioactive decay and leaching

\[
SF_{ij}(t) = \frac{S_{ij}(t)}{S_i(0)}
\]

See Appendix G for more details
Factors Affecting Source Loss

- mixing layer
- erosion
- decay
- leaching

Environmental Transport Factors

- Mathematical representation of the environmental pathways
- ETFs for:
  - External
  - Inhalation
  - Ingestion
    - Water
    - Soil
    - Plant
    - Meat
    - Milk
    - Aquatic Organisms

Source
Environmental Pathway
Exposure Pathway
Dose or Cancer Risk

- Effective Dose
- Equivalent Excess Cancer Risk to an Exposed Individual
Environmental Transport Factors: External Ground

- Appendix A: RESRAD users manual

$$ETF_{ii}(t) = FO_{i} \times FS_{ii} \times FA_{i} \times FCD_{ii}(t)$$

- $FO_{i}$ = occupancy and shielding factor
- $FS_{ii}$ = nuclide specific shape factor
- $FA_{i}(t)$ = nuclide specific area factor
- $FCD_{ii}(t)$ = nuclide specific depth and cover factor

For default case at $t = 0$ for 100 pCi/g of U-238

- $FO_{i}$ = occupancy and shielding factor (0.6)
- $FS_{ii}$ = nuclide specific shape factors (1.0)
- $FA_{i}(t)$ = nuclide specific area factor (0.9912 U-238, 0.94 Pa-234)
- $FCD_{ii}(t)$ = nuclide specific depth and cover factors (1.0)

- $^{238}U$ (4.468 $10^8$ years) $\rightarrow$ 0.999946 $^{234}Th$, 0.000054 spontaneous fission
- $^{234}Th$ (0.0659822 years) $\rightarrow$ 0.998 $^{234}Pa(m)$, 0.002 $^{234}Pa$
- $^{234}Pa(m)$ (0.0000022245 years) $\rightarrow$ 0.9987 $^{234}U$, 0.0013 $^{234}Pa$
- $^{234}Pa$ (0.00076432 years) $\rightarrow$ $^{234}U$ (244500 years)
- 100000 $^{238}U$, 999946 $^{234}Th$, 997946 $^{234}Pa(m)$, 3297 $^{234}Pa$
Environmental Transport Factors: External Ground

- Appendix A: RESRAD users manual

\[ ETF_{\text{i}}(t) = FO_{\text{i}} \times FS_{\text{i}} \times FA_{\text{i}} \times FCD_{\text{i}}(t) \]

For default case at \( t = 0 \) for 100 pCi/g of U-238:
- \( FO_{\text{i}} \) = occupancy and shielding factor (0.6)
- \( FS_{\text{i}} \) = nuclide specific shape factors (1.0)
- \( FA_{\text{i}}(t) \) = nuclide specific area factor (0.9912 U-238, 0.94 Pa-234)
- \( FCD_{\text{i}}(t) \) = nuclide specific depth and cover factors (1.0)
- \( ETF_{\text{i}}(0) \) = 0.6 * 1.0 * 0.9912 * 1.0 = 0.5947 for U-238
- \( ETF_{\text{i}}(0) \) = 0.6 * 1.0 * 0.961 * 1.0 = 0.5766 for Th-234
- \( ETF_{\text{i}}(0) \) = 0.6 * 1.0 * 0.9393 * 1.0 = 0.5636 for Pa-234m
- \( ETF_{\text{i}}(0) \) = 0.6 * 1.0 * 0.94 * 1.0 = 0.564 for Pa-234

\[
\text{Dose from U-238} = \sum \left( DCF \times ETF \times BRF \times SF \right) S(0) = (0.0001031 \times 0.5947 \times 1.0 + 0.0241 \times 0.5766 \times 0.999946 + 0.08966 \times 0.5636 \times 0.997946 + 11.54 \times 0.564 \times 0.003297) \times 100
\]

\[ = 8.58 \text{ mrem/year, Time integrated dose = 8.57 mrem/year} \]

Occupancy and Shielding Factor

- Comprised of
  - \( f_{\text{out}} \): Fraction of time spent outdoors
  - \( f_{\text{ind}} \): Fraction of time spent indoors
  - \( F_{\text{sh}} \): External gamma shielding factor
  - \( F_{\text{sh}} \) is radionuclide INDEPENDENT

\[ FO_{\text{i}} = f_{\text{out}} + \left( f_{\text{ind}} \times F_{\text{sh}} \right) \]

Default Case

\[ FO_{\text{i}} = 0.25 + (0.5 \times 0.7) = 0.6 \]

Important Note!
- \( F_{\text{sh}} = 0 \); completely shielded
- \( F_{\text{sh}} = 1 \); no shielding
**Depth and Cover Factor**
- Allows users to enter
  - Any contaminated zone thickness, and density
  - Any one cover thickness and density
- Based on a regression analysis of FGR 12 DCFs
- FCD's are radionuclide dependent

\[
FCD_{i1} = \frac{DCF_{FGR}^{\text{FGR}}[T_c = C_{i0}, T_s = T(t)]}{DCF_{FGR}^{\text{FGR}}[T_c = 0, T_s = \infty]}
\]

**Examples of FCDs for Two Radionuclide**
- **FCD for Co-60**
  - Variable Contaminated Zone Thickness
  - No cover
- **FCD for U-234**
  - Variable contaminated zone thickness
  - No cover
Examples of FCDs for Two Radionuclides

- FCD for Co-60
  - Contaminated zone thickness = 2m
  - Variable Cover Thickness

- FCD for U-234
  - Contaminated zone thickness = 2m
  - Variable Cover Thickness

Area Factor

- Radionuclide specific factor to correct an infinite geometry (FGR 12) to finite geometry (site-specific)
- Performs point-kernel integration on the dose
- Uses ICRP-38 photon spectra
- Benchmarked against MCNP
**Area Factor Calculation**

- Co-60, Pu-240
  - Example
    - No cover
    - 2 m thick contaminated zone

**Shape Factor: Non-Circular Shapes**

- RESRAD allows users to construct non-circular shaped sources
- Allows users to place receptors anywhere on the source
- Biggest Impact on long rectangular sources
  - Roads
  - Railroad right a way
- Primarily affects the External Pathway
- Still Need to Specify the “Length Parallel to Aquifer Flow”
Environmental Transport Factors: Inhalation Pathway

- Appendix B: RESRAD users manual

\[ ETF_{2} = ASR_{2} \times FA_{2} \times FCD_{2}(t) \times FO_{2} \times FI_{2} \]

- \( ASR_{2} \) = mass loading factor (air/soil concentration ratio)
- \( FA_{2} \) = area factor
- \( FCD_{2}(t) \) = cover and depth factor
- \( FO_{2} \) = occupancy factor
- \( FI_{2} \) = annual intake of air

The DCF for inhalation is the dose from inhaling a unit quantity of radionuclide (mrem/pCi inhaled, slide 37)

- Radionuclide concentration in soil (pCi/g)
  - Radionuclide concentration in air (pCi/m³)
  - Quantity of radionuclide inhaled in one year (pCi inhaled / year)

Environmental Transport Factors: Inhalation Pathway—Example

- Appendix B: RESRAD users manual

\[ ETF_{2} = ASR_{2} \times FA_{2} \times FCD_{2}(t) \times FO_{2} \times FI_{2} \]

- \( ASR_{2} \) = mass loading factor (0.0001 g/m³)
- \( FA_{2} \) = area factor (0.1693)
- \( FCD_{2}(t) \) = cover and depth factor (1.0)
- \( FO_{2} \) = occupancy factor (0.45)
- \( FI_{2} \) = annual intake of air (8400 m³/y)

For default case at \( t = 0 \) for 100 pCi of U-238:

- \( ETF_{2}(0) = 0.0001 g/m³ \times 0.1693 \times 1.0 \times 0.45 \times 8400 m³/y = 0.064 g/yr \)
- Dose from U-238 = \( \Sigma(DCF \times BRF \times ETF \times SF) S(0) \)
- Dose = 0.064 g/yr \times 0.118 mrem/pCi \times 100 pCi/g = 0.755 mrem/yr
- Time Integrated Dose = 0.754 mrem/yr
**Area Factor for Inhalation**

- Ratio of airborne concentration from a finite area source to the airborne concentration of an infinite source.
- Empirical model based on least square regression.
- Inversely proportional to square root of the Area.
- Fit parameters are correlated to wind speed.

![Graph showing Area Factor for Inhalation](image)

**Cover and Depth Factor**

- Fraction of resuspendable soil particulates that are contaminated.
- Assumes uniform mixing within a layer of soil (mixing layer).

![Diagram showing Cover and Depth Factor](image)
**Occupancy Factor**

- Methodology identical to that used for the external pathway
  - Indoor dust filtration factor ($F_{dust}$)
    - 0.4 default
    - 0.0, 100% filtration,
      - Air activity concentration 0 pCi/m³
    - 1.0, No filtration
      - Outdoor air activity concentration = indoor air activity concentration

$$FO_2 = f_{oid} + (f_{iad} \times F_{dust})$$

$$FO_2 = 0.25 + (0.5 \times 0.4) = 0.45$$

**Ingestion Pathways**

- Residual Radioactive Soil Contamination
  - Air
  - Water
  - Plants
  - Meat/Milk
  - Fish
  - Ingestion Dose
**Ingestion Pathways**

- **Water independent**
  - Excludes dose derived from contaminated well or surface water
  - Leaching from the contaminated zone still applies
  - For plant, meat and milk; does not include the contribution from radionuclides in water used for
    - irrigation
    - livestock feed
  - The only component for soil ingestion

- **Water dependent**
  - Dose derived from contaminated well or surface water
  - For plant, meat and milk; the contribution from nuclides in water used for
    - irrigation
    - livestock feed
  - Only component for drinking water and fish

---

**Environmental Transport Factors: Soil Ingestion**

- Appendix F: RESRAD users manual
- Models the incidental ingestion of soil

\[ ETF_{j} = FSI \times FA_{8} \times FCD_{8}(t) \times FO_{8} \]

- **FSI** = annual intake of soil
- **FA_{8}** = area factor
- **FCD_{8}(t)** = cover and depth factor
  - Same model as inhalation pathway
- **FO_{8}** = occupancy factor
  - Total time spent on the site
  - Indoor time fraction + outdoor time fraction
Environmental Transport Factors: Soil Ingestion

- Appendix F: RESRAD users manual
- Models the incidental ingestion of soil

\[
ETF_{fsi} = FSI \times FA_8 \times FCD_8(t) \times FO_8
\]

- FSI = annual intake of soil (36.5 g/y)
- FA_8 = area factor (1.0)
- FCD_8(t) = cover and depth factor (1.0)
- FO_8 = occupancy factor (0.75)

For default case at t=0 for 100 pCi/g of U-238:

- Dose = \(36.5 \text{ g/y} \times 1 \times 1 \times 0.75 \times 0.0002687 \text{ mrem/pCi} \times 100 \text{ pCi/g}\)
  \(= 0.736 \text{ mrem/year}\)
- Time integrated dose = 0.734 mrem/year

Area Factor: Soil Ingestion

- Fraction of work area that might be contaminated

\[
FA_8 = \frac{A}{1000} \quad \text{when} \quad 0 < A < 1000 \text{ m}^2
\]

\[
= 1 \quad \text{when} \quad A > 1000 \text{ m}^2
\]

- A is the area of contaminated zone and 1,000 m² is the assumed play or work area which is approximately the size of a single house lot
Environmental Transport Factors: Plant, Meat and Milk Pathways

- Appendix D: RESRAD users manual

\[ ETF_{\phi,\rho q} = FA_{\phi} \times FCD_{\rho q}(t) \times \sum_{\phi} DF_{\rho k} \times FSR_{\phi,\rho qk}(t) \]

Where
- DF = dietary factor (annual consumption rate)
- FSR(t) = food/soil concentration ratio
- FA = area factor
- FCD(t) = cover and depth factor

For default case at t=0 for 100 pCi/g of U-238:
- Dose = 174kg/y*1000g/kg*0.0025*0.5*1*0.0002687mrem/pCi*100pCi/g
  = 5.84 mrem/yr (from root uptake)
- Time integrated dose = 5.84 mrem/yr (from root uptake)
Area Factor: Plant, Meat & Milk Ingestion

- **Plant Ingestion**
  
  \[ FA_3 = \frac{A}{2000} \text{ when } 0 < A < 1000 \text{ m}^2 \]
  \[ = 0.5 \text{ when } A > 1000 \text{ m}^2 \]

- **Meat and Milk Ingestion**
  
  \[ FA_4 = FA_5 = \frac{A}{20,000} \text{ when } 0 < A < 20,000 \text{ m}^2 \]
  \[ = 1.0 \text{ when } A > 20,000 \text{ m}^2 \]

Cover and Depth Factor: Direct Root Uptake

- **Fraction of root length in the contaminated zone**
**Water Pathway Factors**

- Appendix E: RESRAD users manual

**Leaching Model**

- Rate controlled leaching model
  - If not specified the leach rate will be computed using a Sorption-desorption ion-exchange model
    - The distribution coefficient in the contaminated zone will be used to compute the leach rate
Leaching Model

\[ L_i = \frac{I}{\theta (c_z) T R_{d_i} (c_z)} \]

\[ I = (1 - C_e) \left[ \left( 1 - C_r \right) P_r + I_{rr} \right] \]

\[ \theta = P_i R_s \]

\[ R_{d_i} = 1 + \frac{\rho_b K_{d_i}}{\theta} \]

\[ R_s = \left( \frac{I}{K_{sat}} \right)^{\frac{1}{2b+3}} \]

Note: \( R_s \leq 1 \)
- \( K_{sat} \geq I \)

For default case for U-238:

- \( L = 0.5 \text{m/y}/((0.32) \times 2 \text{m} \times 235) = 0.0033/\text{y} \)
- \( I = (1-0.5) \times [(1-0.2) \times 1.0 + 0.2] = 0.5 \text{ m/y} \)
- \( \theta = 0.4 \times 0.8 = 0.32 \)
- \( R_d = 1 + (1.5 \text{g/cm}^3 \times 50 \text{cm}^3 / \text{g})/(0.32) = 235 \)
- \( R_s = (0.5/10)^{(1/(2\times5.3+3))} = (0.5/10)^{0.0735} = 0.8 \)
### Leaching Model

- **Radionuclide-specific $K_d$**
- **Hydraulic conductivity (m/yr)**
  - 33 [Silty Clay]
  - to 5,500 [Sand]
- **Soil-specific “b” parameter**
  - 4 [Sand]
  - to 11.4 [Clay]
- **Field capacity**
  - Lower limit of volumetric water content
- See Data Collection Handbook for more information

### Effect of $K_d$ on Leaching and Transport

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<thead>
<tr>
<th>Case A</th>
<th>Case B</th>
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<td><img src="#" alt="Low Kd" /></td>
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<td><img src="#" alt="Contaminated water" /></td>
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<tr>
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<td><img src="#" alt="High Kd" /></td>
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<tr>
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<tr>
<td><img src="#" alt="Low Kd" /></td>
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</tbody>
</table>

**TABLE E.2 Representative Values of Saturated Hydraulic Conductivity, Saturated Water Content, and the Soil-Specific Exponential Parameter**

<table>
<thead>
<tr>
<th>Texture</th>
<th>Hydraulic Conductivity, $K_c$ (m/yr)</th>
<th>Saturated Water Content, $\theta_s$</th>
<th>Soil-Specific Exponential Parameter, $b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay</td>
<td>$4.05 \times 10^3$</td>
<td>0.482</td>
<td>11.49</td>
</tr>
<tr>
<td>Clay loam</td>
<td>$7.5 \times 10^3$</td>
<td>0.476</td>
<td>8.52</td>
</tr>
<tr>
<td>Loam</td>
<td>$2.19 \times 10^4$</td>
<td>0.451</td>
<td>5.39</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>$4.01 \times 10^3$</td>
<td>0.410</td>
<td>4.38</td>
</tr>
<tr>
<td>Sand</td>
<td>$5.55 \times 10^3$</td>
<td>0.395</td>
<td>4.65</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>$8.6 \times 10^3$</td>
<td>0.420</td>
<td>10.40</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>$1.99 \times 10^3$</td>
<td>0.420</td>
<td>7.12</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>$1.09 \times 10^3$</td>
<td>0.415</td>
<td>6.00</td>
</tr>
<tr>
<td>Silty clay</td>
<td>$3.26 \times 10^3$</td>
<td>0.402</td>
<td>10.40</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>$5.16 \times 10^3$</td>
<td>0.477</td>
<td>7.75</td>
</tr>
<tr>
<td>Silty loam</td>
<td>$2.27 \times 10^3$</td>
<td>0.485</td>
<td>5.30</td>
</tr>
</tbody>
</table>

Source: Data from Clepp and Hornberger (1976).
**Dilution Factor: Non-dispersive Flow**

- Function of
  - Length parallel to aquifer
  - Contaminated area
  - Infiltration rate
  - Saturated hydraulic conductivity
  - Hydraulic gradient
  - Well depth
  - Well pumping rate

---

**Dilution Factor: Non-dispersive Flow**

- All parameters set to default except
  - Contaminated area
  - Length parallel to aquifer

- All parameters set to default except
  - Hydraulic gradient
Special Radionuclides: H-3 and C-14

- Appendix L of RESRAD Users Manual
- Special models to take into account the behavior of carbon and hydrogen in the environment.
- Submodels are used to estimate C-14 and H-3 concentrations in the soil, soil water, air and food products
- C-14 and H-3 concentrations in the groundwater are derived using the RESRAD leaching and groundwater models

Tritium Submodels

- Tritium air concentration
  - Calculates the amount of H-3 in the soil water
  - Releases the H-3 in the form of water vapor
  - RESRAD accounts for the loss of H-3 due to radioactive decay, leaching and the release of H-3
  - RESRAD applies an area factor to account for finite areas and accounts for the relative humidity and the evapotranspiration rate
  - Used to model the inhalation of tritium
    - 50% increase to model adsorption through the skin
  - Converts pCi \(^{3}\)H in g of soil to pCi \(^{3}\)H in g soil moisture
  - Wind speed,
  - Area (square contamination)
  - Mixing height
  - Humidity (upper limit)
Tritium Submodels

- **Plant Ingestion**
  - H-3 from soil to plants follows the path of stable hydrogen from soil to plants
  - H-3 is incorporated into the plant via direct root uptake and irrigation.
  - Incorporation of H-3 into plants via foliar deposition and dust is negligible

Tritium Submodels

- **Meat Milk and Aquatic Foods**
  - The ratio of H-3 to stable hydrogen in the food items to the intake of H-3 hydrogen is equal to the ratio of stable hydrogen in the food item to the intake of stable hydrogen

- **Aquatic Foods**
  - Obtained by multiplying the water concentration by a bioaccumulation factor
  - 1 L/Kg
**Carbon-14 Submodels**

- Similar in approach to the H-3 submodels
  - Air pathway
    - Releases C-14 as CO₂ over a given depth
      - Evasion depth
        - 30 cm (user specified)
      - RESRAD accounts for all source loss including:
        - Erosion, leaching, radioactive decay and release to the atmosphere
    - Inhalation of particulate and gaseous C-14 are included

---

**Carbon-14 Submodels**

- Plant Ingestion
  - C-14 is incorporated into the plant mainly due to photosynthesis
    - 98% photosynthesis
    - 2% direct root uptake
  - RESRAD uses the C-14 air concentration, the stable carbon air concentration and the stable carbon plant concentration to calculate the concentration of C-14 in the plants from photosynthesis (98%)
  - the C-14 soil concentration, and the stable carbon concentration in soil is also used with the stable carbon plant concentration to account for the root uptake component (2%, user specified)

- Meat and Milk Ingestion
  - C-14 follow the same route as stable carbon.
  - The ratio of the stable carbon concentration to stable carbon intake is equal to the ratio of the C-14 concentration to the C-14 intake
Carbon-14 Submodel

- Aquatic Foods
  - RESRAD uses the concept of the bioaccumulation factor
  - Ratio of carbon in the aquatic organism to the carbon in the water
  - Fish/water = 50,000
  - Crustacea-mollusk/water = 9,100

Introduction to the Radon Model

- Radionuclides:
  - Radon-222
  - Radon-220 (thoron)

- Media:
  - Soil
  - Water
  - Building Material
**Radon Pathway Considerations**

- Radon-222 is a decay product of the U-238, U-234, Th-230, and Ra-226 decay chain
- Radon-220 is a decay product of the Th-232, Ra-228, and Th-228 decay chain
- Indoor radon is regulated independently of other exposure pathways
- Generic concentration limits for Ra-226, Ra-228, Th-230, and Th-232 are 5 pCi/g in surface and 15 pCi/g in subsurface soil
- Indoor air radon decay product concentration limit is 0.02 WL
- Radon diffuses through soil, concrete flooring, etc. and dissolves in water
- Indoor and outdoor air exchange

---

**Radon Flux**

\[ J = -D \frac{dC}{dz} \]

- Where
  - \( J \) = radon flux
  - \( D \) = radon diffusion coefficient,
  - \( C \) = radon concentration in pore space, and
  - \( z \) = distance in direction of diffusion
Radon Diffusion

\[ \frac{dC}{dt} = \frac{d}{dz} \left( D \frac{dC}{dz} \right) - \lambda C + \frac{\lambda \varepsilon p_b S_{Ra}}{p_t} \]

- where:
  - \( P_t \) = total porosity,
  - \( \lambda \) = radon decay constant,
  - \( \varepsilon \) = radon emanation power,
  - \( p_b \) = soil density, and
  - \( S_{Ra} \) = radium concentration in soil
Solutions to the Radon Diffusion Equation: Outdoor Radon

\[ C_o = J_o \frac{F_{ao}}{A} \left( 1 - \exp\left( -\frac{\lambda \sqrt{A}}{2U} \right) \right) \]

where:
- \( J_o \) = outdoor radon flux
- \( F_{ao} \) = outdoor area factor
- \( A \) = area of contaminated zone
- \( U \) = annual average wind speed, and
- \( H_o \) = height into which plume is uniformly mixed

\( C_o \leq 500 \text{ s/m for radon-222} \)
\( J_o \leq 10 \text{ s/m for radon-220} \)

Solutions to the Radon Diffusion Equation: Indoor Radon

\[ C_i = \frac{J_i \frac{F_{ai}}{H} + (\nu C_o)}{\lambda + \nu} \]

where:
- \( J_i \) = indoor radon flux
- \( F_{ai} \) = indoor area factor
- \( H \) = ceiling height, and
- \( \nu \) = ventilation rate
Radon Inhalation from Water Usage

\[
\frac{C_{air}}{C_{water}} = \frac{f_{wa} U_w}{(\lambda + v)V}
\]

where:
- \(f_{wa}\) = transfer efficiency of radon from water to air
- \(U_w\) = household water usage
- \(V\) = volume of house (= volume of air exchange)
- \(v\) = ventilation rate

Radon Pathway Parameters
- Available when Ra-226 or Ra-228 are selected
- Or when these radionuclides are generated by a parent radionuclide
  - Examples
    - \(^{238}\)U generates Ra-226
    - \(^{232}\)Th generates Ra-228
**Working Levels**

- One working level = $1.3 \times 10^5$ MeV of potential alpha energy per liter of air

- **Radon-222:**
  - $WL = 1.03 \times 10^{-3} \,[\text{Po-218}] + 5.07 \times 10^{-3} \,[\text{Pb-214}] + 3.73 \times 10^{-3} \,[\text{Bi-214}]$

- **Radon-220:**
  - $WL = 9.48 \times 10^{-7} \,[\text{Po-216}] + 1.23 \times 10^{-1} \,[\text{Pb-212}] + 1.17 \times 10^{-2} \,[\text{Bi-212}]$

- Radon progeny concentrations (pCi/L) are calculated using Bateman’s Equations

**Radon Dosimetry**

- **Radon-222:**
  - 1 WLM = 760 mrem
  - For indoor exposure

- **Radon-220:**
  - 1 WLM = 250 mrem
  - For outdoor exposure

- Note: User may change these defaults

- References: ICRP 32 and 47, and National Research Council (1988 [BEIR IV], 1991)
An Example

- An industrial site is contaminated with U-238 at 400 pCi/g and Cs-137 at 20 pCi/g. The contamination extends down to the first 15 cm of soil. The unsaturated zone is 2.9 m thick and the water table stays at the same elevation. Assuming unrestricted use, estimate the total effective dose equivalent to an individual for up to 1000 years after license termination. Assume a residential farming scenario.
  - U-238 400 pCi/g
  - Cs-137 20 pCi/g
  - Set all pathways including Radon
  - Calculation times 1, 2, 3, 4, 5, 6, 10, 13 and 1000
  - 128 graphical points, linearly spaced
  - 0.15 m thick contamination
  - 2.9 m thick unsaturated zone
  - Water table drop rate is 0 m/y
  - Square contamination
  - Sensitivity analysis
    - on outdoor occupancy
    - By a factor of 2
Total Effective Dose Equivalent (TEDE)
**Which Radionuclides Contribute to the Dose?**

DOSE: All Nuclides Summed, All Pathways Summed

**Which Transport Pathways Contribute to the Dose?**

DOSE: All Nuclides Summed, Water Independent & Dependent Subtotals
Components of TEDE from $^{137}$Cs

Components of TEDE from $^{238}$U
**Sensitivity Output**

- External Pathway
  - Cover thickness
  - Contamination thickness
  - Occupancy Factors
  - Shielding Factors
  - Erosion rates
  - Leach rates

- Ingestion Pathways
  - Cover thickness
  - Contamination thickness
  - Depth of roots
  - Ingestion rates
  - Erosion rates
  - Leach rates

**Water Independent Components**

- Cover thickness
- Contamination thickness
- Erosion rates
- Leach rates

Contaminated Zone

Unsaturated Zone

Saturated Zone
**RESRAD Leaching /Unsaturated Zone Transport Model**

- Leach-rate is a function of:
  - \( K_d \) (Distribution Coefficient)
  - Total porosity
  - Saturation ratio
  - Infiltration rate

- Transport time in the "unsaturated zone" is a function of:
  - \( K_d \) (Distribution Coefficient)
  - Saturation ratio
  - Thickness of unsaturated zone(s)
  - Infiltration rate
  - Effective porosity

**Radionuclide Transport**

- Some Water Dependent Pathway Parameters:
  - Distribution coefficients
  - Area of contaminated zone
  - Length parallel to aquifer flow
  - Well depth
  - Well pumping rate
  - Infiltration rate
  - Groundwater flow rate
  - Ingestion rates
Characteristics of TEDE Versus Time

Analysis Tools
**RESRAD Reports**

- **Summary Report**
  - Documents the
    - Dose conversion factors that were used
    - Input parameters uses
    - Dose by pathway at each user time
    - Dose to Source Ratios at the user times, total peak dose, radionuclide peak dose
    - Soil guidelines at the user times, total peak dose and radionuclide peak dose
    - Doses and Guidelines are for initially present nuclides

---

**Concentration Report**

- Provides media concentrations at the user specified times
  - Contaminated zone
  - Surface soil
  - Surface water
  - Well water
  - Drinking water
  - Leafy Vegetables
  - Nonleafy vegetables
  - Fodder (meat ingestion)
  - Fodder (milk ingestions)
  - Meat
  - Milk
  - Fish
  - Crustacea
**Daughter Report**

- Provides the dose contribution from the principle radionuclides and their associate progeny at the user specified times
  - Not just the initially present radionuclides
  - But all the principle nuclides at the location of exposure

**Health Risk Report**

- Provides documentation of the risk coefficients uses
- Intake amount (pCi/yr)
- Excess cancer risk by pathway
Detailed Report
- Provides intermediate calculations for use in problem diagnostics and troubleshooting

RESRAD Graphics
- Provides temporal plots of
  - Doses
  - Dose to source ratios
  - Risks
  - Soil guidelines (DCGL’s)
  - Radionuclide concentrations
- Provides results of sensitivity analysis
- Results can be imported into Microsoft Excel for further analysis
Sensitivity Analysis

- An analysis to determine the degree to which model results change by changing a parameter in the model

- If the model results “significantly” change by changing the input parameter then that parameter is deemed as being “sensitive”

- Sensitivity analysis can be used to set priority in data collection

- What is significant?

Sensitivity Analysis

- Direct perturbation method
  - Perturb one parameter while leaving the rest constant
    - Can only perform sensitivity analysis on one parameter at a time
    - Effects of one parameter on another can not be studied

- RESRAD employs the direct perturbation method
  - Multiply parameter P by x and 1/x
  - RESRAD provides temporal plots of
    - P
    - P * x
    - P / x
Sensitivity Analysis: An Example

- Residential Farmer Scenario
  - U-238 and U-234 @ 100 pCi/g each
  - 0.5 m cover
  - No erosion of cover material
  - Water table drop rate set to 0
  - All other parameters set to default
  - Sensitivity analysis performed on
    - Thickness of contaminated zone x2
    - Precipitation rate x2
    - Distribution coefficient in the unsaturated zone x10
  - Time horizon 10000 years
  - Number of time points 256

Base Case
Summary of Results

- Sensitivity to the Thickness of Contaminated Zone
  - Peak dose occurs at the same point in time
  - Breakthrough occurs at the same time
  - Dose is insensitive to the thickness at early times
  - Contribution over the entire depth of the well at this time
  - Travel time in the unsaturated zone is not affected by thickness of the contamination
  - Water independent doses
  - Initial stage of Water dependent doses
Summary of Results

- Sensitivity to the Thickness of Contaminated Zone
  - Peak dose occurs at the same point in time
  - Breakthrough occurs at the same time
  - Dose is insensitive to the thickness at early times
  - The overall magnitude of the dose increases with increasing thickness
  - Longer tail with increased thickness
  - “Significant” change in dose?

- Only the near edge is contributing at the breakthrough time
  - Are the initial concentrations (pCi/m³) of the releases the same?
    - Equilibrium partitioning
  - Is the initial release rate (pCi/year) independent of the thickness?
    - Inventory \( \rightarrow \) Thickness
    - Leach rate \( \rightarrow \) Thickness\(^{-1}\)

- Water table is not affected by the thickness of the contaminated zone
  - When the thickness of the contaminated part above the water table changes
  - the thickness of the uncontaminated part will also change
**Summary of Results**

- **Precipitation Rate**
  - Time of peak dose changes
  - Breakthrough time changes
  - Overall magnitude of the dose is about the same
  - Dose is insensitive to the precipitation rate in early times
  - Decreasing the precipitation rate pushes the peak past 1000 years
    - *Would this be a cause for concern?*
  - What other parameters may be affected by the precipitation rate?
  - Would the precipitation rate be considered "significant"?
Summary of Results

- Overall magnitude of the dose decreases for one out of 3 simulations and remains about the same for the other two simulations
- Multiple breakthrough times and peak doses for one simulation
- One peak past the 1000 year timeframe
- Are there other parameters that may be correlated to the $K_d$ of U-238 in the unsaturated zone?
- How might they affect the results?
- Does changing the $K_d$ in the unsaturated zone significantly change the dose?
What is Significant?

RESRAD Application
Elza Gate Site: Oak Ridge TN

- The Elza Gate Site, located in Oak Ridge, Tennessee, was used by the Manhattan Engineer District to store high-grade uranium ore and ore processing residues in the early 1940s. The site was transferred to the U.S. Atomic Energy Commission in 1946 and was used as an equipment storage area for Oak Ridge National Laboratory. In the 1970s, the site was vacated and decontaminated, transferred to the City of Oak Ridge, and later sold to a private metal fabrication company.

- In 1988, the property was surveyed for contamination and was transferred to FUSRAP. In 1991 and 1992, DOE remediated radioactive contamination on concrete pads and in soils and removed polychlorinated biphenyl and lead contamination. The site was released for unrestricted use in 1993.

Natural Uranium Guideline

- RESRAD calculates single radionuclide guidelines (DCGLs)
- Users have to derive guidelines for
  - Natural “Total uranium”
  - “Depleted Uranium”
  - Etc.
- Procedure
  - Calculate activity based weighting factors for radionuclide mix
  - Example: Natural Uranium
    - $W_{U-234} = 0.488$
    - $W_{U-235} = 0.0225$
    - $W_{U-238} = 0.490$
### Residual Radioactive Material Guidelines for the Elza Gate Site

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<th></th>
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<td>2400</td>
<td>5400</td>
<td>590</td>
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<td>Uranium-235</td>
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<td>1600</td>
<td>3600</td>
<td>430</td>
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<tr>
<td>Uranium-Tot</td>
<td>1800</td>
<td>4000</td>
<td>470</td>
<td>120</td>
</tr>
</tbody>
</table>

A = Industrial-use scenario (current use)
B = Recreationist
C = Residential-use scenario (pond water)
D = Residential-use scenario (well water)

Guideline set by DOE: 70 pCi/g Total Uranium

* Based on dose limit of 100 mrem/yr

---

### Post Remediation Dose Assessment for the Elza Gate Site

Average Radionuclide Concentrations:
4.9 pCi/g U-238 (measured)
4.9 pCi/g U-234, 0.22 pCi/g U-235 (derived)

<table>
<thead>
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<td>1.5</td>
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</tbody>
</table>

A = Industrial-use scenario (current use)
B = Recreationist
C = Residential-use scenario (pond water)
D = Residential-use scenario (well water)
Application of DOE’s ALARA Policy at the Elza Gate Site

Uranium Cleanup Guidelines at Elza Gate

Note: volume estimate based on DOE’s residual contamination guidelines for Ra-226, Th-230, Th-232, and a variable U-238 guideline.

Procedures to Determine & Apply Site-Specific Guidelines

- Determine exposure scenario(s)
- Determine exposure pathway(s)
- Gather data
- Understand calculations
- Calculate guidelines
- Cleanup

Sounds easy…
but…
**Determine Exposure Scenario**

- Expected or plausible?
- Can future land-use plans be applied?
- What if the site does not match RESRAD assumptions?
  - Contaminated concrete
  - Leaky pipes
  - Contaminated groundwater
  - Contamination buildup from irrigation
  - New scenarios: drilling wells into contamination
  - Nonuniform contamination

**Determine Exposure Pathway**

- How can pathway use be justified?
  - Groundwater use
    - Potable
    - Yield
    - Likely
  - Agriculture
    - Land suitable
    - Expected use
    - Yield
  - Indoor exposure
    - Building on the contamination
    - Gamma shielding factor(s)
**Gather Data**

- Point value or distribution?
- Site specific, average, or maximal?
- Current or future?
  - Chemical form for DCF’s and Kd’s
- Correlations?

**Contaminated zone total porosity vs. Density of contaminated zone**

![Graph showing relationship between contaminated zone total porosity and density of contaminated zone]

**Uranyl Nitrate**

**Understand Calculations**

- That is… Does it make sense? Is it robust?
- Explore the data
  - Identify major nuclide, pathway, and time
  - Graphics
  - Detailed and intermediate calculations
  - Sensitivity
  - Uncertainty
  - Comparison to other guidelines
- Are other scenarios likely to be considered?
- Often this process requires iteration through this process

**Am-241**
**Calculate Guidelines**

- Guidelines or Dose Calculations?
- Do the nuclides have peak doses at different times?
- Can the guidelines be implemented with instrumentation?
- Will nuclides be surrogates for others?
- Guidelines for what areas?
- Multiple contaminated sources in an area?
- Elevated regions? Hotspots?

**Need for Operational DCGLs**

- Dose Limit (25 mrem/yr)
- Single Radionuclide DCGLs
- Operational DCGLs (compliance demonstrated with MARSSIM)

\[ \sum_{r=1}^{s} \sum_{t=1}^{l} \frac{Con_{s,t}}{DCGL_{s,t}} \leq 1 \]

- Regulations
- Pathway Analysis
- Field Implementation
Considerations in Designing and Performing an ALARA Cleanup

- Engineering safety factors
- Limitation of cleanup equipment
- Presence of other radionuclides or chemicals
- Inclusion of areas that are uncontaminated

Verification and Validation
Definitions

- **VERIFICATION**
  - Refers to the task or procedure by which a mathematical solution to an arbitrarily complex problem is tested for internal mathematical consistency and accuracy

- **VALIDATION**
  - Refers to the task or procedure by which the mathematical model is tested against accurately measured, independent sets of field or laboratory observations made over the range of conditions for which application of the model is intended

Benchmarking

- An exercise that consists of solving the same set of problems with several different computer codes and comparing results
- Not model verification
- Not model validation in most cases
**RESRAD Validation**

- Conducted leaching experiment (batch and column tests) to validate leaching model
- Participating in international code-comparison exercises -- VAMP, BIOMOVS II, BIOMASS and EMRAS -- in some cases using Chernobyl data

---

**Results**

**External Dose (Ground Exposure)**
27 April 1986 - 31 December 1990

![Graph showing data for External Dose (Ground Exposure)]

**Inhalation Dose (Resuspension)**
27 April 1986 - 31 December 1990

![Graph showing data for Inhalation Dose (Resuspension)]
Results

Long-term dose prediction compared very well with calculated dose based on observation data.

RESRAD Quality Assurance

- Changes to RESRAD must be approved by the Project Leader and Program Manager.
- A modification must be reviewed by:
  - An independent scientist or programmer
  - The Project Systems Analyst
  - The Project Leader
  - The Program Manager
- All modifications are reviewed prior to release by all programmers.
Thank You for Attending this RESRAD Workshop!

- Please send comments and questions to:
- E-mail: RESRAD@anl.gov
- Web Site: http://www.evs.anl.gov/RESRAD