U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Radiation Protection Limits, Dose Calculations, and Internal Dosimetry

Jim Durham
CNWRA

Radiation Measurements

- Why do we measure radiation levels?
  - Dose Limits
  - Contamination Limits

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Limits

- Occupational, Adults:
  - 50 mSv/y (5 rem/y) (external plus internal)
  - 500 mSv (50 rem) to any individual organ
  - 150 mSv (15 rem) to eyes
  - 500 mSv (50 rem) to skin or extremities

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Limits

- Occupational, Minors
  - 10% of Adult Limits
- Occupational, Fetus
  - 5 mSv (0.5 rem) for declared pregnant women over period of gestation
- General Public
  - 1 mSv/y (0.1 rem/y)

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Contamination Limits

- Vary depending on radionuclide
- Different limits apply to fixed and removable contamination
  - Removable limits are usually several times lower than fixed limits

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Contamination Limits

	Contamination limits (dpm/100 cm2)		
Radionuclides	Average	Maximum	Removable
Transuranics, I-125, I-129, Ra-226,	500	1500	20
Ac-227, Ra-228, Th-230, Pa-231			
Th-natural, Sr-90, I-126, I-131	1000	3000	200
I-133, Ra-223, Ra-224, U-232, Th-232			
U-natural, U-235, U-238,	5000	15000	1000
alpha emitters, beta-gamma emitters			
Tritium	10000	10000	10000

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Alpha Particle Dose Calculations

- Estimation of external α radiation dose
  - External doses not generally required
  - Minimum energy of 7.5 MeV required to penetrate dead skin layer

Beta Dose Calculations

- Estimation of external β radiation dose not in contact with skin
  - Rule of thumb, valid over a wide range of beta energies

$$\dot{D} = \left(27 \frac{rad - m^2}{Ci - hr} \right) \frac{A}{d^2}$$

- Assumes point source and no attenuation in air or source material
- Expect large errors at distances greater than 1 m (overestimates absorbed dose)

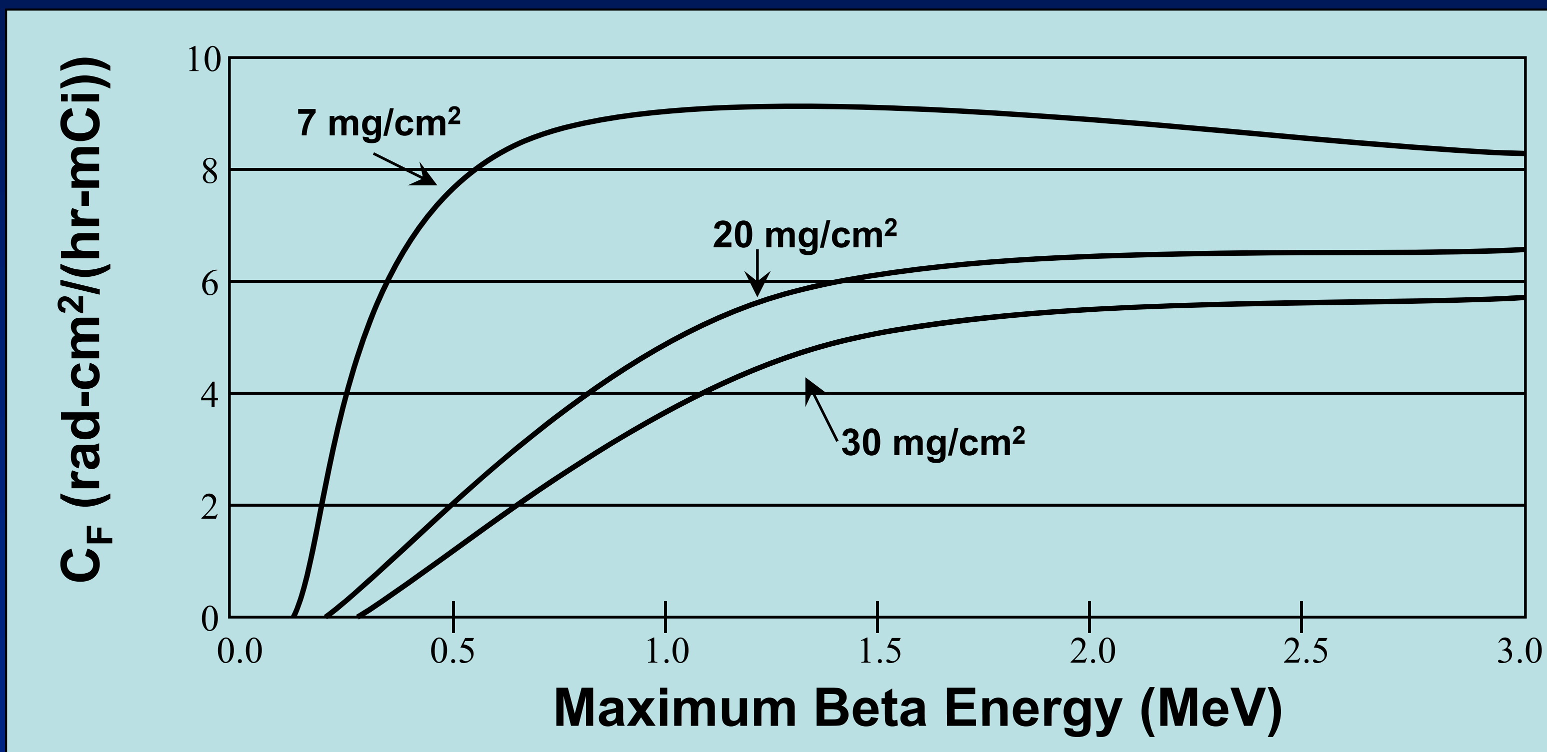
U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Calculations

- Estimation of external β radiation dose in contact with skin
  - 70 μm (7 mg/cm^2) dead skin layer acts as shield
  - Complex empirical formulas and techniques to compute skin dose at 70 μm
  - Healy Curves
    - Infinitely thin area sources (liquid on skin)
    - Several shield thicknesses
      - 7 mg/cm^2: dead skin layer shield
      - 20 and 30 mg/cm^2: dead skin layer plus 1 or 2 gloves for shielding

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Rate Conversion Factor versus Maximum Beta Energy: Healy Curves



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Beta Dose Calculations

- Estimation of external β radiation dose in contact with skin

$$\dot{D} = C_f \frac{A}{a}$$

  - A is the activity of the contamination in mCi
  - a is the area of contamination in cm^2

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Calculations

- Estimation of external γ radiation dose
  - Unshielded point source

$$\dot{X} = \Gamma \frac{A}{d^2}$$

  - Γ is the specific gamma-ray constant in ((R-m^2)/(hr-Ci))
    - tabulated
  - A is the activity of the contamination in Ci
  - d is the distance from the source in cm

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Calculations

- Specific gamma ray constant

Nuclide	Γ (R-m^2)/(hr-Ci)	Nuclide	Γ (R-m^2)/(hr-Ci)
^{133}Ba	0.24	^{125}I	0.07
^{51}Cr	0.116	^{131}I	0.22
^{137}Cs	0.33	^{192}Ir	0.48
^{57}Co	0.09	^{54}Mn	0.47
^{60}Co	1.32	^{226}Ra	0.825
^{198}Au	0.23	^{22}Na	1.20

Dose Calculations

- Converting a Gamma-Ray Exposure Rate to Dose Equivalent Dose Rate
  - Three depths
    - 1.0 cm: used for “Deep” absorbed dose
    - 0.3 cm: used for dose to lens of the “Eye”
    - 0.007 cm: used for “Shallow” or skin dose

$$\boxed{\dot{H} = C_d \dot{X}}$$

  - C_d is the rem/R conversion factor

Dose Calculations

- rem/R conversion factor

Photon Energy	Conversion Factors at Depth		
	1.0 cm (“Deep”)	0.3 cm (Lens of Eye)	0.007 cm (“Shallow”)
15	0.28	0.67	0.9
20	0.58	0.79	0.94
30	1.00	1.07	1.11
40	1.28	1.29	1.34
50	1.46	1.46	1.50
60	1.47	1.47	1.52
70	1.45	1.45	1.50
80	1.43	1.43	1.48
90	1.41	1.41	1.45
100	1.39	1.39	1.43
110	1.37	1.37	1.40
120	1.35	1.35	1.36
130	1.33	1.33	1.34
140	1.32	1.32	1.32
150	1.30	1.30	1.30
662	1.03	1.03	1.03

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Internal Dosimetry

- Assume someone had radioactivity in the body. What type of information is needed to determine the dose?
- Internal dosimetry deals with the destiny of radioactivity in the body

$\frac{dN}{dt}$: The rate of change of number of atoms in an organ as a function of time

  – solve for N(t)
    - gives the number of atoms at a given instant of time

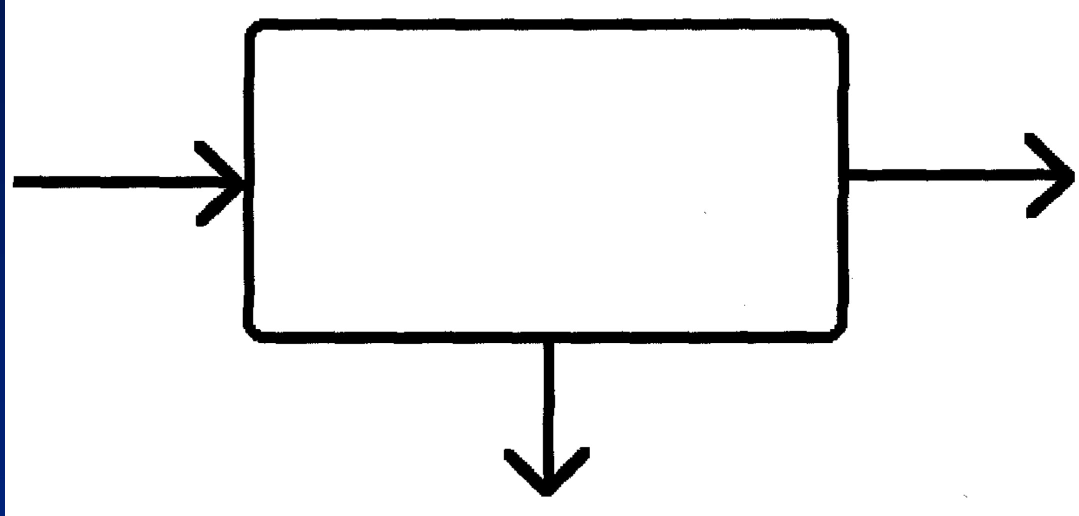
Internal Dosimetry

- Can get $A(t) = \lambda N(t) = q(t)$
    - this gives us radioactivity or # of disintegrations
  - Then we want the number of transformations over a time period T

$$U(T) = \int_{t_1}^{t_2} q(t)\,dt$$

Internal Dosimetry

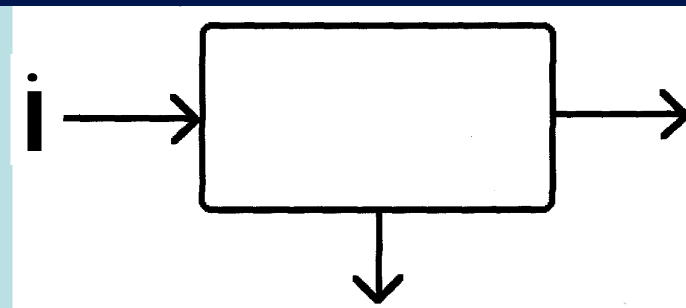
- Compartment Model



$$\frac{dN}{dt} = \text{Rate in} - \text{Rate out}$$

Internal Dosimetry

- **Example 1:** Continuous Constant Intake



$$\frac{dq}{dt} = \dot{I} - \lambda_B q - \lambda_r q = \dot{I} - \lambda_{eff} q$$

$$dq = \dot{I}\,dt - \lambda_{eff} q\,dt$$

$$e^{\lambda_{eff} t} dq + \lambda_{eff} q e^{\lambda_{eff} t} dt = \dot{I} e^{\lambda_{eff} t} dt$$

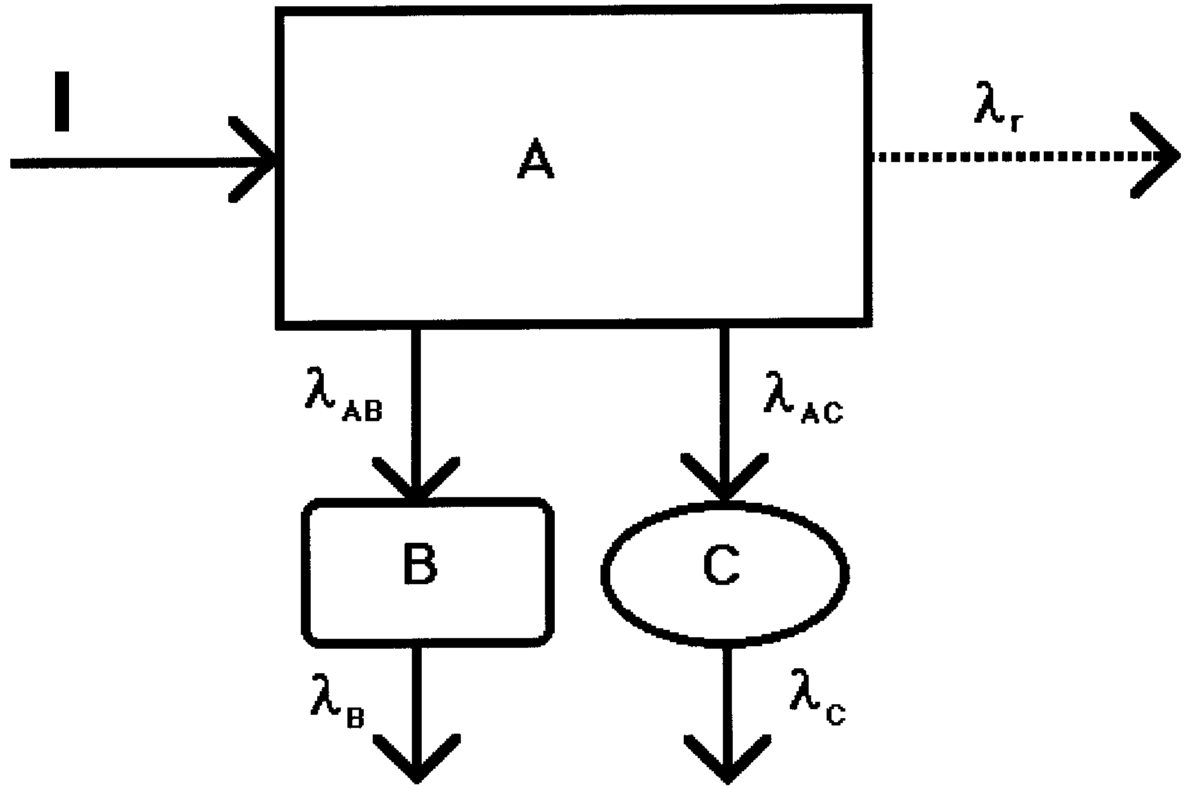
$$d\left[q e^{\lambda_{eff} t}\right] dt = \dot{I} e^{\lambda_{eff} t} dt \quad \Rightarrow \quad q e^{\lambda_{eff} t}\Big|_0^t = \frac{\dot{I}}{\lambda_{eff}} e^{\lambda_{eff} t}\Big|_0^t$$

$$\text{at } t = 0,\ q = 0: \quad q e^{\lambda_{eff} t} = \frac{\dot{I}}{\lambda_{eff}}\left[e^{\lambda_{eff} t} - 1\right]$$

$$q = \frac{\dot{I}}{\lambda_{eff}}\left[1 - e^{-\lambda_{eff} t}\right]$$

$$U(t) = \int_0^t q\,dt = \frac{\dot{I}}{\lambda_{eff}}\left[t + \frac{1}{\lambda_{eff}}\left(e^{-\lambda_{eff} t} - 1\right)\right]$$

Internal Dosimetry



$$\frac{dN_A}{dt} = I - \lambda_{AB}N_A - \lambda_{AC}N_A - \lambda_R N_A$$

Internal Dosimetry

$$\frac{dq_B}{dt} = \lambda_{AB} q_A - \lambda_B q_B - \lambda_r q_B$$

$$\frac{dq_B}{dt} = \lambda_{AB} I e^{-(\lambda_A + \lambda_r)t} - (\lambda_B + \lambda_r) q_B$$

$$dq_B + (\lambda_B + \lambda_r) q_B = \lambda_{AB} I e^{-(\lambda_A + \lambda_r)t}$$

$$e^{(\lambda_B + \lambda_r)t} dq_B + e^{(\lambda_B + \lambda_r)t} (\lambda_B + \lambda_r) q_B = \lambda_{AB} I e^{(\lambda_B + \lambda_r)t} e^{-(\lambda_A + \lambda_r)t}$$

$$d\left(q_B e^{(\lambda_B + \lambda_r)t}\right) = \lambda_{AB} I e^{(\lambda_B - \lambda_A)t} dt$$

at $t = 0$, $q_B = 0$

$$q_B e^{(\lambda_B + \lambda_r)t}\Big|_{t=0}^{t} = q_B e^{(\lambda_B + \lambda_r)t} = \frac{\lambda_{AB} I}{(\lambda_B - \lambda_A)}\left[e^{(\lambda_B - \lambda_A)t} - 1\right]$$

$$q_B = \frac{\lambda_{AB} I}{(\lambda_B - \lambda_A)}\left[e^{-(\lambda_A + \lambda_r)t} - e^{-(\lambda_B + \lambda_r)t}\right]$$

Internal Dosimetry

- Dose

$$\overline{D}_{Ti}$$

- Dose from particle type i, averaged over the whole organ or tissue T
- Dose Equivalent

$$\overline{H}_T = \sum_i Q_i \overline{D}_{Ti}$$

- Effective Dose Equivalent

$$\overline{H}_E = \sum_T w_T \sum_i Q_i \overline{D}_{Ti}$$

Internal Dosimetry

- Committed Dose

$$\overline{D}_{50Ti}$$

  - Total Absorbed dose during 50 years <u>after</u> the intake
  - Dose is averaged over the whole organ or tissue for particle type i
- Committed Dose Equivalent

$$\overline{H}_{50T} = \sum_{i} Q_i \overline{D}_{50Ti}$$

  - Total dose equivalent during 50 years <u>after</u> the intake
  - Dose equivalent is averaged over the whole organ or tissue and summed over all particles

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Internal Dosimetry

- Committed Effective Dose Equivalent (CEDE)

$$\overline{H}_{50E} = \sum_{T} w_T \sum_{i} Q_i \overline{D}_{50Ti}$$

- Total Effective Dose Equivalent (TEDE)

$$H_E = \overline{H}_{50E} + H_{ext\ E}$$

  - Dose: what happened
  - Dose Equivalent: how it happened
  - Effective Dose Equivalent: where it happened
  - CEDE: when it happened

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

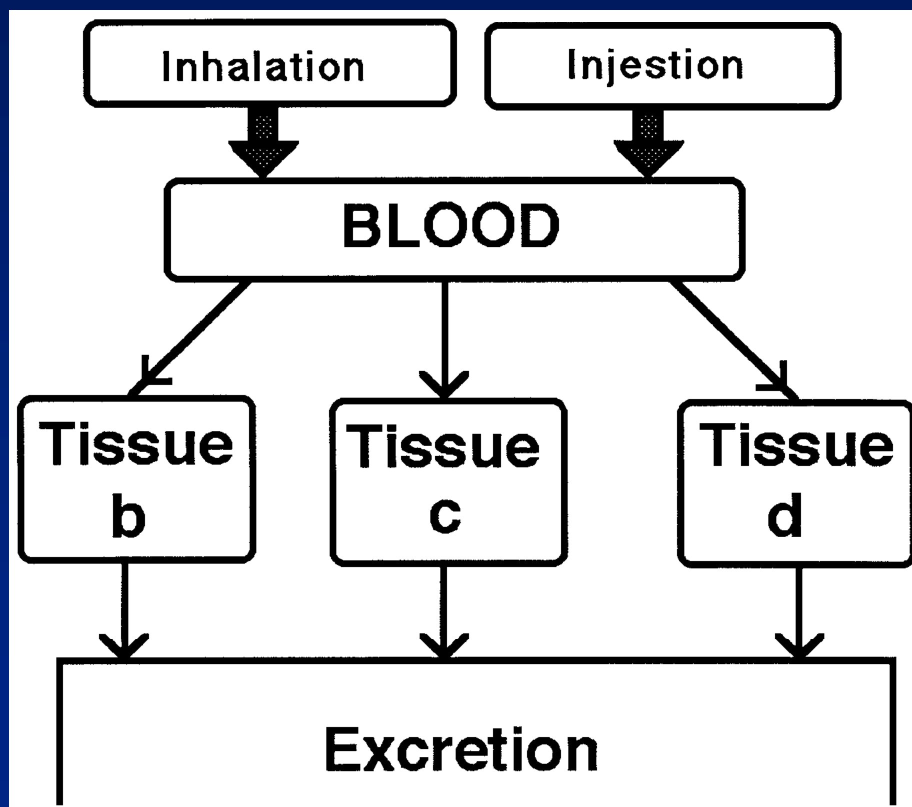
Internal Dosimetry

- Reference Person

Source organs	Mass (g)	Target organs	Mass (g)
Ovaries	11	Ovaries	11
Testes	35	Testes	35
Muscle	28 000	Muscle	28 000
Red marrow	1 500	Red marrow	1 500
Lungs	1 000	Lungs	1 000
Thyroid	20	Thyroid	20
ST content	250	Bone surface	120
SI content	400	ST wall	150
ULI content	220	SI wall	640
LLI content	135	ULI wall	210
Kidneys	310	LLI wall	160
Liver	1 800	Kidneys	310
Pancreas	100	Liver	1 800
Cortical bone	4 000	Pancreas	100
Trabecular bone	1 000	Skin	2 600
Skin	2 600	Spleen	180
Spleen	180	Thymus	20
Adrenals	14	Uterus	80
Bladder content	200	Adrenals	14
Total body	70 000	Bladder wall	45

Internal Dosimetry

- What happens to material that is taken into the body?
  – After inhalation or ingestion, a radionuclide will be translocated to the body fluids



Internal Dosimetry

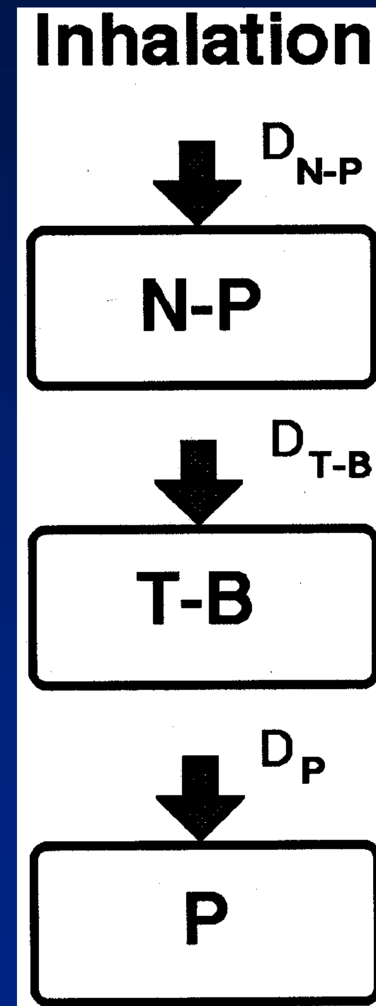
- Blood Compartment (body fluids)
  - Cleared by first order kinetics with a half life of 0.25 day, unless otherwise specified
  - Decays occurring in blood are assumed to be uniformly distributed throughout the body (m = 70 kg)

Internal Dosimetry

- Tissue Compartments
  - represent tissues or organs consisting of one or more compartments
  - radionuclides are translocated from each compartment to excretion at an appropriate rate
  - no feedback from excretion and no transfer between organs
    - it is known that some feedback occurs in practice

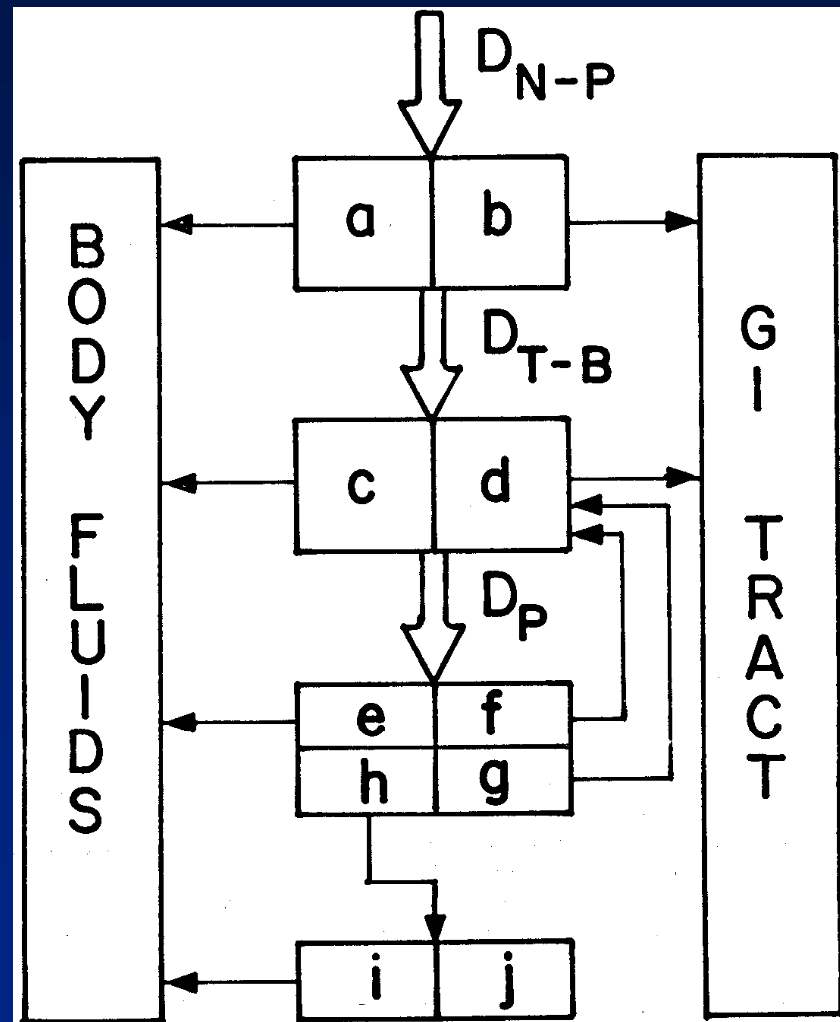
Internal Dosimetry

- Lung Model
  - Nasal Passage (N-P)
  - Trachea and Bronchial Tree (T-B)
  - Pulmonary Parenchyma (P)
  - Inhalation results in deposition in each of these regions
    - $D_{N-P} = 30\%$
    - $D_{T-B} = 8\%$
    - $D_{P} = 25\%$



Internal Dosimetry

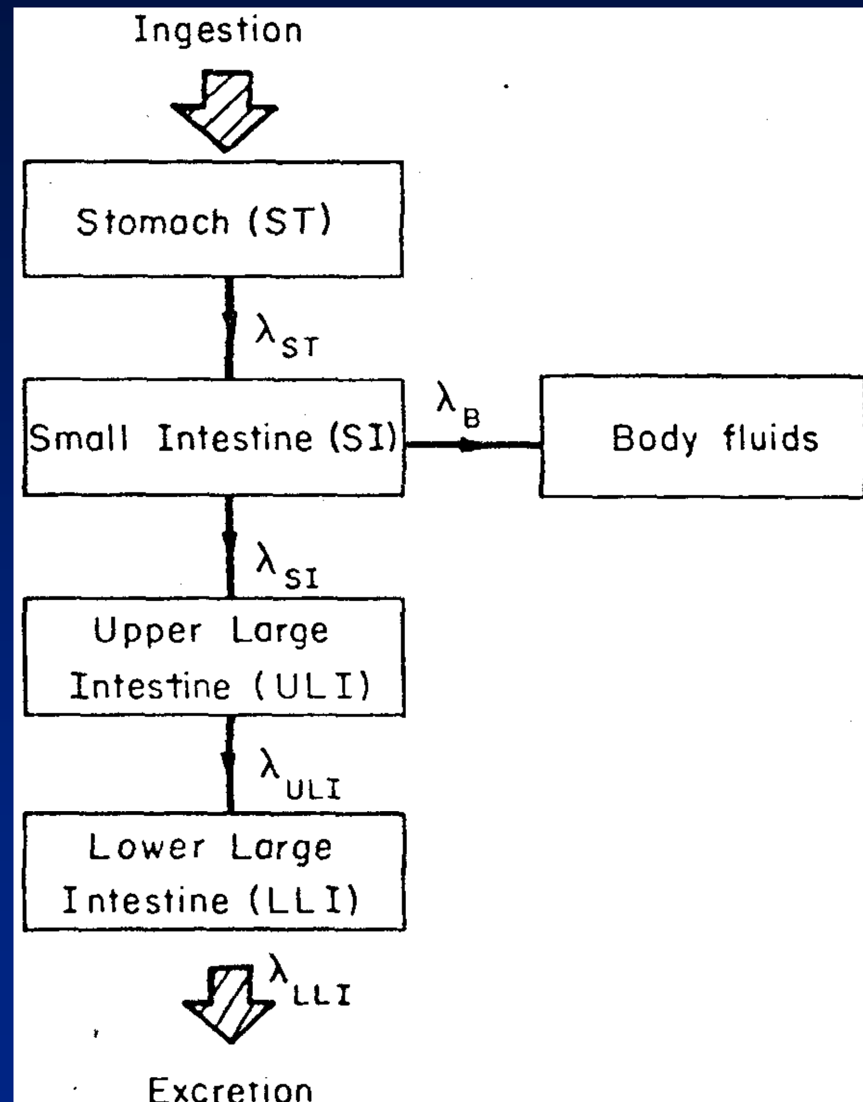
- Lung Model
  - N-P: compartments a (absorption) and b (particle removal through mucous)
  - T-B: compartments c (absorption) and d (particle removal through mucous)
  - P: compartments e (absorption), f (fast removal to trachea), g (slow removal to trachea), and h (removal to lymph nodes)
  - Pulmonary Lymph Nodes (L): compartments i (slow absorption) and j (no removal)



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Internal Dosimetry

- Dosimetric Model for the GI Tract
  - absorption to body fluids (blood) is through the Small Intestine only



Internal Dosimetry

- New models for the lung and GI tract have been developed and are currently being introduced into regulations
  - More detailed
  - Take advantage of the availability of high speed personal computers

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Conversion Factors

- A dose conversion factor (DCF) converts a soil or water concentration of a radionuclide to effective dose equivalent
  - Includes both external sources and internal sources
- The DCF takes into account the type of radiation and the irradiated organs of the body for the radionuclide
  - Includes internal dosimetry of the radionuclide for ingestion and inhalation

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Dose Conversion Factors

- Types of DCFs:
  - Inhalation
  - Ingestion of food
  - Ingestion of tap water
  - Air submersion
  - Water immersion
  - Exposure to contaminated ground surface
  - Exposure to soil contaminated to a depth of 1 cm
  - Exposure to soil contaminated to a depth of 5 cm
  - Exposure to soil contaminated to a depth of 15 cm
  - Exposure to soil contaminated to an infinite depth

Dose Conversion Factors

- Dose Conversion Factors are tabulated in
  - Federal Register Guidance Document 11 (ingestion and inhalation)
  - Federal Register Guidance Document 12 (external sources)
  - Federal Register Guidance Document 13 (age and gender differences)
    - Uses new lung model

Dose Conversion Factors

- Given the DCFs, now all we need to do is determine the water, soil, and air contamination
- At CNWRA, this can be accomplished using the Total-system Performance Assessment (TPA) computer code

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

Summary

- For external sources, dose calculations are fairly simple
- For internal sources, calculations are very complex
- Newer models are increasing the complexity
- Dose Conversion Factors allow determination of a reasonable dose without the complex calculations

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

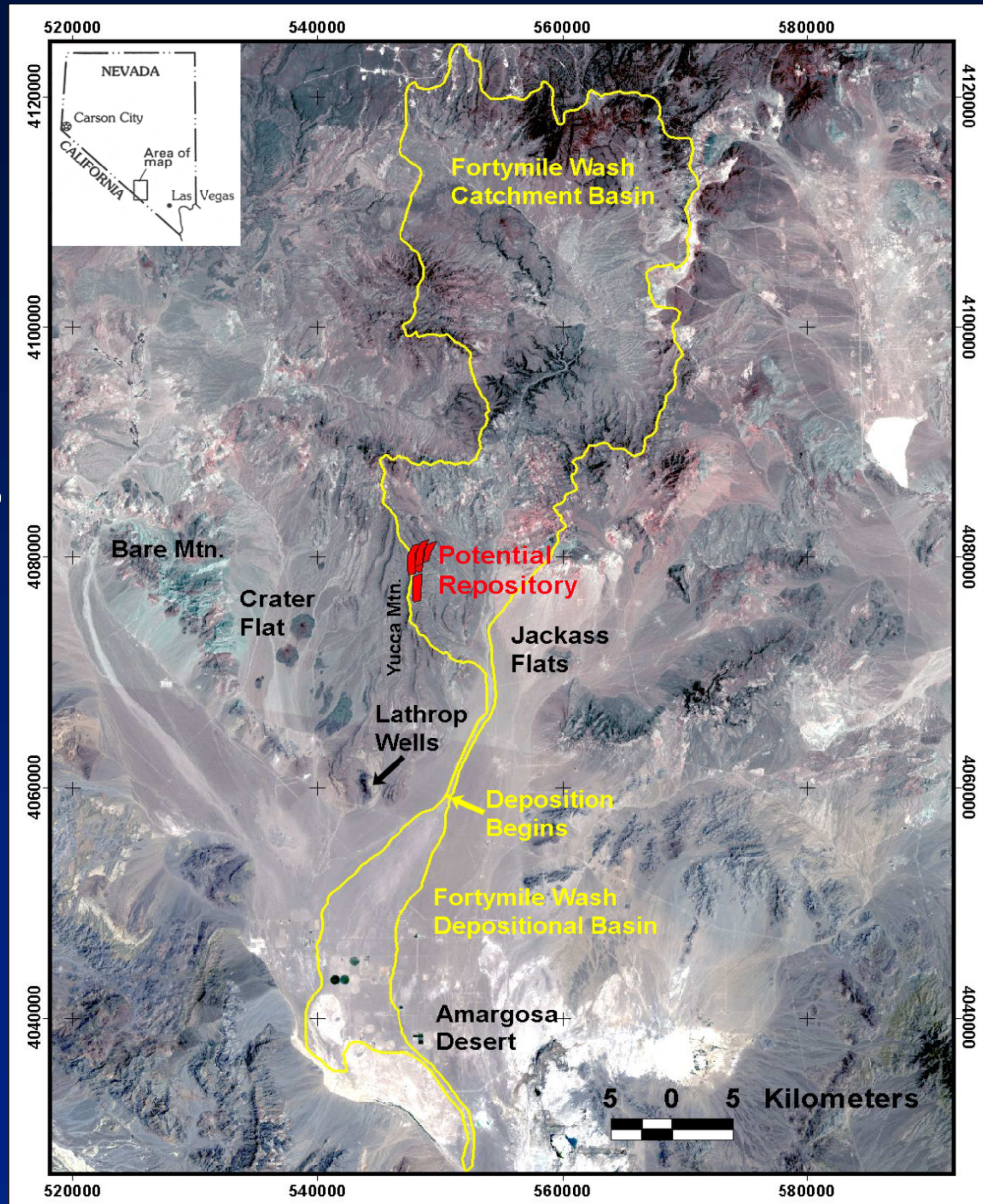
- Purpose
  - Develop regulatory risk insights that can help to focus a licensing review of the potential geologic repository at Yucca Mountain, Nevada
  - Secure a detailed and quantitative understanding of the overall risk significance of key factors that control
    - Degradation of the engineered barrier system
    - Release of contaminants from the potential repository
    - Subsequent transport of contaminants through various environmental pathways
    - Possible human exposure

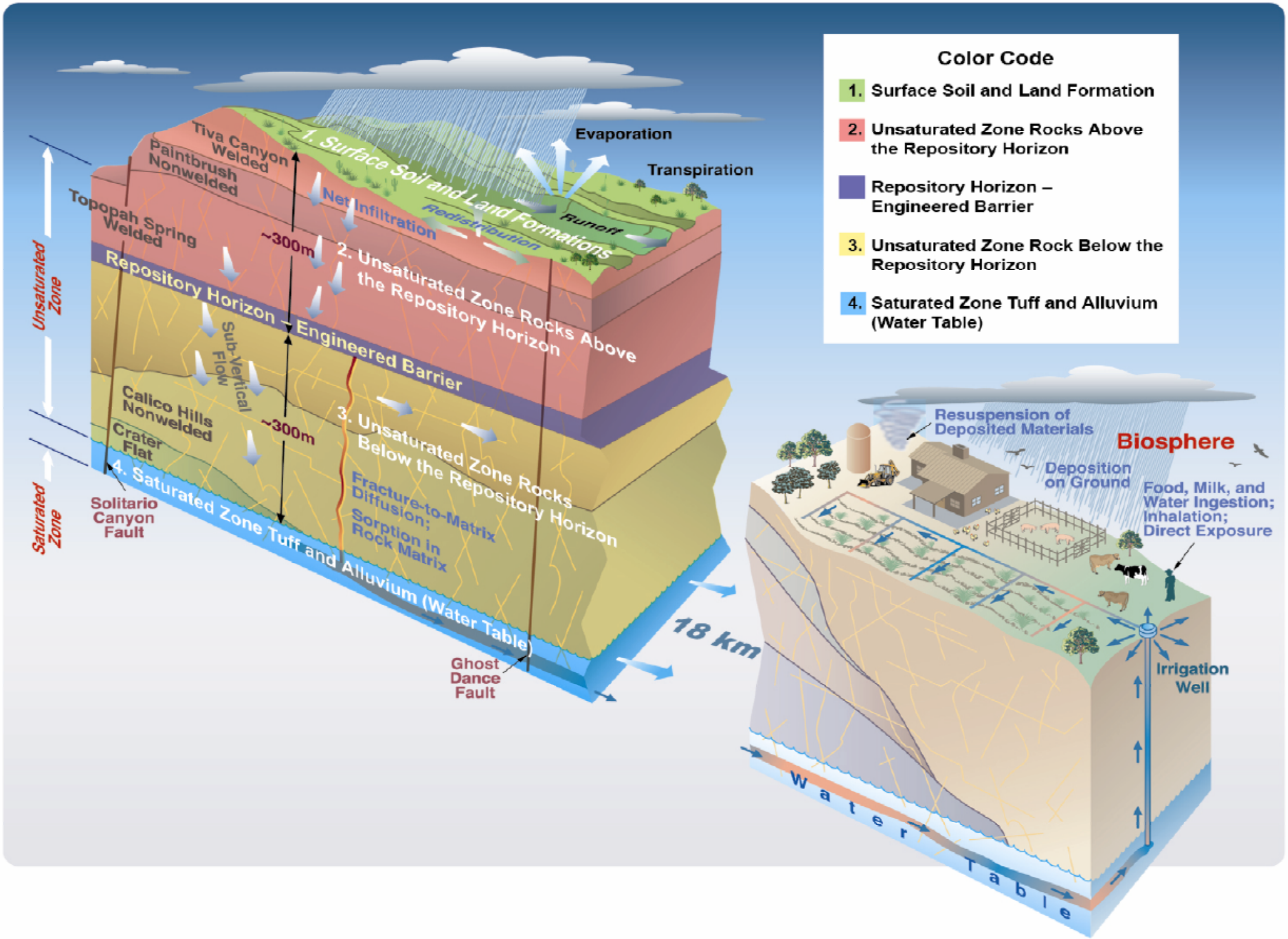
TPA Computer Code

- Potential repository system is modeled in a probabilistic manner
  - Yields a range of potential future evolutions of the potential repository system
    - 10,000 years to 1,000,000 years
  - Avoids limitations associated with completely deterministic scenario-based assessments
    - Inability to account for uncertainty in model parameter and site characterization data

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

- Nye County, NV 120 km [75 mi] northwest of Las Vegas

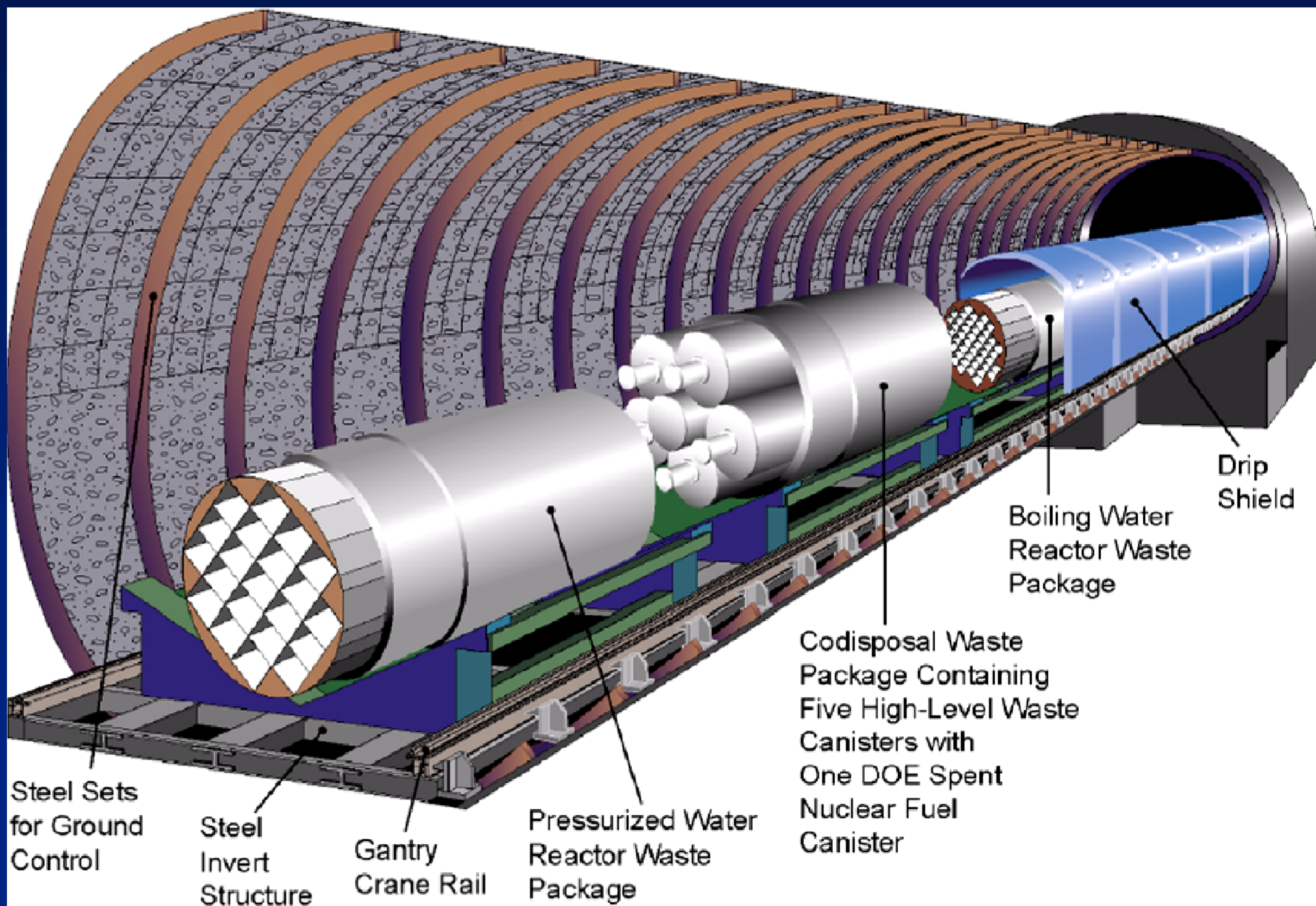




Color Code
1. Surface Soil and Land Formation
2. Unsaturated Zone Rocks Above the Repository Horizon
Repository Horizon – Engineered Barrier
3. Unsaturated Zone Rock Below the Repository Horizon
4. Saturated Zone Tuff and Alluvium (Water Table)
Evaporation
Transpiration
Runoff
Redistribution
Net Infiltration
1. Surface Soil and Land Formations
Tiva Canyon Welded
Paintbrush Nonwelded
Topopah Spring Welded
~300m
2. Unsaturated Zone Rocks Above the Repository Horizon
Repository Horizon – Engineered Barrier
Sub-Vertical Flow
Calico Hills Nonwelded
Crater Flat
~300m
3. Unsaturated Zone Rocks Below the Repository Horizon
Fracture-to-Matrix Diffusion;
Sorption in Rock Matrix
4. Saturated Zone Tuff and Alluvium (Water Table)
Unsaturated Zone
Saturated Zone
Solitario Canyon Fault
Ghost Dance Fault
18 km
Resuspension of Deposited Materials
Biosphere
Deposition on Ground
Food, Milk, and Water Ingestion; Inhalation; Direct Exposure
Irrigation Well
Water Table

TPA Computer Code

- Waste Package and Drip Shield in Drift

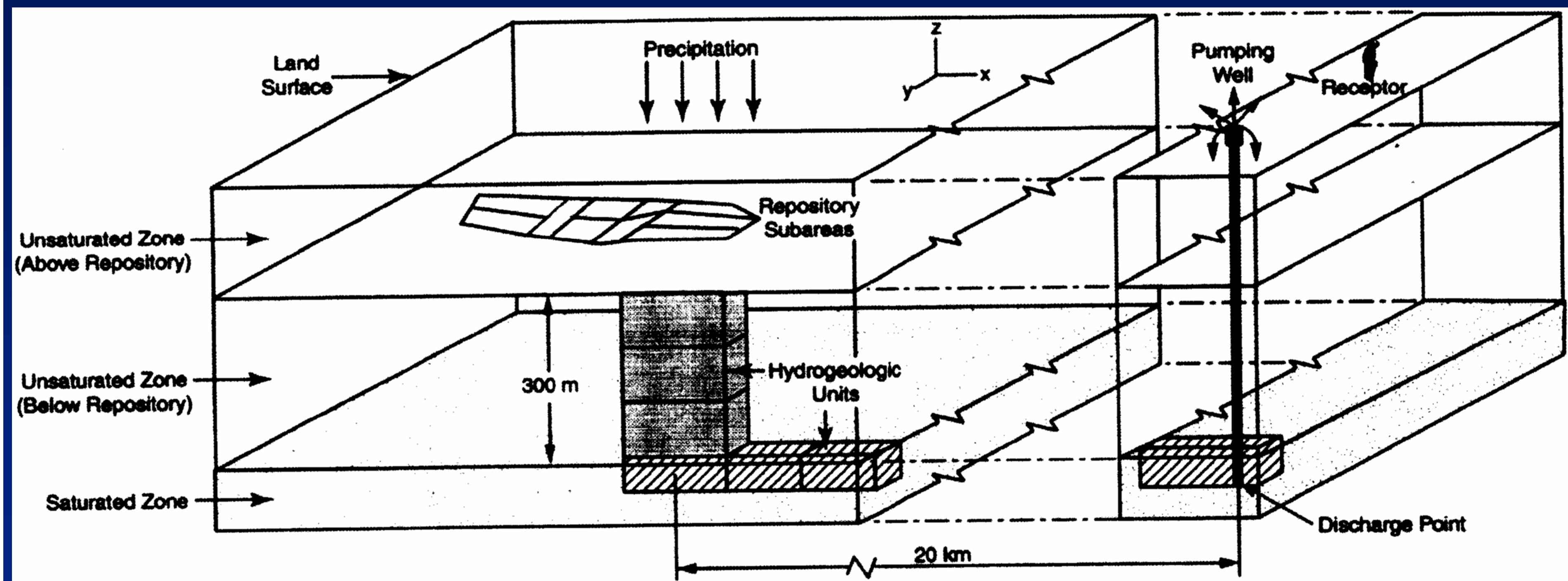


TPA Computer Code

- Drip Shield: Titanium Grade 7
- Waste Package: Alloy 22 Outer Container with a Stainless Steel Type 316-NG Inner Container
- Invert is a V-Shaped Support Pallet

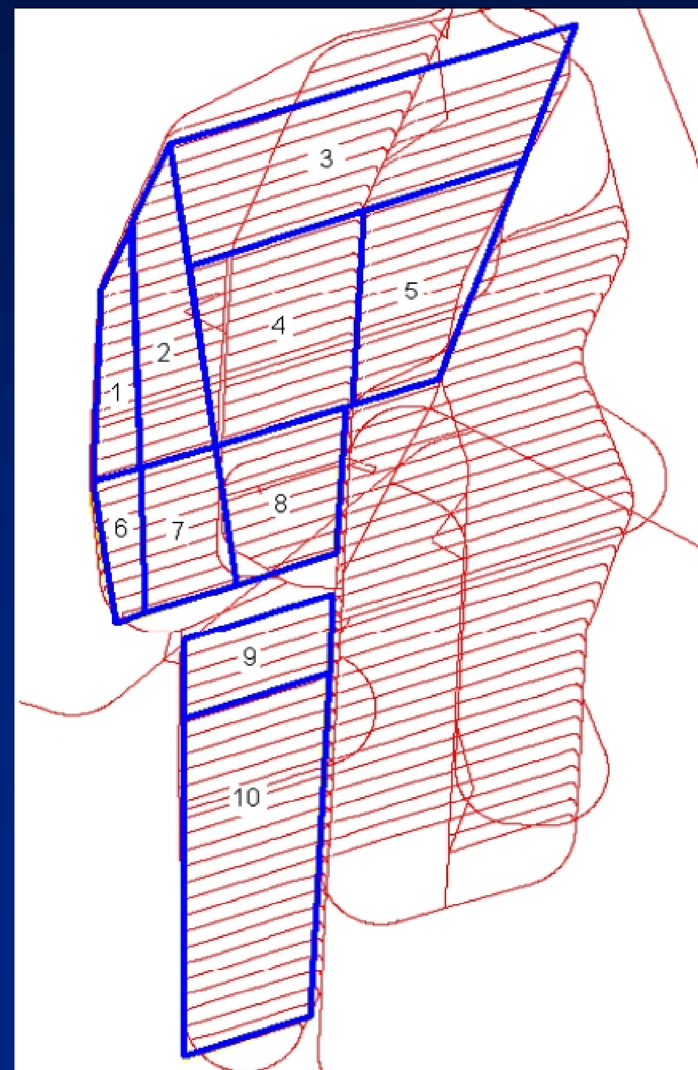
TPA Computer Code

- Conceptual Model



TPA Computer Code

- Subareas represent individual subregions of the repository
- Radionuclide releases are calculated by modeling a single representative waste package for each subarea and for each failure type

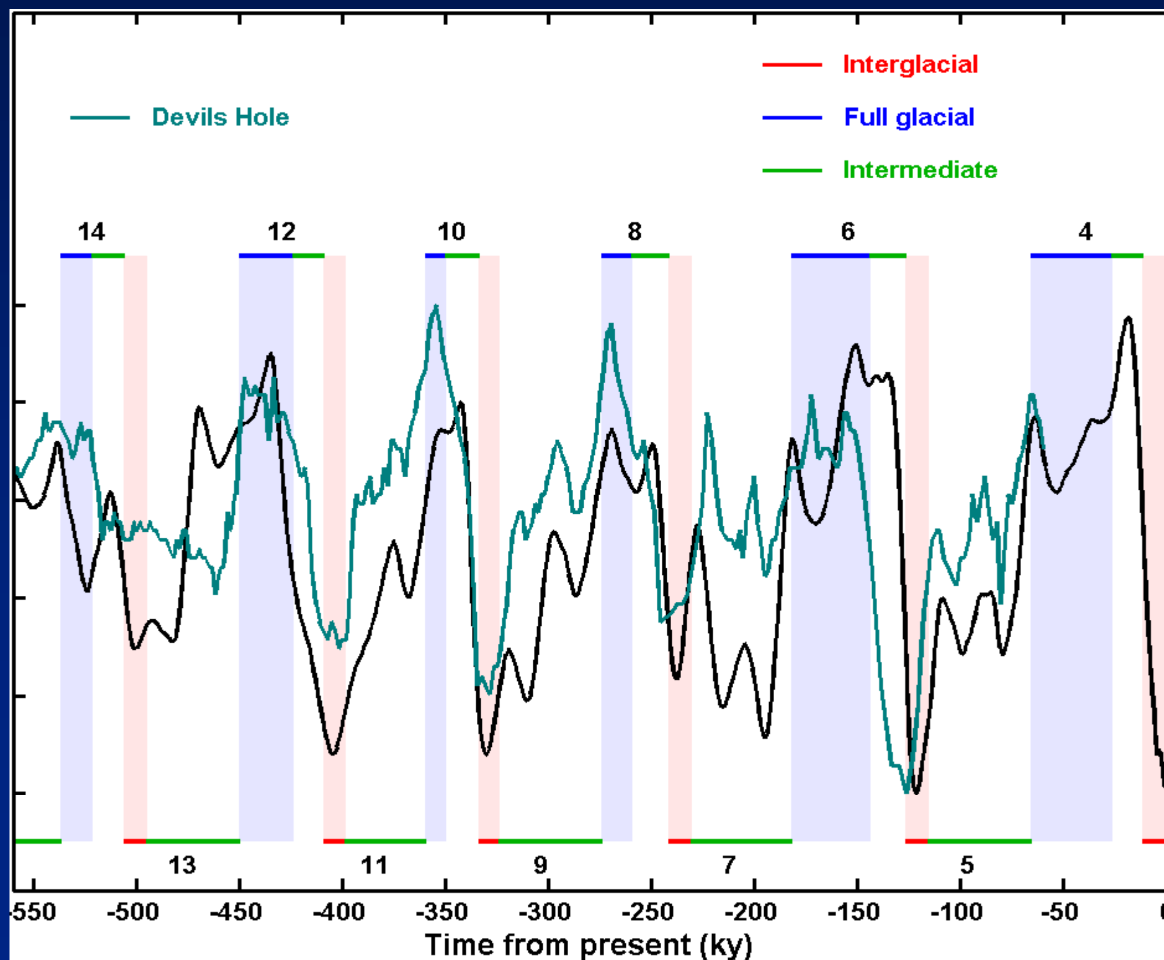


TPA Computer Code

- Types of Failure
  - Localized corrosion failure
  - Mechanical failure
  - General corrosion failure
  - Initially defective waste packages

TPA Computer Code

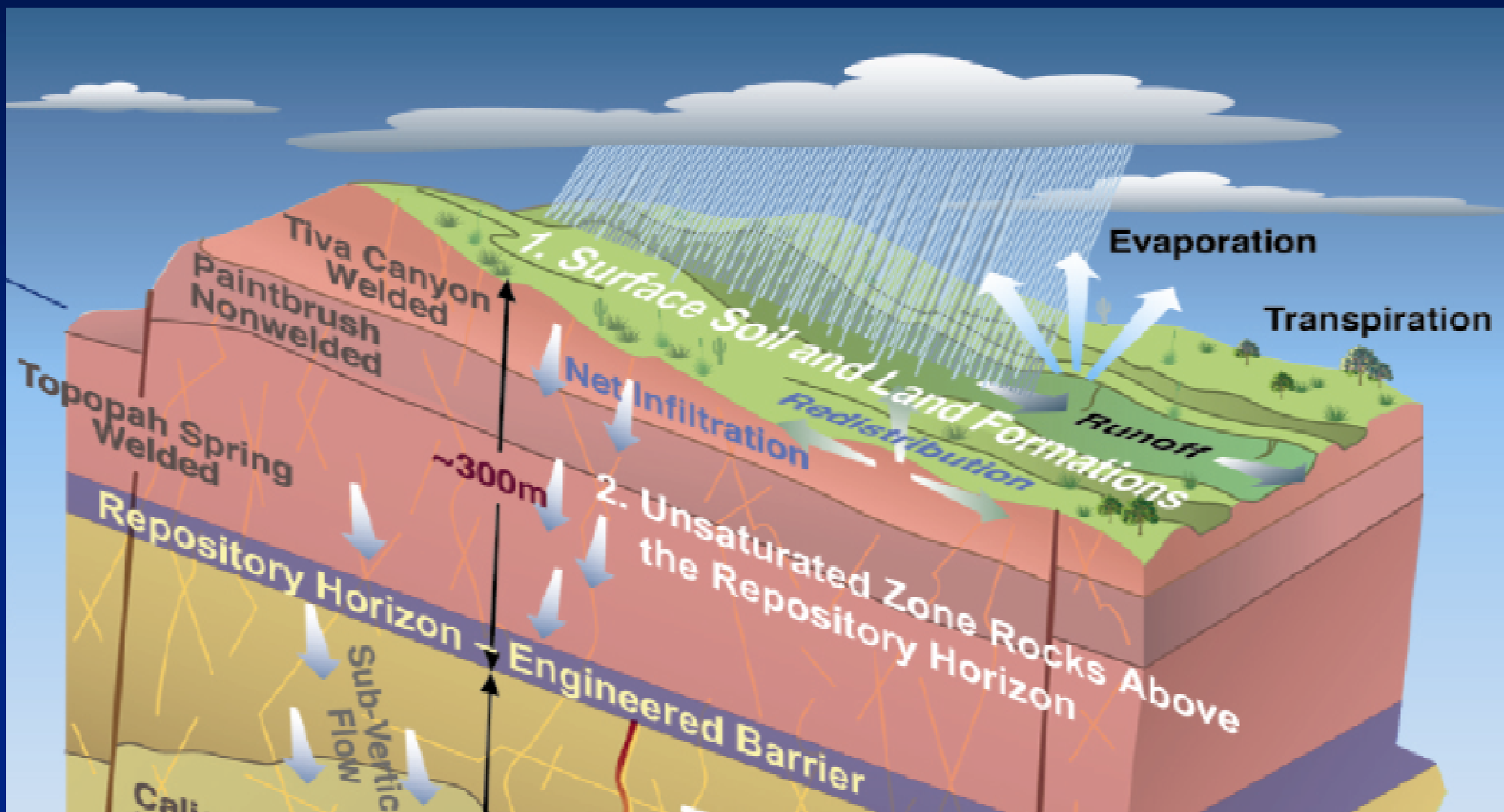
- Precipitation



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

- Deep Percolation



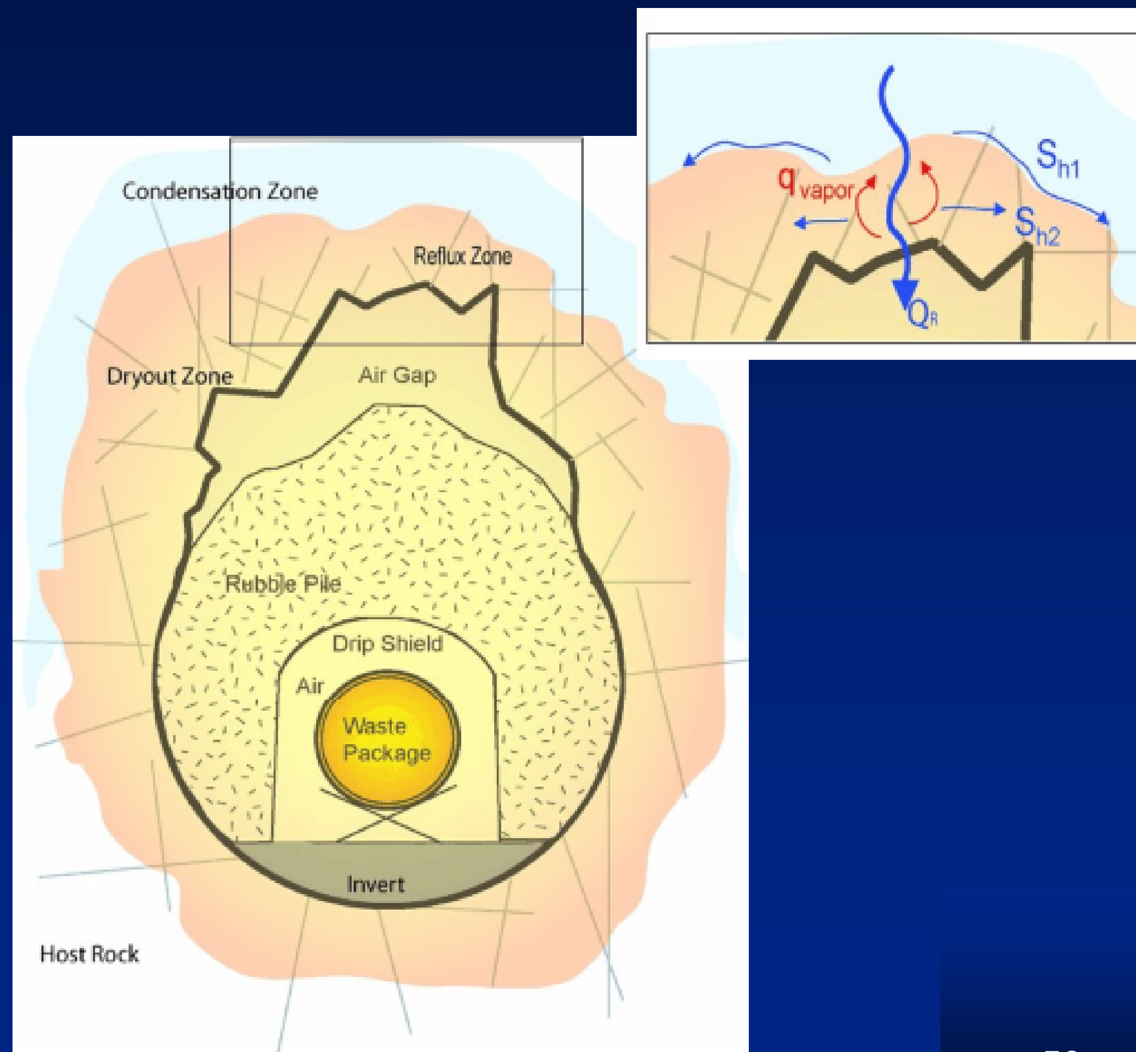
U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

- The Near-Field Environment May Affect Performance of the Engineered Barrier System
  - Heat transfer
  - Water–rock geochemical interactions
  - Refluxing of condensate water
  - Chemical composition of seepage water
- Important Parameters
  - Temperature
  - Relative humidity
  - pH
  - Ion concentration (chloride, carbonate)

TPA Computer Code

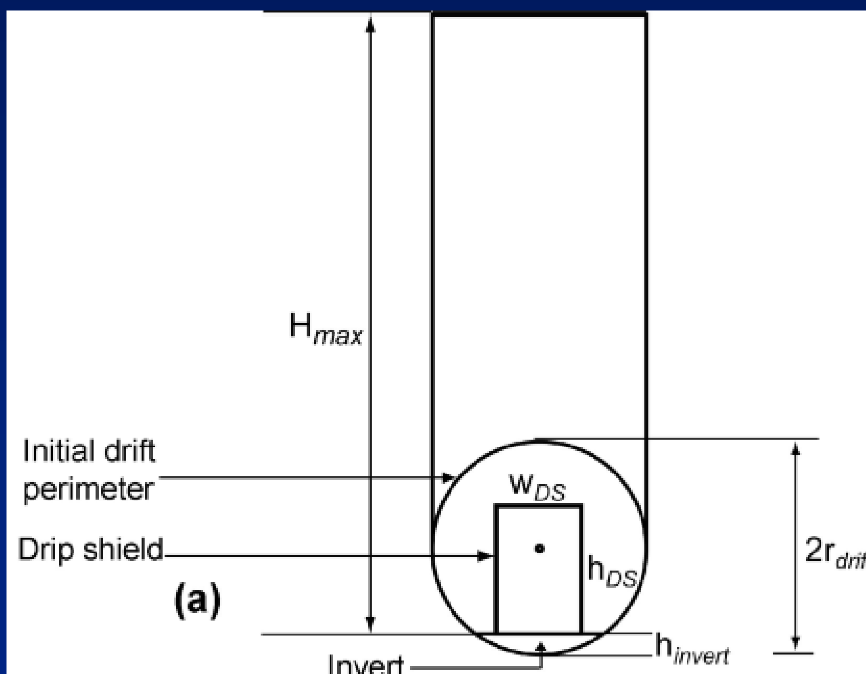
- Near-Field Environment Depends on the Amount of Water Reaching the Waste Package and the Buildup of Rubble



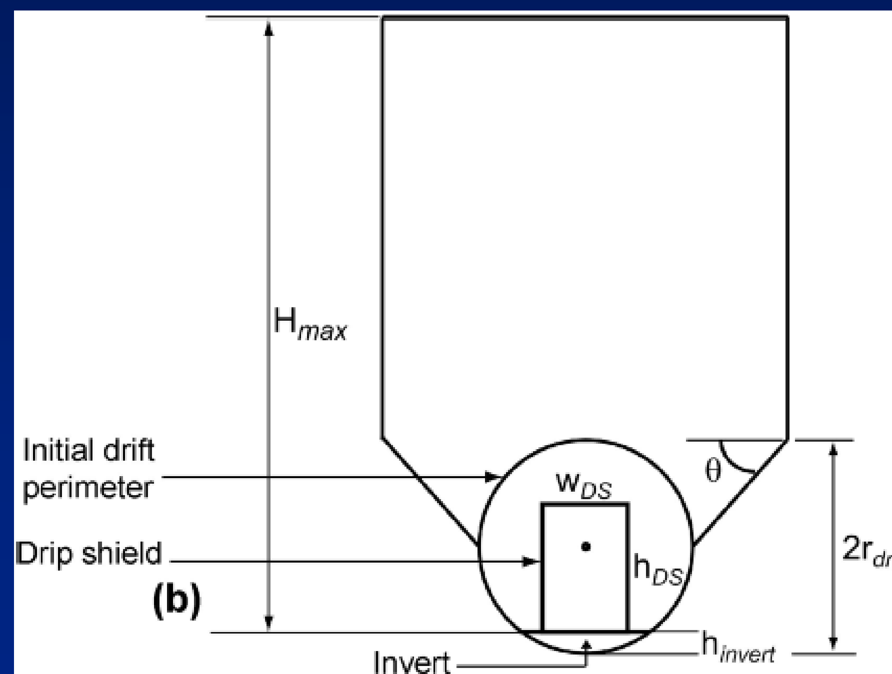
TPA Computer Code

- Drift Failure Causes Rubble to Collect on Drip Shield

Chimney Accumulation



Trapezoidal Accumulation



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

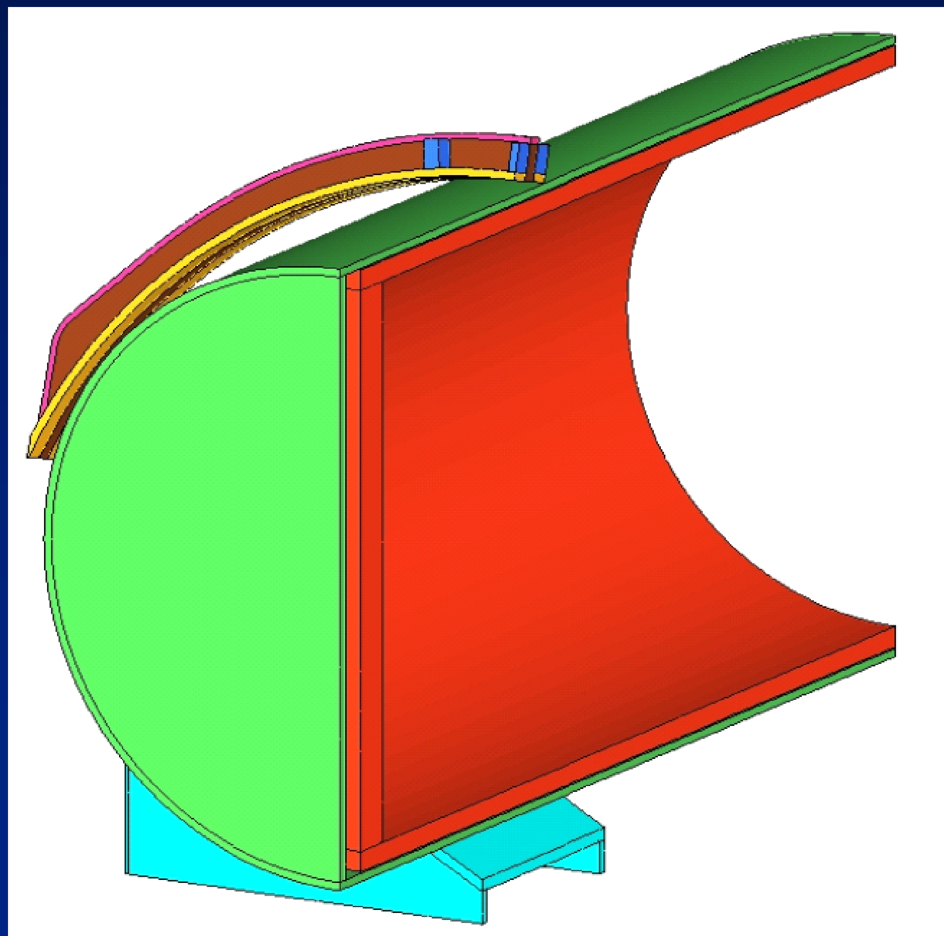
TPA Computer Code

- Corrosion
  - Causes thinning of the drip shield wall, simulated as a constant rate
  - Drip shield fails when demand from rubble exceeds the vertical-load-carrying capacity of the drip shield wall or when the drip shield thickness is 0
  - General (uniform) corrosion also causes thinning of the waste package containers
  - Localized corrosion causes openings to form in the waste package containers

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

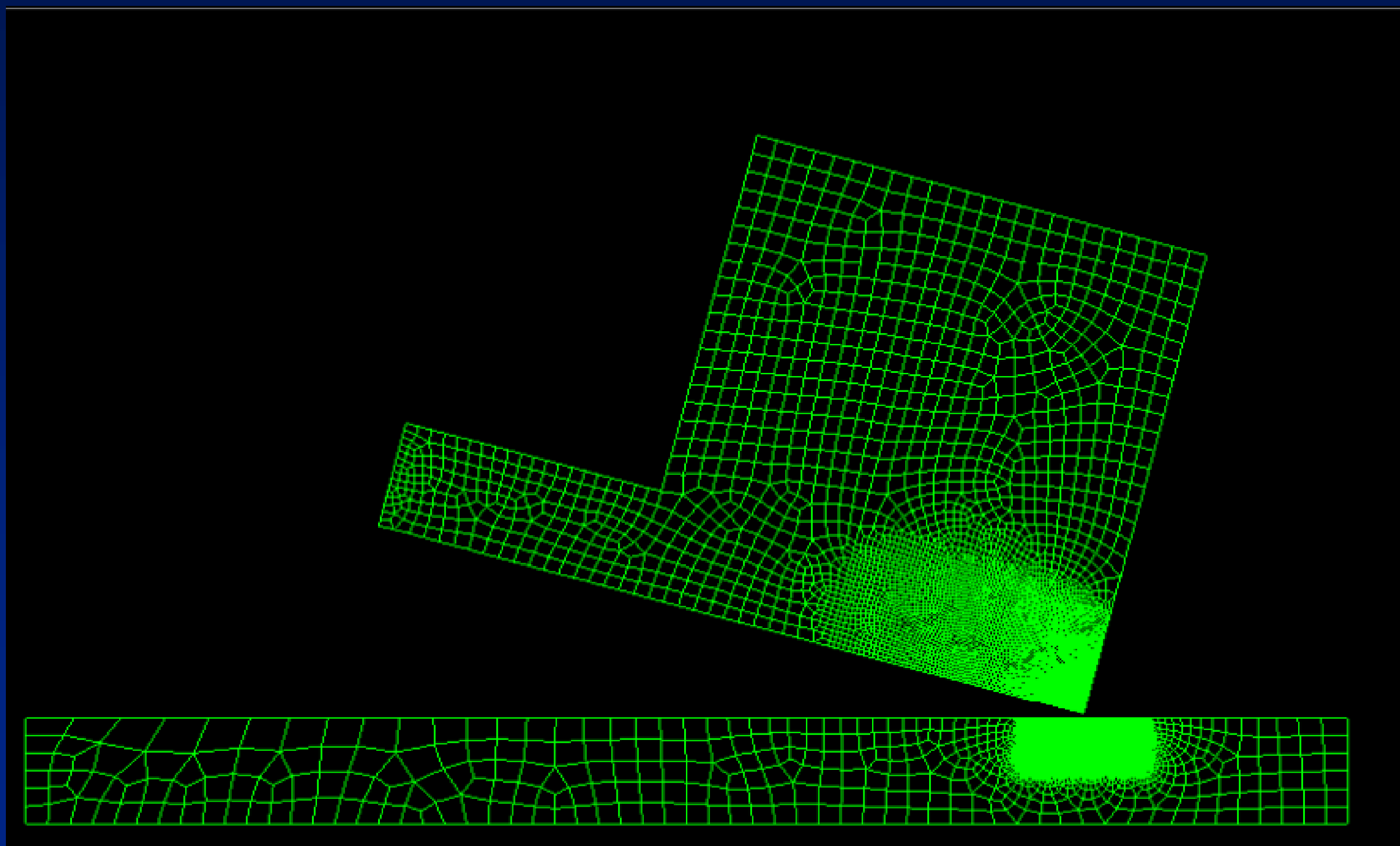
- Waste Package Mechanical Failure



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

- Waste Package Mechanical Failure



TPA Computer Code

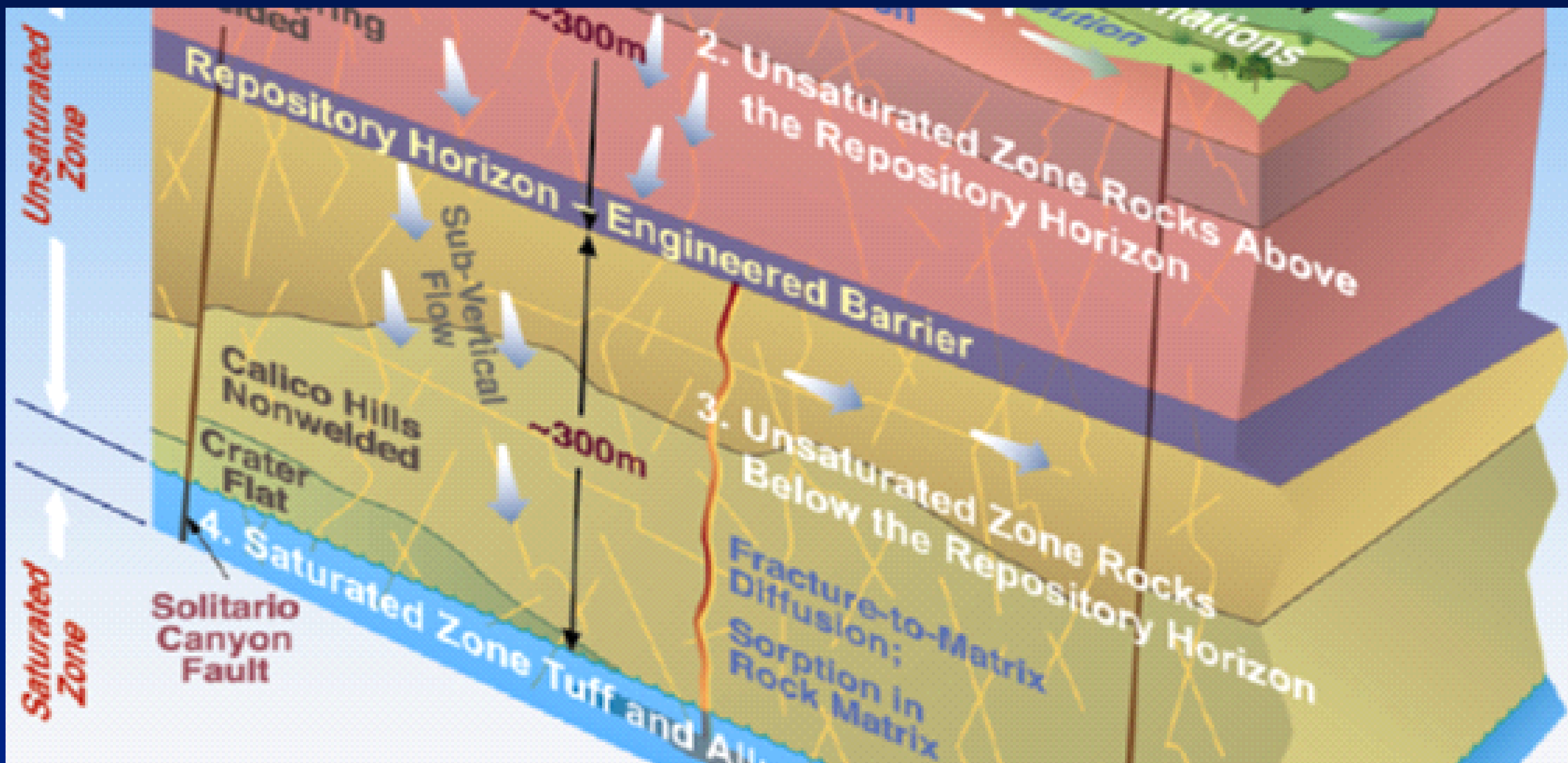
- Waste package fails mechanically when the load from the failed drip shield exceeds the ultimate tensile strength of the outer container
- If the outer container thickness reaches 0 before mechanical failure, the waste package fails from general corrosion

TPA Computer Code

- Release of radionuclides from the EBS depends on
  - Water delivery to waste forms inside breached packages
  - Waste form dissolution
  - Dissolved and colloid-facilitated release
  - Transport to the Saturated Zone

TPA Computer Code

- Unsaturated Zone



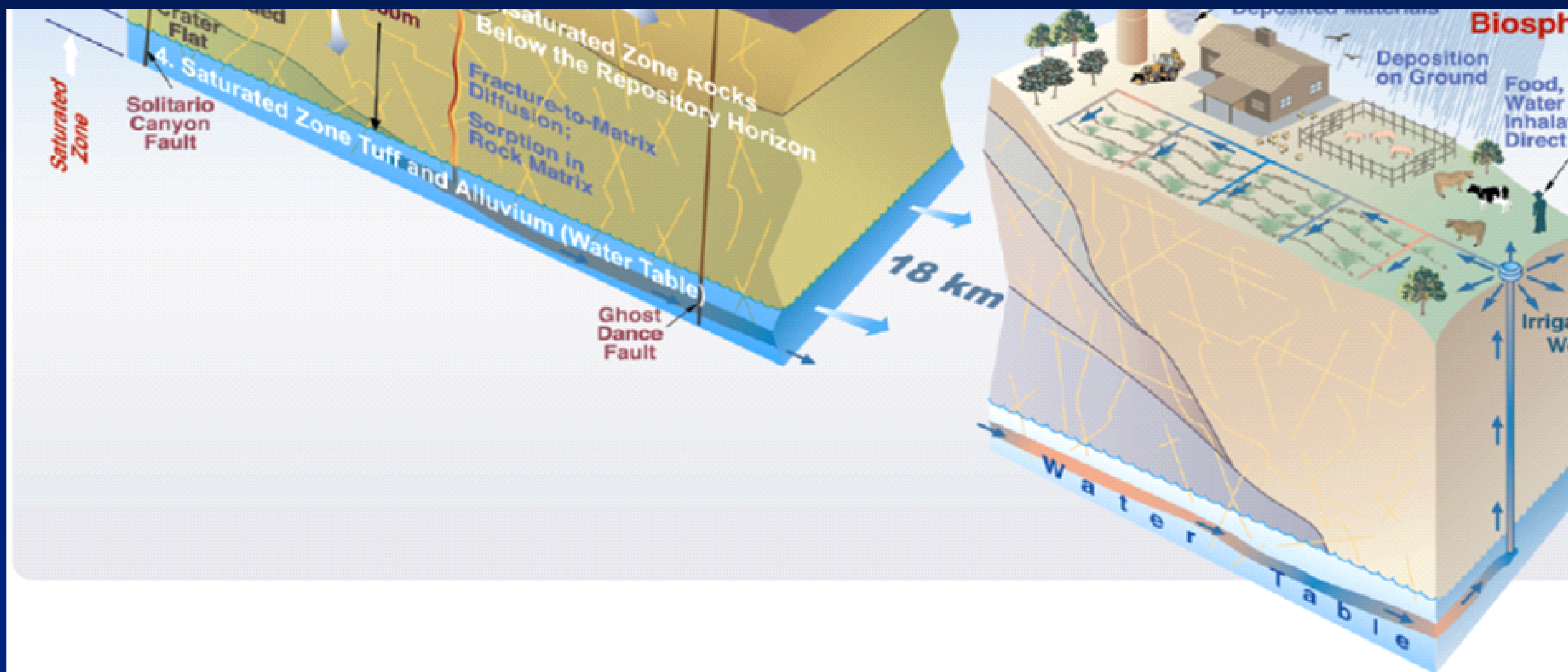
U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

- Transport through the Unsaturated Zone between the repository and the water table
  - 1-D Model
  - Rocks in UZ are represented by up to 6 layers
  - Thickness of layers differs between subareas

TPA Computer Code

- Transfer through the Saturated Zone



U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

- Transport through the Saturated Zone is between the location of the flow paths from the UZ to the receptor location
- Both SZ and UZ transport includes
  - Dispersion
  - Sorption of radionuclides to host rock
  - Migration on colloids
  - Radioactive decay and ingrowth

U.S.NRC
UNITED STATES NUCLEAR REGULATORY COMMISSION
Protecting People and the Environment

TPA Computer Code

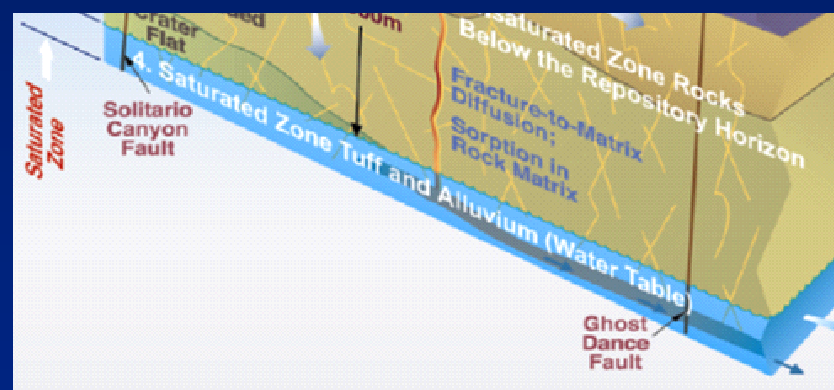
- Disruptive Scenarios
  - Seismicity
  - Faulting
  - Volcanism

TPA Computer Code

- Seismicity
  - Seismic events are expected to occur with a frequency of 10^{-4}/yr to 10^{-8}/yr, with higher probability events having fewer consequences
  - Seismic events affect
    - Accumulation of rubble
    - Dynamic loads on the waste package

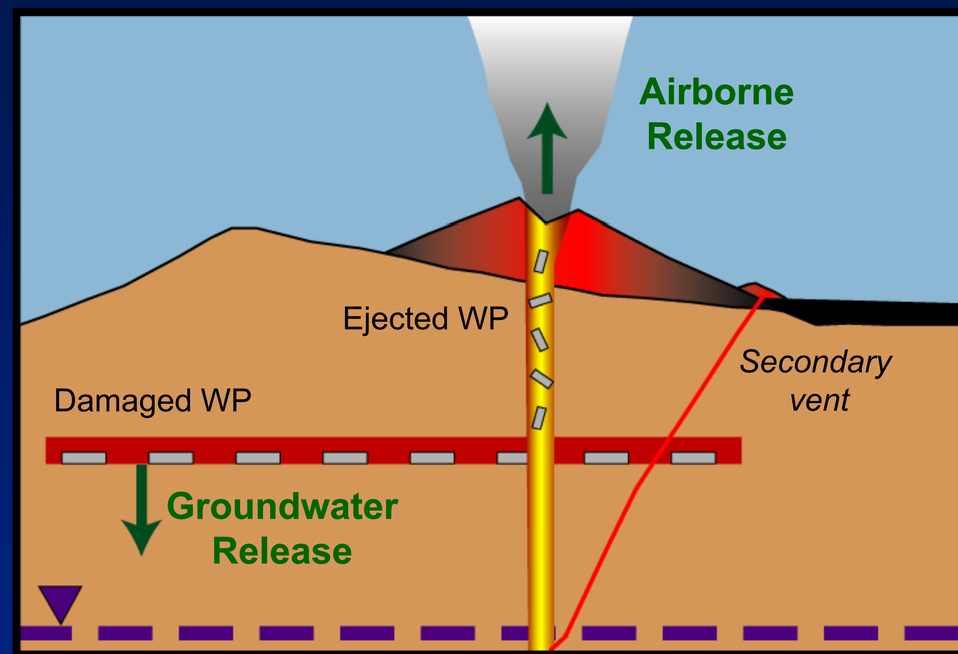
TPA Computer Code

- Faulting
  - One time event that results in the release of waste from waste packages
  - Waste ultimately ends up in the groundwater



TPA Computer Code

- Volcanism
  - Intrusive events result in release to groundwater
  - Extrusive events (eruptions) lead to release to ground surface



TPA Computer Code

- Redistribution of Radionuclides following volcanism
  - Includes direct deposition, fluvial redistribution, and eolian redistribution