6. Health Effects and Economic Consequences

U.S. DEPARTMENT OF ENERGY
NNSA National Nuclear Security Administration

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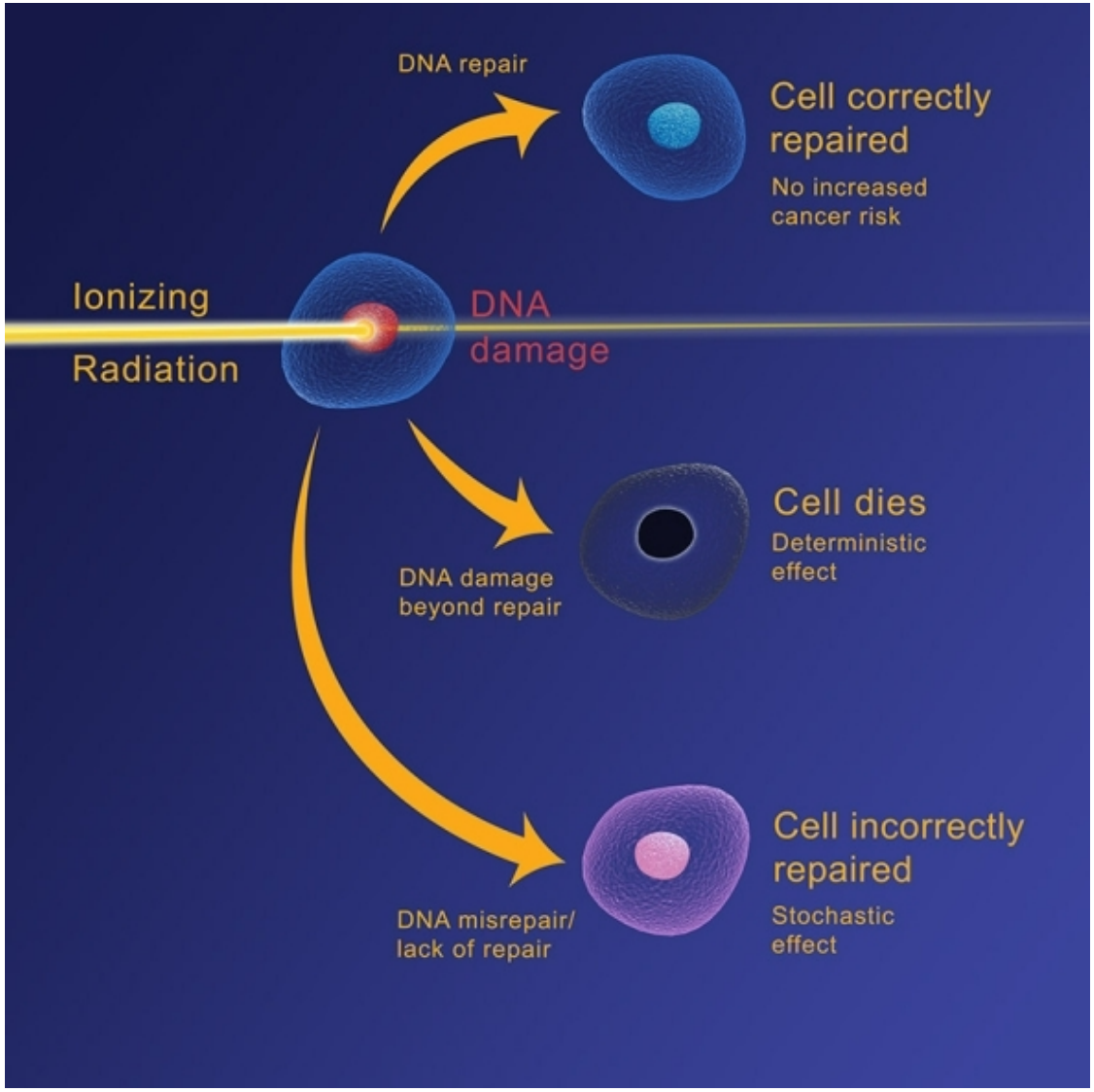
Outline

- Objectives
- Background
- Types of dose response
- Dosimetry
- Health effects and risk
- Economic consequences
- Summary
- References

Objectives

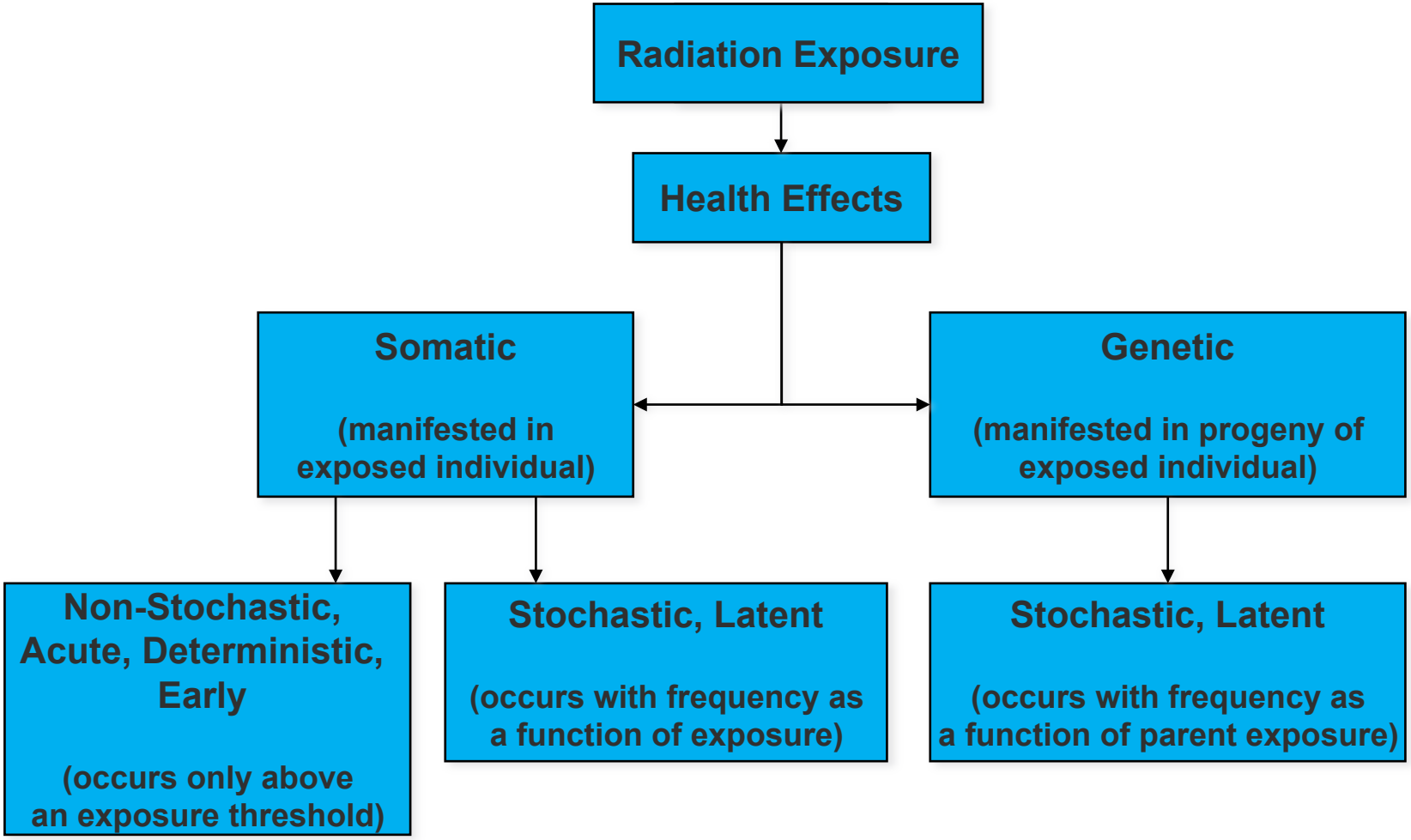
- Learn the basis for relating exposure to health effects
- Understand categorization of health effects
- Calculate health effects for a given dose
- Learn about research done on the health effects
- List the costs that are calculated by MACCS
- Describe the general formulas relating to the various types of costs
- Discuss other costs not calculated in MACCS

Effects of Radiation on Cells



- Cells undamaged by dose
- Cells die as a result of dose
- Damaged cells operate normally following repair
- Damaged cells operate abnormally following repair

Somatic and Genetic Health Effects

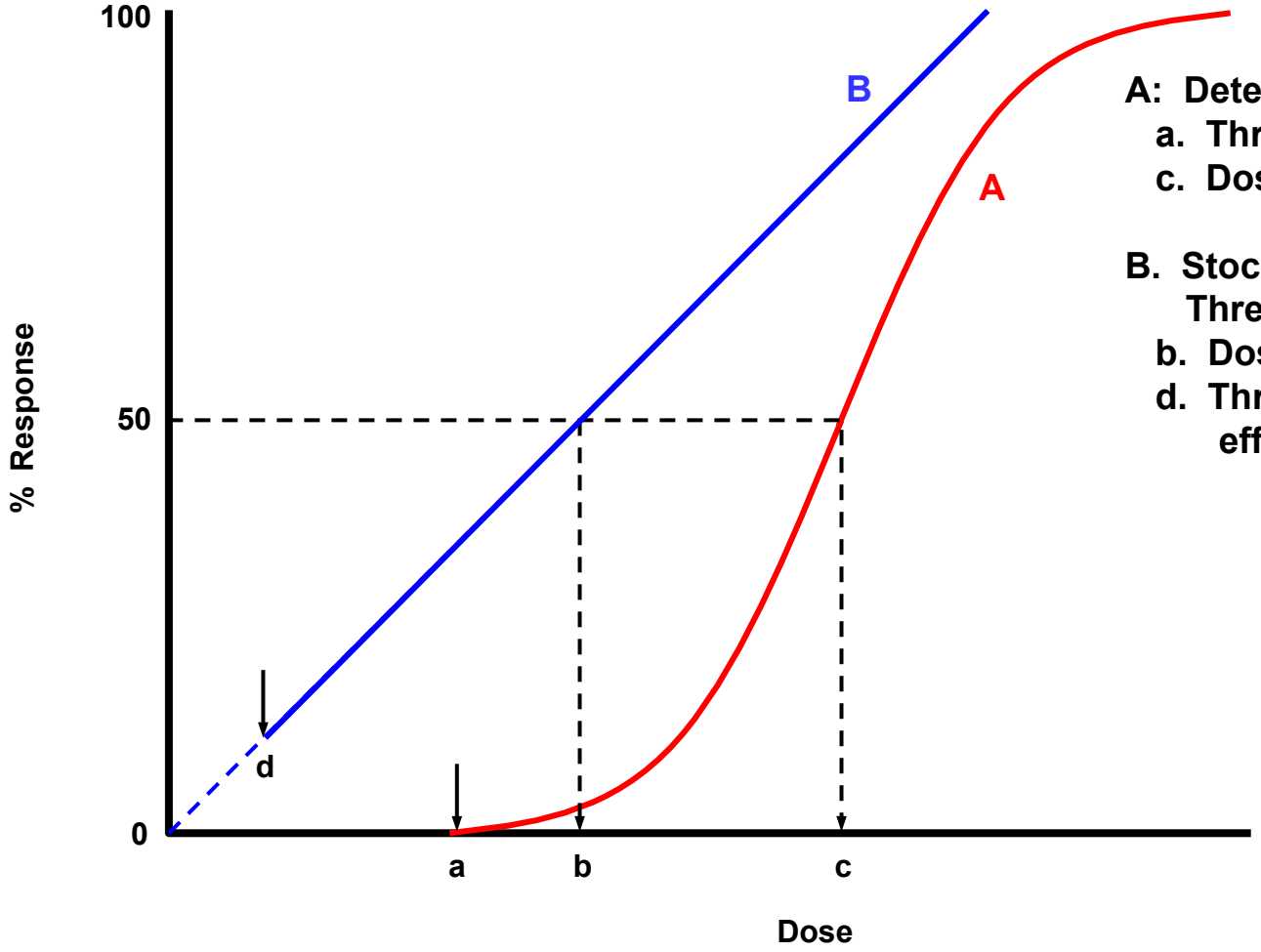


Dose-Response Curves

Relationship for a population between dose and response

- Response varies with end point in question:
  - Type of acute injury or syndrome
  - Site of solid tumor
  - Leukemia
- Response depends on other factors
  - Quality factor of radiation (radiation weighting factor or relative biological effectiveness (RBE))
  - Dose rate
  - Sex
  - Age at exposure
  - Other

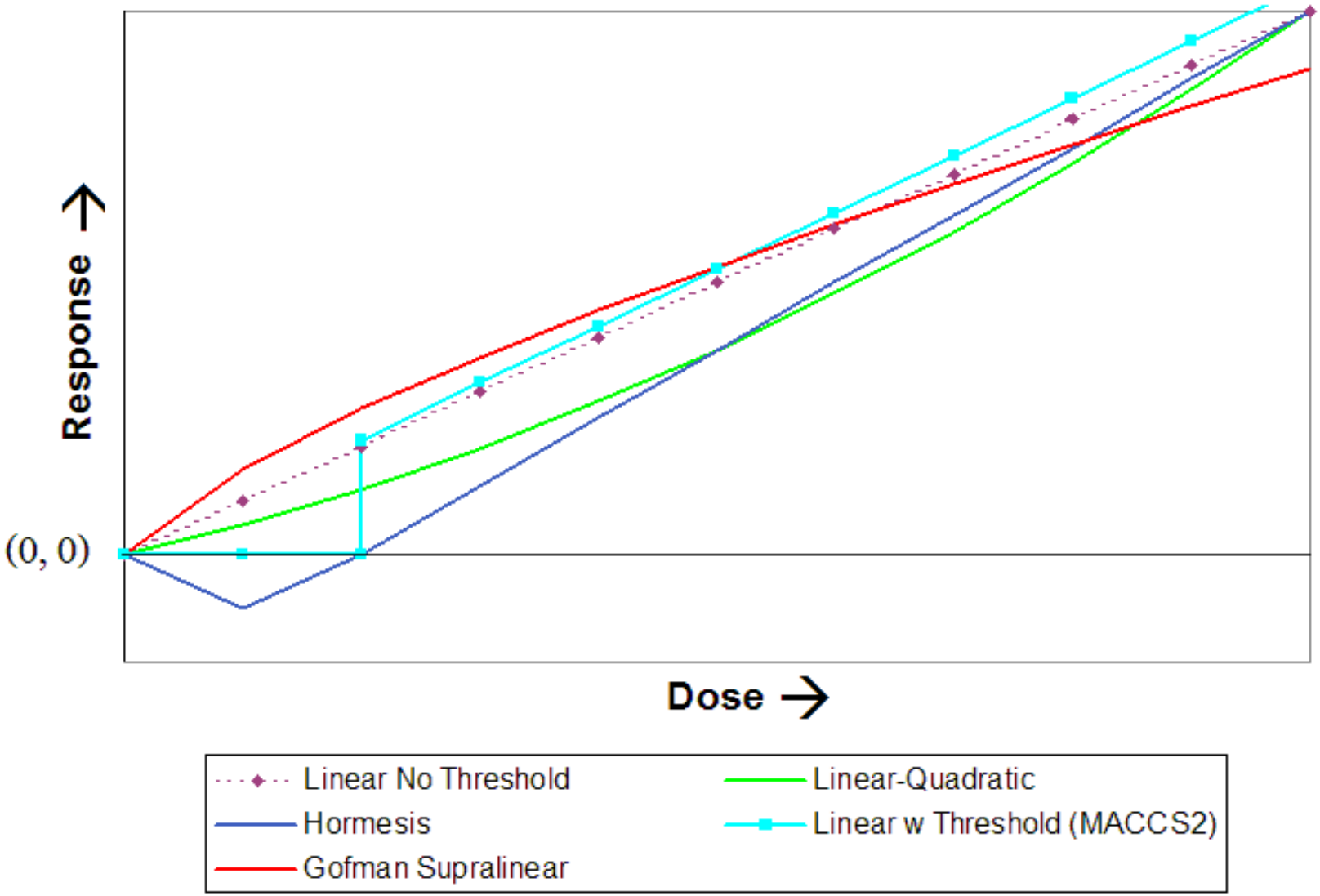
Dose-Response Curves



A: Deterministic (Acute):
- **a. Threshold dose**
- **c. Dose → 50% incidence**

B. Stochastic (Linear No-Threshold (LNT)) :
- **b. Dose → 50% incidence**
- **d. Threshold of observable effects**

Other Possible Dose-Response Curves for Stochastic Health Effects



Dose-Response Curves In WinMACCS

- Dose-Response function specified in EARLY code module:
  - Acute radiation fatalities - “Early Fatality Parameters” screen
  - Acute radiation injury - “Early Injury Parameters” screen
  - Cancer risk model - “Latent Cancer Parameters” and “Latent Cancer Thresholds” screens

Exposure Types

- Acute and Chronic Radiation Exposures
  - Acute exposure - a high dose of radiation is received during a short period of time
    - Acute exposures modeled in EARLY
  - Chronic exposure - long-term, low-level exposure
    - Chronic Exposures modeled in EARLY and CHRONC
- Acute Exposure Characteristics:
  - Dose $\geq$ 10 rad or 0.1 Gray (10^3 erg/gram)
  - Exposure duration up to a few days (EARLY $\leq$ 40 days)
  - May cause a pattern of clearly identifiable symptoms minutes to months after exposure (EARLY acute injuries or fatalities)
  - May cause latent cancers (EARLY latent cancers) or other effects (cataracts, etc.) that do not appear for decades

Acute Dose and Effects

- Acute exposure
  - Stochastic effects (cancers and heritable effects)
    - Probability of occurrence increases with dose
    - Severity of occurrence is independent of the dose
    - Classified as "latent" or “late” effects
  - Non-stochastic effects (Other effects)
    - Thresholds appear at various levels for different acute effects. *See slides concerning MACCS acute health effects model.*
    - Severity and probability of occurrence within a population depend on dose.

Acute Doses and Effects

Table 3-2. Acute Radiation Syndrome[a]

Feature or Illness	Effects of Whole Body Absorbed Dose from External Radiation or Internal Absorption, by dose range in rad (Gray)				
	0-100 (0-1 Gy)	100-200 (1-2 Gy)	200-600 (2-6 Gy)	600-800 (6-8 Gy)	>800 (>8 Gy)
Nausea, Vomiting	None[25]	5-50%	50-100%	75-100%	90-100%
Time of Onset		3-6 hr	2-4 hr	1-2 hr	< 1 hr to minutes
Duration		< 24 hr	< 24 hr	< 48 hr	< 48 hr
Lymphocyte Count	Unaffected	Minimally Decreased	<1000 at 24 hr	< 500 at 24 hr	Decreases within hours
Central Nervous System Function	No Impairment	No Impairment	Cognitive impairment for 6-20 hr	Cognitive impairment for > 20 hr	Rapid incapacitation
Mortality	None	Minimal	Low with aggressive therapy[26]	High	Very High: Significant neurological symptoms indicate lethal dose

[a] Percentage of people receiving whole body doses within a few hours expected to experience acute health effects.

Source: Medical Management of Radiological Casualties, Second Edition, Armed Forces Radiobiology Research Institute. Bethesda, MD, April 2003 (DoD 2003).

Table from the 2017 EPA PAG Manual

Acute Doses and Effects (Strom, 2003)

Dose[a] (Sv or Gy)	Death?	Effect of Acute Uniform Dose	Source of Dose of This Magnitude
>42,000	yes	>10°C temperature rise (water); >20°C temperature rise (paper)	Mail irradiation for biological sterilization of spores
4,184	yes	1°C temperature rise in water	Industrial processes, medical sterilizers
1,000	yes	(bottom end of food irradiation scale)	Food irradiation, medical sterilizers
300	yes		
100	yes	"prompt, immediate incapacitation" -- U.S. Army	1 km from neutron bomb
30	yes	60-90 Gy: tumoricidal dose; cerebro-vascular syndrome; desquamation	criticality or severe accident; deliberate radiation therapy
10	yes	gastrointestinal syndrome; marrow ablation; erythema, epilation, sterility	12 Gy in leukemia therapy; max dose to Chernobyl fireman
3	?	50% die 60 days no medical care; bone marrow (hematopoietic) syndrome	Japanese A-bomb survivors; fluoroscopy in cardiac catheterization
1		mild clinical symptoms in some	teratogenesis in Japanese A-bomb survivors unborn children
0.3		no clinical symptoms; chromosome aberrations	planned special exposure; lots of x-rays on same day
0.1		increased risk of cancer (?) and heritable ill-health (?)	planned special exposure; some nuclear medicine procedures
0.03		no observed effects in humans	0.05 Sv/y occupational limit; bone scan, several x-rays
0.01		no observed effects in humans	dose/y to air crew; partial body dose from 1 lumbar spine x-ray
0.003		no observed effects in humans	1 dental x-ray; annual rad. worker; annual background
0.001		no observed effects in humans	av. medical + dental dose = 0.0005/y)
0.0003		no observed effects in humans	partial body dose from chest x-ray
0.0001		no observed effects in humans	flight from Seattle to Tokyo

Chronic Exposure

- Chronic exposure - long-term, low-level exposure
  - Organisms can tolerate more radiation if exposure is spread out over time.
  - Effects of overexposure may not be apparent for years.
  - Risk has been difficult to quantify due to:
    1. High background cancer rate in the general population
    2. Lack of statistical power in low dose region
    3. Robust studies are expensive and time consuming
    4. Missing or inadequate radiation dosimetry and bioassay data & primitive analytical methods during 1940s – 1970s → Inadequate historical data
    5. Potential for bias, confounding, effect modification, and possibility of distorting outcomes

Dose and Effects

- Chronic exposure
  - Stochastic effects
    - Probability for occurrence can be estimated (extrapolated) from dose-effect curve for high doses (Curve B, page 6-7).
    - Epidemiological data cannot confirm or refute the currently used risk models at current occupational levels.
  - Non-stochastic effects
    - Deterministic effects can occur with long-term exposure if dose exceeds the threshold for the effect.
    - Current dose limits are set such that these thresholds are not expected to be reached in a normal working lifetime.

Dosimetry Guidance

Date	Publication	Remarks
1953	NBS Handbook 52	Obsolete.
1959	ICRP Publication 2, NBS Handbook 69	Current EPA Maximum Contaminant Levels (MCLs) (drinking water, other), Current OSHA Regulations (29 CFR 1910.1096), Current NRC (10 CFR 100, others).
1977	ICRP-26	Introduces system of dose limitation and the tissue-weighting scheme used in ICRP-30, 10 CFR 20 & 10 CFR 835, FGR-11.
1980 to 1982	ICRP-30	Metabolic and bio-kinetic models integrated with the ICRP-26 dose limitation framework to provide the bases for current 10 CFR 20 and H_E values in Federal Guidance Reports 11 and 12.

Dosimetry Guidance (continued)

Date	Publication	Remarks
1991	ICRP-60	Revision of the system of dose limitation, tissue-weighting scheme introduced by ICRP-26. DOE adopted ICRP 60 in 10 CFR 835 (proposal 71 FR 154, p. 45996).
1991	ICRP-61	Transitional annual limits of intake and dose coefficients based on ICRP-60 and the metabolic and bio-kinetic models in ICRP-30. "E" values listed in FGR-11 and FGR-12 databases. Not incorporated in U.S. regulations.
1993 to 1996	ICRP-67 through 72	New dose coefficients based on ICRP-60 dose limitation system and updated metabolic and bio-kinetic models. Not incorporated in regulations. Appear as dose coefficients in Federal Guidance Report 13. DOE adopted ICRP 68 in 10 CFR 835 (proposal 71 FR 154, p. 45996).
1999	Federal Guidance Report 13	Updates to ICRP 72 by ORNL with changes approved by US EPA

Dosimetry Guidance (continued)

Date	Publication	Remarks
2007	ICRP 103	• Updates from ICRP-60 for the radiation and tissue weighting factor used to define equivalent and effective doses. • Deterministic effects and stochastic risk remain fundamentally unchanged. Heritable risk is lower. • Internal and external doses calculated using computational phantom based on medical images. Tissue weighting factors are age- and sex-averaged. (ICRP 110)
2010	ICRP 116	• This report gives fluence-to-dose conversion coefficients for both effective dose and organ absorbed doses for various types of external exposures, consistent with ICRP 103.

Doses from Inhalation and Ingestion: Changing Terminology

- 50-yr organ doses from intakes are referred to as:
  - Committed dose equivalent (ICRP-30)
  - Committed equivalent dose (ICRP-60)
- 50-yr effective doses from intakes are referred to as:
  - Committed effective dose equivalent (ICRP-30)
  - Committed effective dose (ICRP-60)

NRC Guidance on ICRP 103 SRM-SECY-12-0064 (2012)

- The Commission concluded there was insufficient risk and safety basis for changes to the occupational dose limits.
  - TEDE = 5 rem (0.05 Sv), Lens = 15 rem (0.15 Sv), and Skin = 50 rem (0.5 Sv), Occupational = 50 rem (0.5 Sv)
- Commission Direction:
  - Align 10 CFR 20 with most recent methodology and terminology, e.g.,
    - Tissue weighting factors to ICRP 103
    - Current metabolic models
  - Disapproved reducing occupational limit on TEDE
  - Continue stakeholder discussions on dose limit for the lens of the eye
    - Staff recommended limits of 5 rem (50 mSv) or 2 rem (20 mSv) per year
    - ICRP: 2 rem average over 5 years, with 5 rem maximum
  - Continue discussions on embryo/fetus dose limit of 100 mrem
    - Consider whether to apply over entire gestation period or after declaration
    - ICRP: 100 mrem after declaration

Dose Equivalent, Absorbed Dose, and Quality Factors (ICRP-26 and -30)

- Absorbed dose, D, is absorbed energy per unit mass
  100 rad = 1 J/kg = 1 gray
- Dose Equivalent to tissue "T"; H_T

  Dose equivalent accounts for biological effectiveness for inducing latent cancers and heritable effects
- Quality factor, Q. Per ICRP 26 and 10 CFR 20:

$$H_T = \sum_R Q_R \times D_{T,R}$$

X-rays, gamma, beta	Neutrons, Protons	Alpha Particles
1	10	20

Equivalent Dose, Absorbed Dose, and Weighting Factors (ICRP-60)

- See Section 6 endnotes for update
- Equivalent dose to tissue "T": W_R is analogous to Q
- Equivalent dose to a tissue needed to determine stochastic health effects
- Radiation weighting factor, $W_{R,}$ from ICRP 60:

$$H_T = \sum_R W_R \times D_{T,\,R}$$

X-rays, gamma, beta	Neutrons *	α - particles
1	Energy dependent (5 to 20)	20

* Need to know neutron energy spectrum to take advantage of this.

Non-uniform Irradiation

- ICRP 26 & 30: Effective Dose Equivalent (H_E)

$$H_E = \Sigma H_T * W_T$$

- ICRP 60: Effective Dose (E)

$$E = \Sigma H_T * W_T$$

- H_E and E: measures of dose equivalent and risk for non-uniform irradiation
- Leggett and Eckerman (2003)-Comparison of ICRP-26 and 30 with newer ICRP guidance

Tissue Weighting Factor Comparison*

Issue	ICRP 26	ICRP 60	ICRP 103	Part 20
Tissue Weighting Factors, w_T				
Gonads	0.25	0.20	0.08	0.25
Breast	0.15	0.05	0.12	0.15
Red bone marrow	0.12	0.12	0.12	0.12
Lung	0.12	0.12	0.12	0.12
Thyroid	0.03	0.05	0.04	0.03
Bone surfaces	0.03	0.01	0.01	0.03
Colon	-	0.12	0.12	-
Stomach	-	0.12	0.12	-
Bladder	-	0.05	0.04	-
Oesophagus	-	0.05	0.04	-
Liver	-	0.05	0.04	-
Brain	-	-	0.01	-
Kidney	-	-	-	-
Salivary Glands	-	-	0.01	-
Skin	-	0.01	0.01	-
Remainder	0.30[6] (105)	0.05[7] (Table 2 and S-2)	0.12[8] (Table B.2 and B.3.5)	0.30[9] (§20.1003)

[6] The remainder is composed in part of the following additional tissues and organs: stomach, salivary glands, lower large intestine, and liver. When the gastrointestinal tract is irradiated, the stomach, small intestine, lower large intestine and upper large intestine are treated as four separate organs and be included in the remainder tissues.

[7] The remainder is composed of the following additional tissues and organs: adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, and uterus.

[8] The remainder is composed of the following additional tissues and organs: adipose tissue, adrenals, connective tissue, extrathoracic airways, gall bladder, heart wall, kidney, lymphatic nodes, muscle, pancreas, prostate, small intestine wall, spleen, thymus, and uterus/cervix.

[9] 0.30 results from 0.06 for each of the 5 "remainder" organs (excluding the skin and lens of the eye) that receive the highest dose.

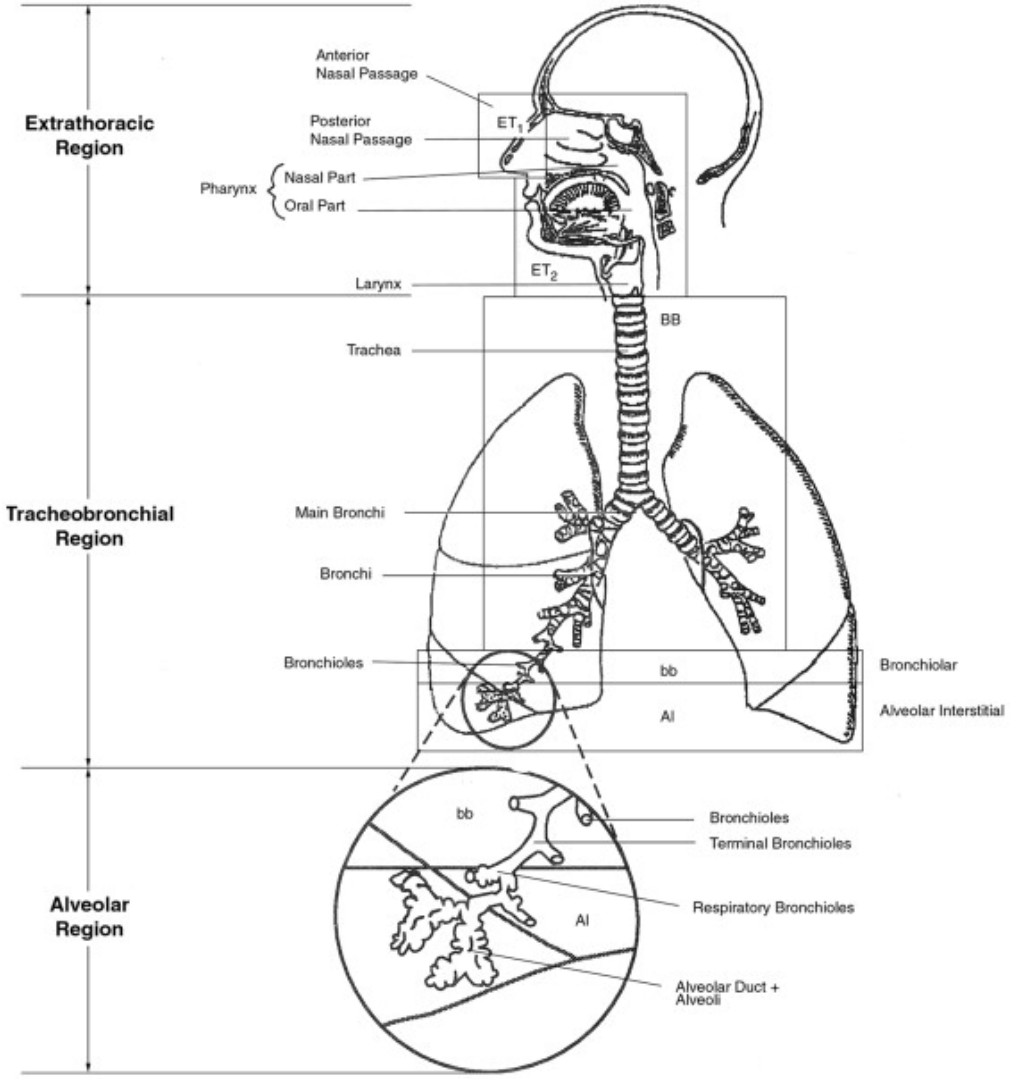
***SECY-08-0197**

Radiation Weighting Factor Comparison*

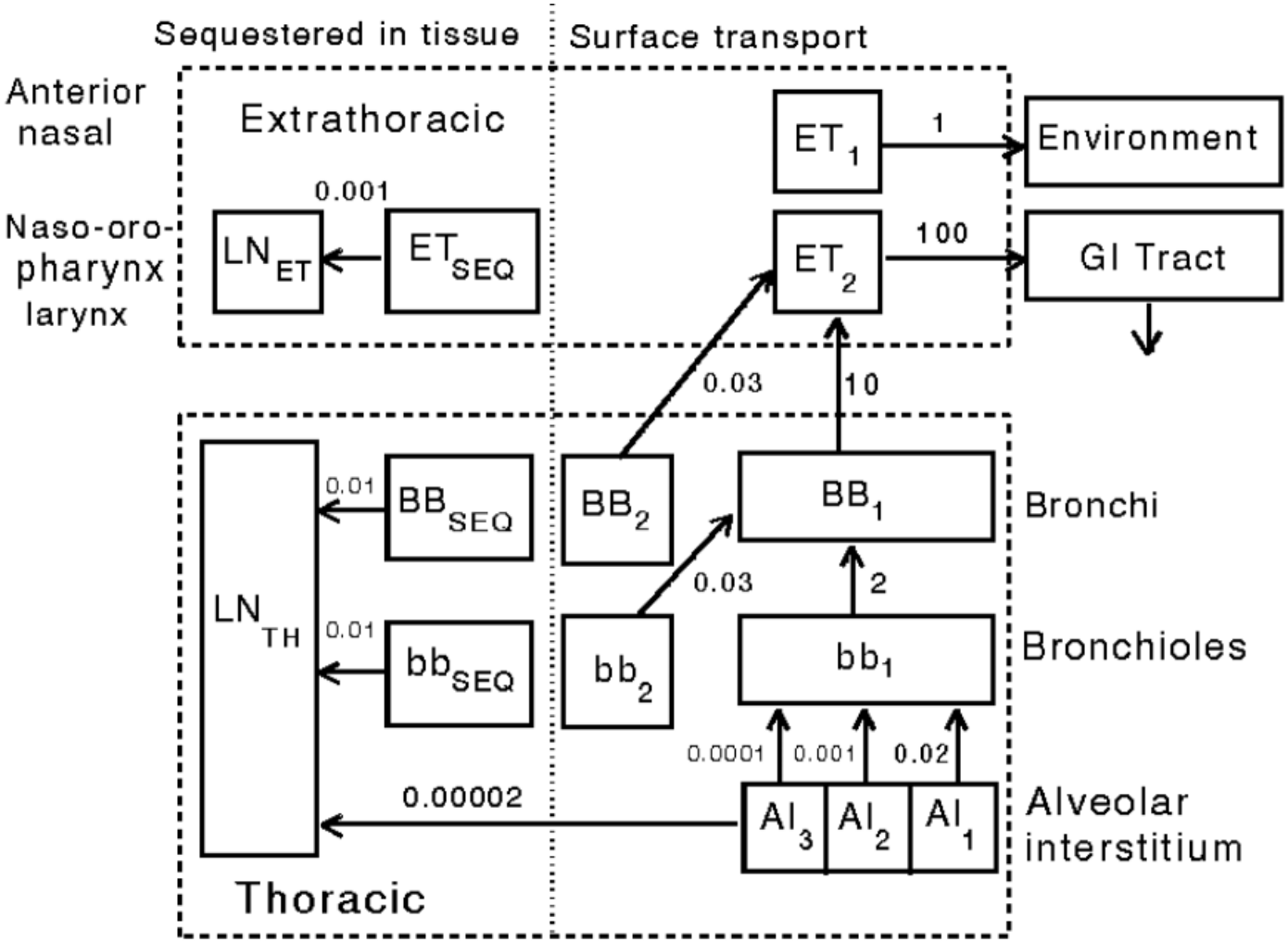
Issue	ICRP 26	ICRP 60	ICRP 103	Part 20
Radiation Weighting Factors, w_R				
Photons, all energies	1	1	1	1
Electrons and muons, all energies	1	1	1	1
Neutrons, all (unknown) energies	10	Step function	continuous function	10
< 10 keV		5	2.5	2 to 2.5
10 - 100 keV		10	2.5 to 10	2.5 to 7.5
100 - 2 MeV		20	10 to 20	7.5 to 11
2 to 20 MeV		10	7 to 17.5	8 to 9
> 20 MeV		5	5 to 7	3.5 to 8
Protons, energy > 2 MeV	10	5	2	10
Alpha particles, fission fragments heavy nuclei	20 (20)	20 (Table 1 and S-1)	20 (Table 2)	20 (Tables 1004(b) 1 & 2)

*SECY-08-0197

ICRP-66 Respiratory Tract Model (1994)



ICRP-66 Respiratory Tract Model



AI – Alveolar Interstitium
BB – Bronchi
bb – Bronchioles
ET – Extrathoracic
GI – Gastrointestinal
LN – Lymph Nodes
SEQ – Sequestered
TH – Thoracic

Source: Eckerman, Federal Guidance Report No. 13, September 1999

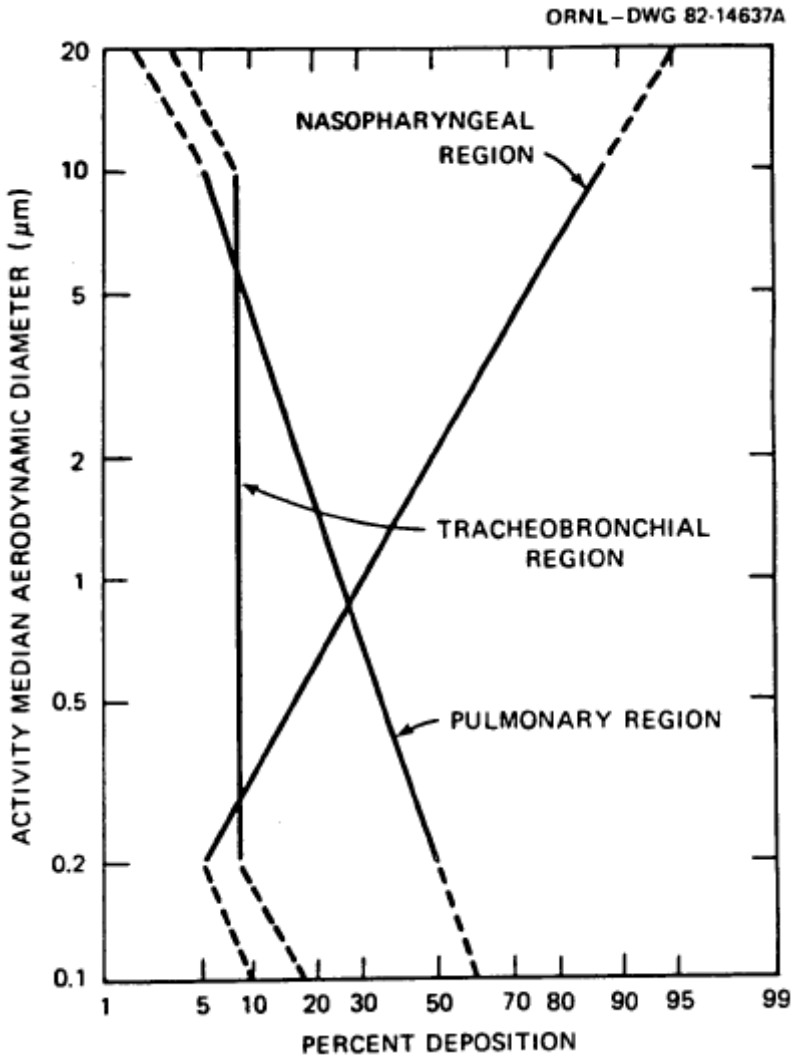
Doses from Inhalation

- Based on Lung Clearance Model
  - Speed at which a contaminant is removed from the lungs

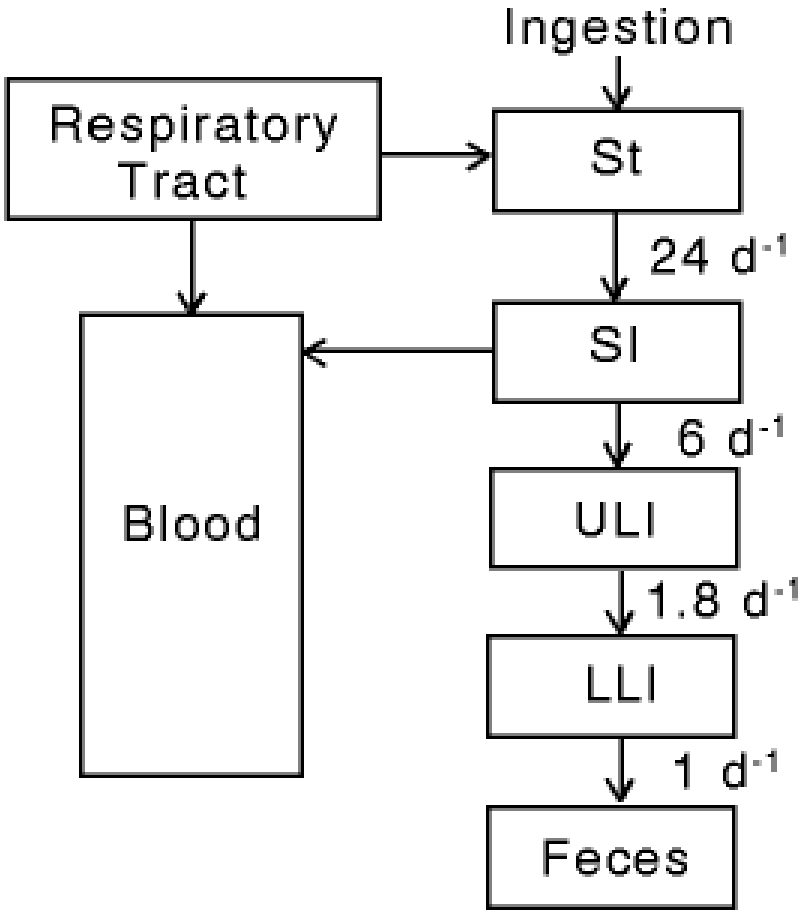
Clearance Class (ICRP 26, 30)	Absorption Type (ICRP 66, 72)	Pulmonary Region Clearance Half-Time (days)
Y	S	> 100
W	M	10-100
D	F	< 10

Doses from Inhalation

- Respiratory deposition is a function of Activity Mean Aerodynamic Diameter (AMAD) [ICRP 30]
- Activity Mean Aerodynamic Diameter (AMAD) (µm) is the diameter of a unit density sphere with the same terminal settling velocity in air as that of an aerosol particle of mean activity.



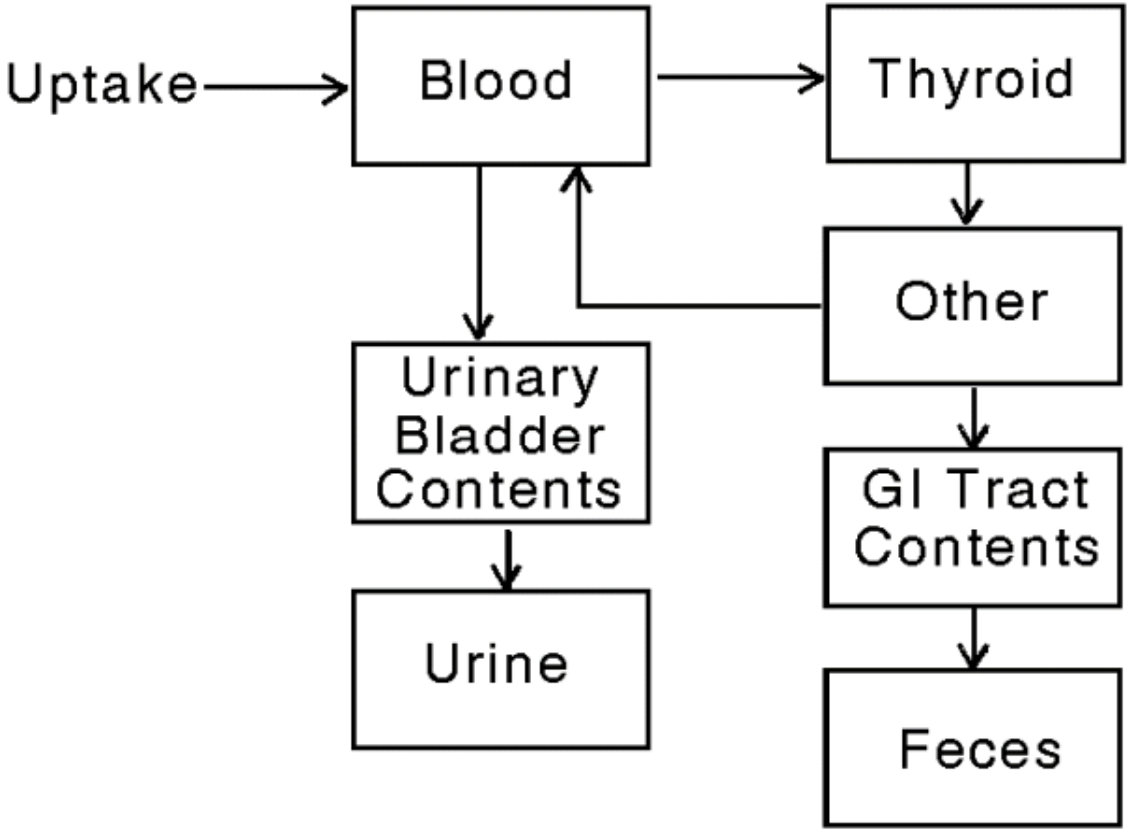
ICRP-30 Gastrointestinal Tract Model (1979)



St – Stomach
SI – Small Intestine
ULI – Upper Large Intestine
LLI – Lower Large Intestine

Source: Eckerman, Federal Guidance Report No. 13, September 1999

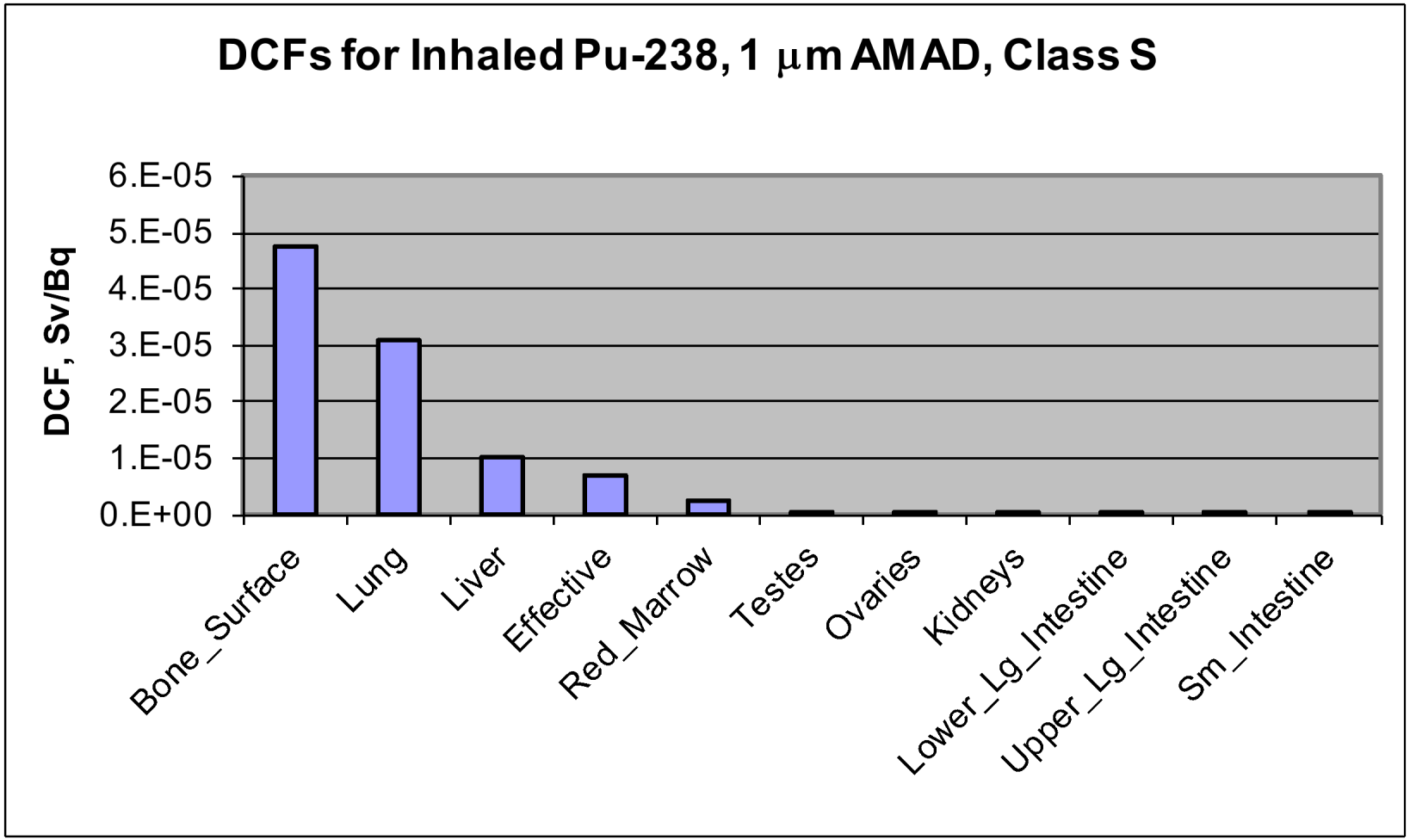
ICRP-56 Biokinetic Iodine Model (1989)



Source: Eckerman, Federal Guidance Report No. 13, September 1999

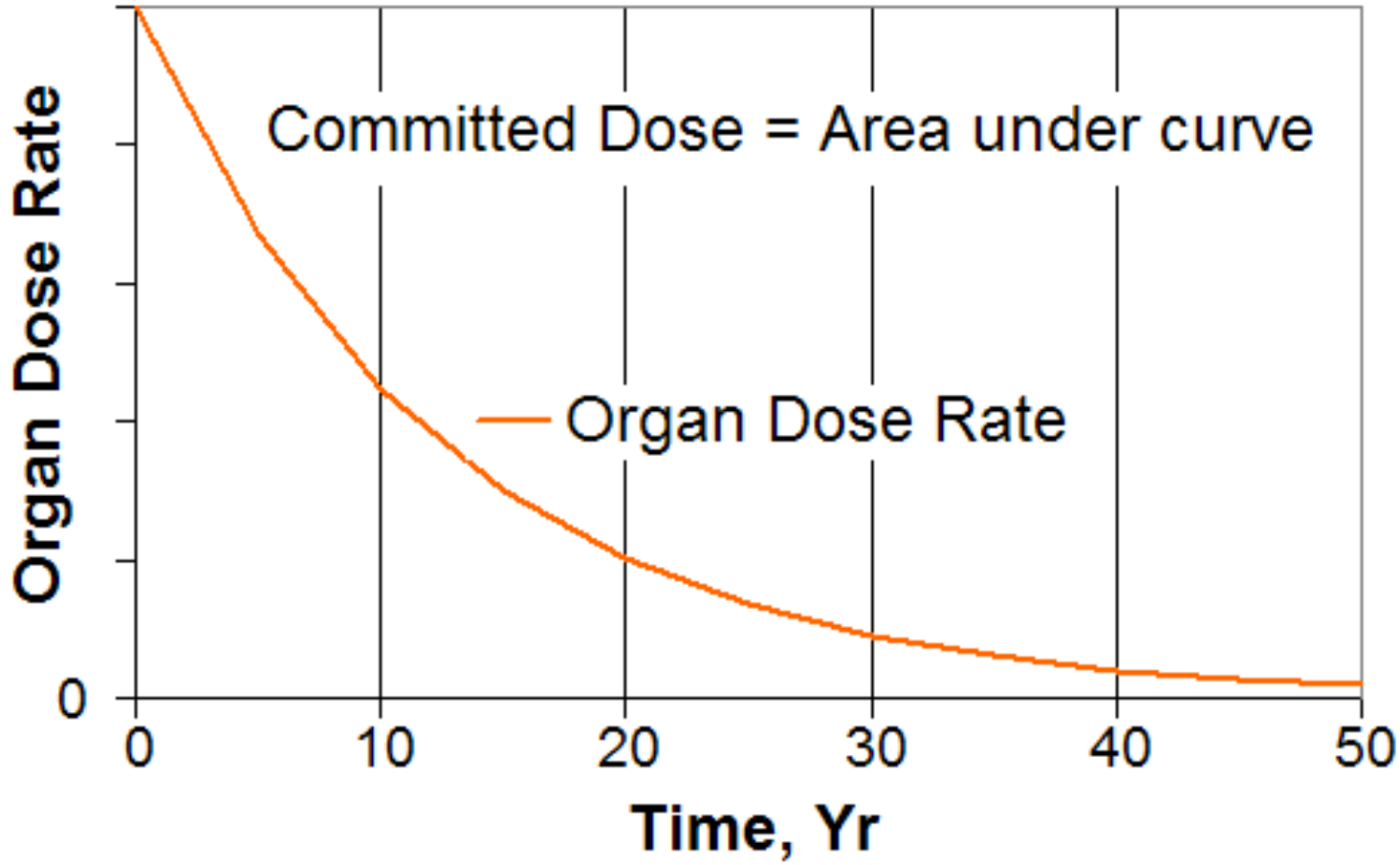
Non-Uniform Irradiation

Intakes of radioactive material can lead to non-uniform distributions of dose to organs



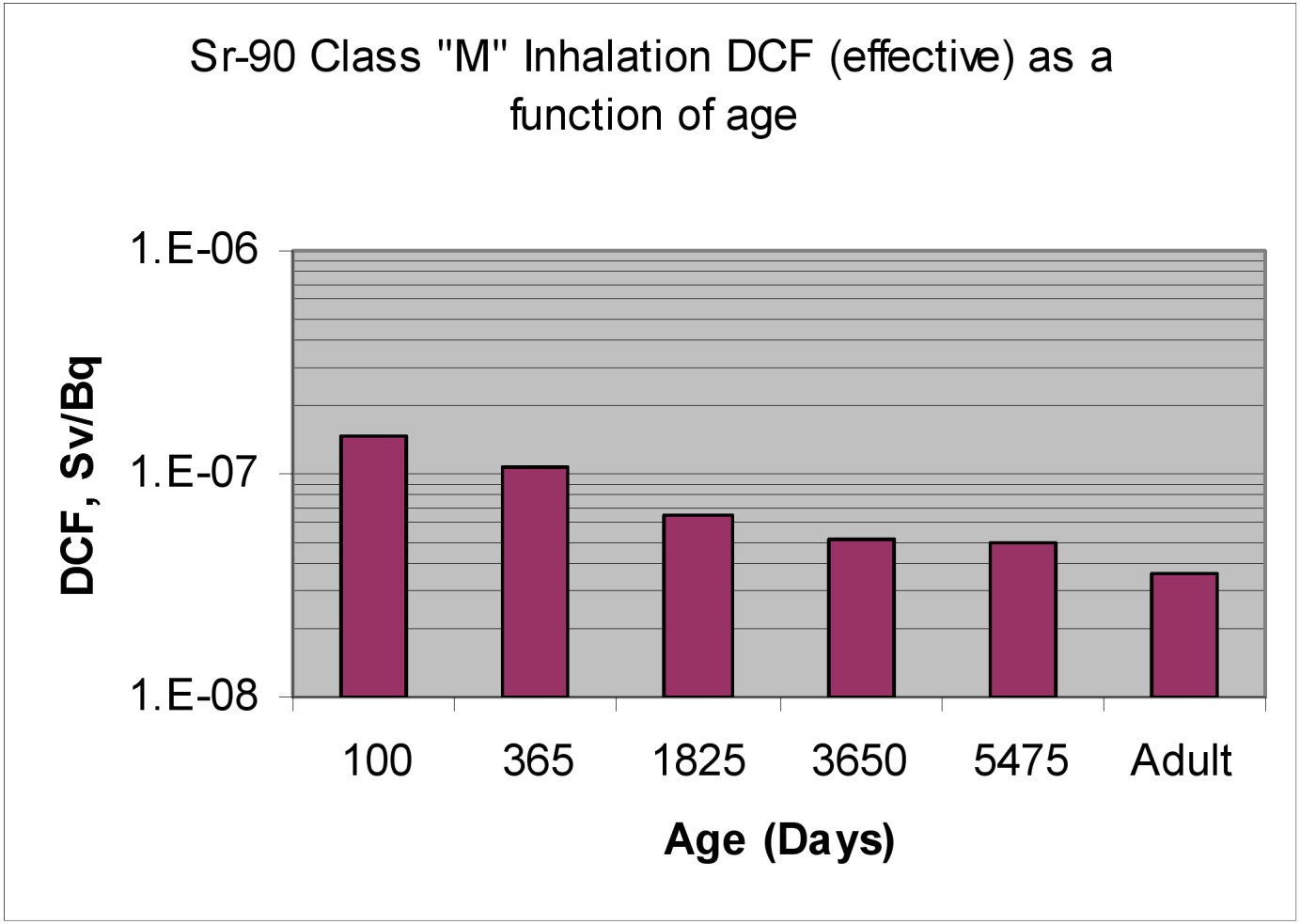
Doses from Inhalation and Ingestion

Committed dose equivalent following an intake of Pu-238



Doses from Inhalation and Ingestion

- **Effect of age at time of exposure**



Dose Coefficient Files Supplied with MACCS

DOSFAC2 (dosdata20organs.inp)

- External factors from DOE/EH-0070 (older than FGR12)
- Internal factors from FGR-11
- Tissue weighting based on ICRP-26 and ICRP-60
- Radionuclides important to reactor accidents (60)
- Adult only
- Used in NUREG-1150 (historical significance)
- Acute, annual, and 50-yr DCFs
- Primarily NRC users

Dose Coefficient Files Supplied with MACCS

FGR13DCF

- External factors from FGR-12
- Internal factors derived from FGR-13 dose rate vs time data
- Tissue weighting based on ICRP-60
- ICRP-66 lung model, recent (1990s) metabolic models
- 825 isotopes
- Adult, but data are available to calculate internal factors for other age groups (newborn, 1, 5, 10, 15 yr & adult male)
- 1 μm AMAD particle size, but data are available for other sizes
- Acute, annual, and 50-yr DCFs

Dose Coefficient Files Supplied with MACCS

FGR13GyEquiv_RevA

- Same as FGR13DCF with the following exceptions
  - Relative biological effectiveness factor (RBE) for breast is 10 for high-LET (alpha) radiation.
  - RBE for bone marrow is 1 for high-LET radiation.
- Changes were recommended by Keith Eckerman to be consistent with FGR 13 health effect modeling.
- Dose coefficients are consistent with those used in SOARCA study.

Radiation Epidemiology

- National Academy of Sciences (NAS) Committee On The Biological Effects of Atomic Radiation (BEAR) – Numerous reports, 1950s and 1960s. *Historic interest.*
- NAS Committee On The Biological Effects of Ionizing Radiation (BEIR)
  - BEIR (1972) – The Effects On Populations of Exposure to Low Levels of Ionizing Radiation.
  - BEIR III (1980) – Generated controversy on cancer induction at low doses. *Mostly of historic interest.*
  - BEIR IV (1988) – Concerned with Radon and Alpha Emitters
  - BEIR V (1990) – Health Effects of Exposure to Low Levels of Ionizing Radiation
  - BEIR VI (1998) – Radon
  - BEIR VII (2006) – Risks from Low-LET Radiation
- United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) - Various annual reports in most years since the 1970's
- U.S. Nuclear Regulatory Commission – National Academy of Sciences Study
  - Cancer in Populations Living Near Nuclear Facilities (1990)
  - Analysis of Cancer Risk in Populations Near Nuclear Facilities Feasibility Study (2011), Phase 2: Pilot Planning of 7 Sites (2014) – Cancelled

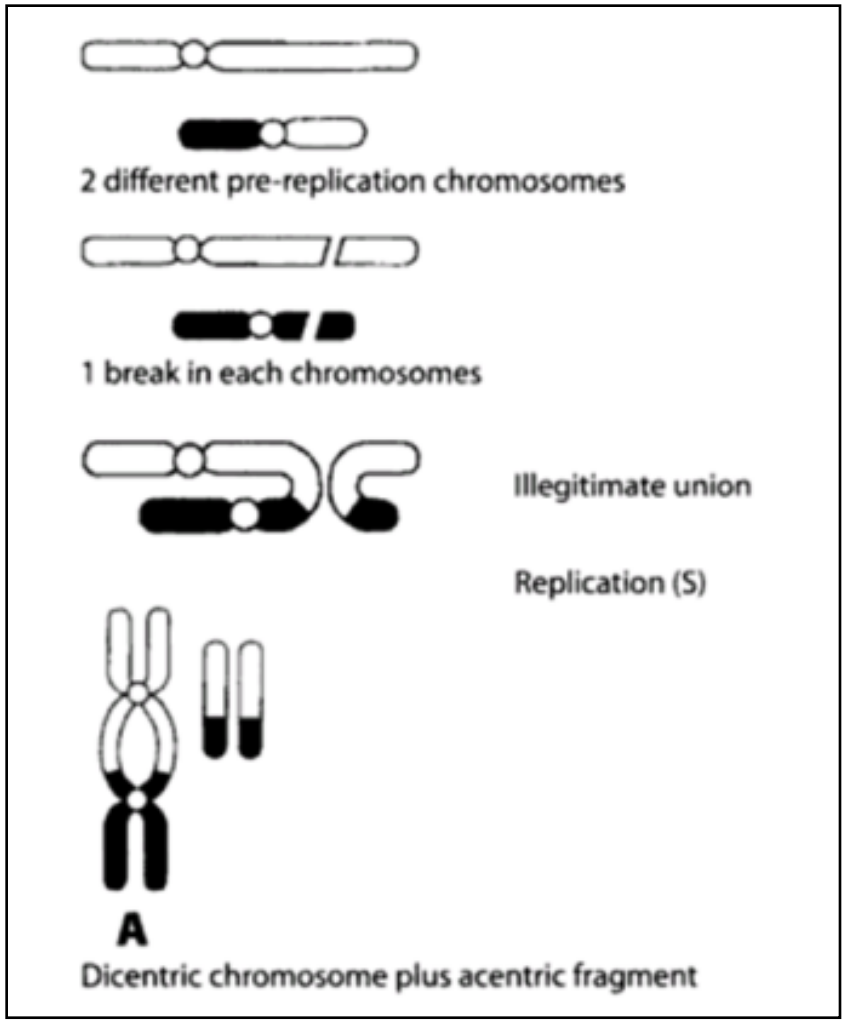
Non-Cancer Health Effects

- Irradiation of Embryo or Fetus (ICRP-49, ICRP-90)
  - Failure of fertilized egg to implant
  - Fetal death, malformations, low body weight, slow growth rate
  - Diminished intelligence, severe mental retardation, small head size, central nervous system abnormalities
  - Increased infant mortality from nuclear testing fallout? (Busby, 1995)
- Degenerative Diseases (e.g., *cataracts, vascular diseases*)

Chromosomal Damage

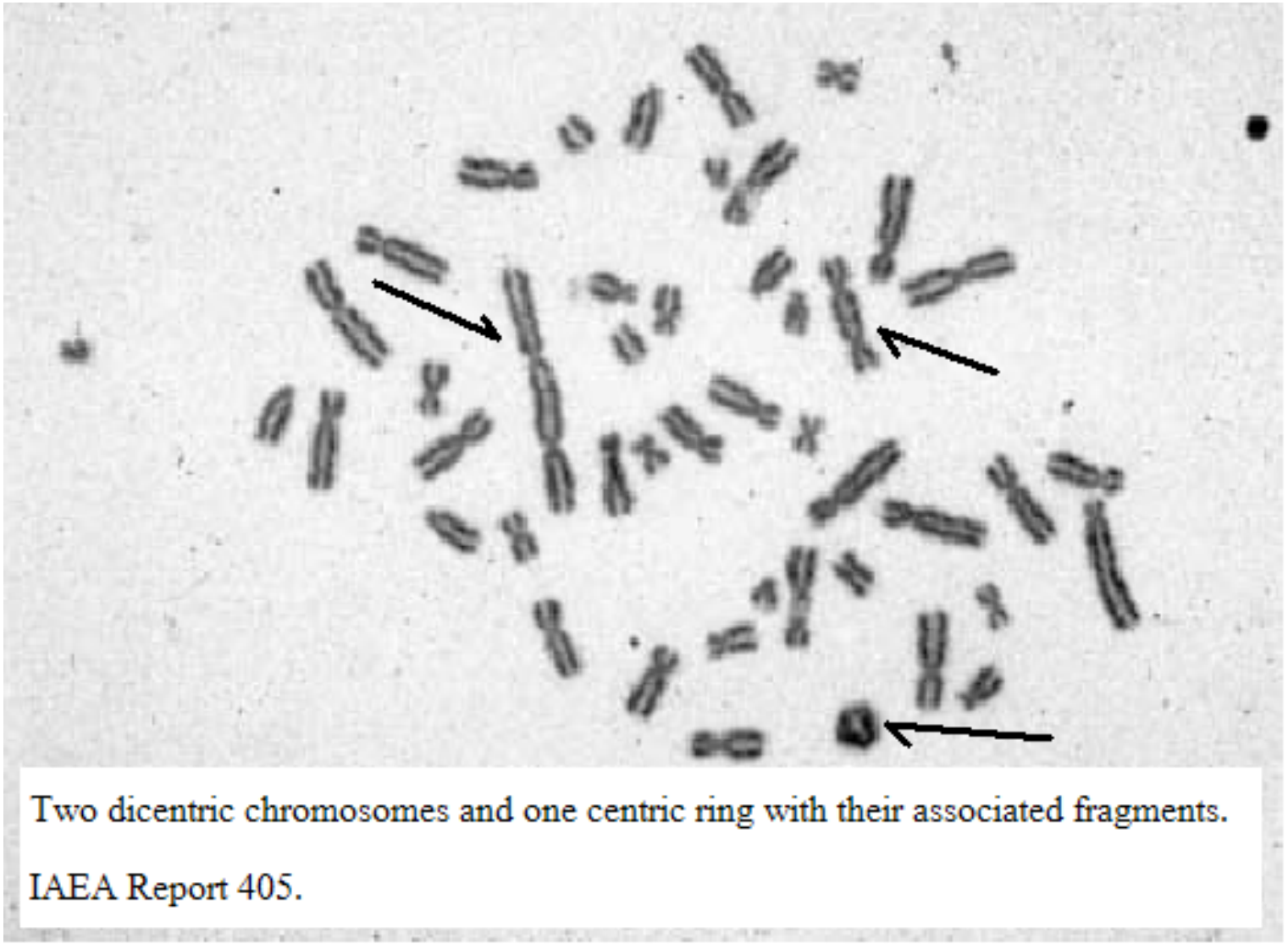
- Double-strand break
- Sticky ends
- Chromosomal abnormalities:
  - Rings
  - Di-centrics
  - Acentric fragments

Double Strand Break (DSB) → Sticky Ends → Join Together → Replicate → Di-centric



Levitt, 2008

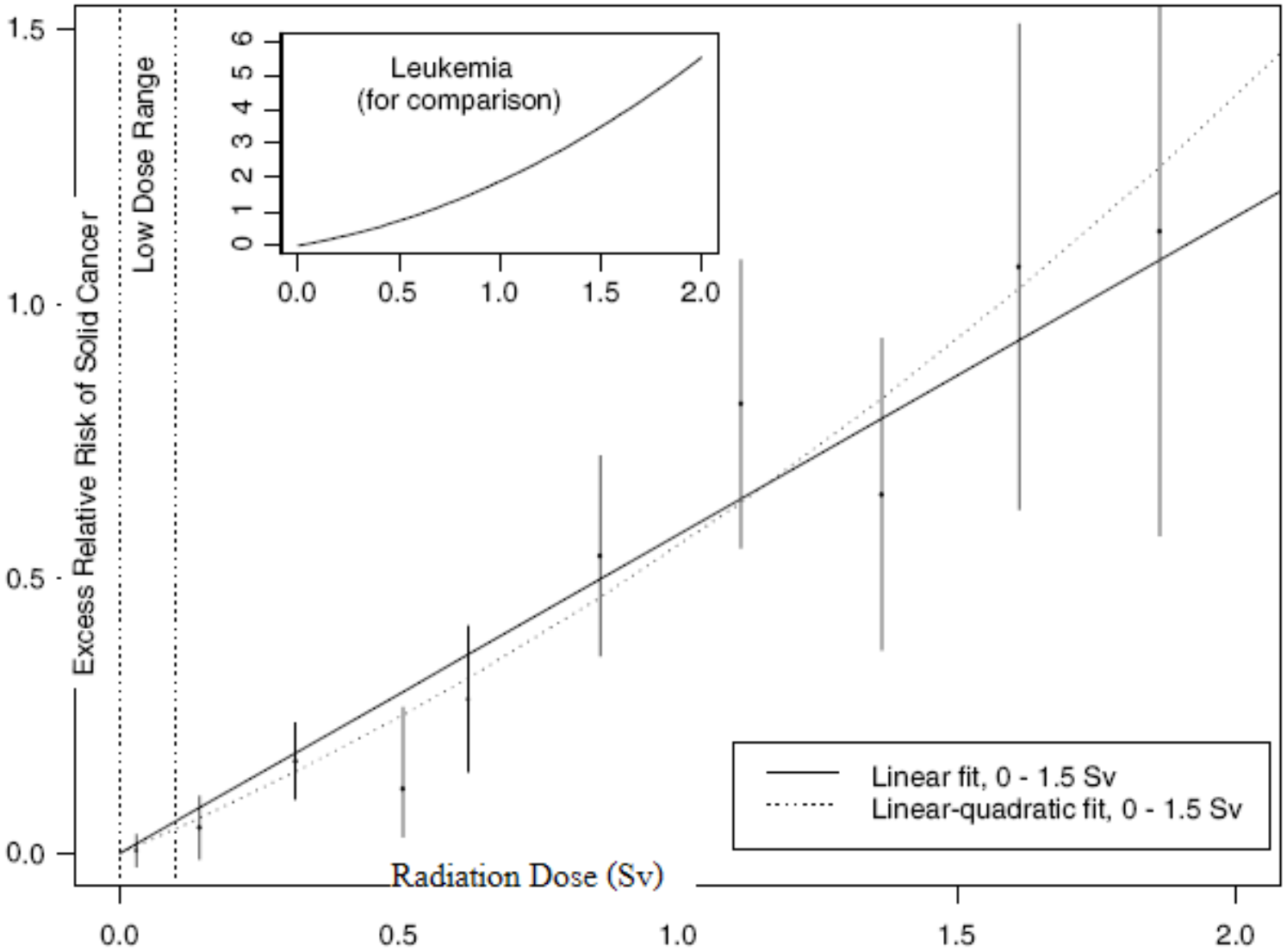
Abnormal Chromosomes



Two dicentric chromosomes and one centric ring with their associated fragments.

IAEA Report 405.

Health Effects: BEIR VII cancer risk conclusions on a relative risk basis



Other Opinions on LNT

- "Evidence for formation of DNA repair centers and dose-response nonlinearity in human cells" (Neumaier, 2011)

  The standard model currently in use applies a linear scale, extrapolating cancer risk from high doses to low doses of ionizing radiation. However, our discovery of DSB [double-strand breaks] clustering over such large distances casts considerable doubts on the general assumption that risk to ionizing radiation is proportional to dose, and instead provides a mechanism that could more accurately address risk dose dependency of ionizing radiation. ***http://www.pnas.org/content/109/2/443***

- Also see the Lawrence Berkeley National Laboratory article at http://newscenter.lbl.gov/news-releases/2011/12/20/low-dose-radiation/
- Life Span Study indicates that if there is a threshold, then it appears to be below 6 rem, if a threshold exists at all. (ICRP 99)
- "Calculation of the number of cancer deaths based on collective dose from trivial individual exposures should be avoided." (ICRP 103)

Carcinogenic Effects

- BEIR VII uncertainty estimate: +100% to -50%
- Statistically significant effects observed only above 0.1 Sv and at high dose rates (BEIR V)
- Accumulation over weeks or months (chronic) reduces risk by a factor of 2 (BEIR V) or 1.5 (BEIR VII) using the Dose and Dose Rate Effectiveness Factor (DDREF)
  - BEIR V states risk per unit dose observed at high acute doses should be divided by 2 before applying to low dose.
  - BEIR V and VII define “Low Dose” < 0.2 Gy and “Low Dose Rate” < 0.1 mGy/min.

Carcinogenic Risks per BEIR VII

BEIR VII, Tables 12-5A, 12-5B, 12-6. Lifetime Attributable Risk of Solid Cancer and Leukemia per Gy (linearized)

Organ	Average Incidence (per Gy)	Average Mortality (per Gy)
Stomach	5.8E-03	3.3E-03
Colon	1.9E-02	9.2E-03
Liver	2.9E-03	2.3E-03
Lung	3.3E-02	3.1E-02
Breast	2.3E-02	5.5E-03
Prostate	3.3E-03	6.8E-04
Uterus	1.5E-03	3.8E-04
Ovary	3.0E-03	1.8E-03
Bladder	1.4E-02	3.8E-03
Other	4.4E-02	1.9E-02
Thyroid	9.1E-03	--
All solid cancers	1.8E-01	9.2E-02
Leukemia	1.3E-02	9.0E-03

Mixed age population. Equal numbers of males and females. DDREF=1.5. Values based on 0.1 Gy.

Exercise 5

- Open WinMACCS Projects\SOARCA\SurryR7\SurryISLOCA-11-21-08
- Open EARLY/Model Basis/Organs of Risk
  - Add organs listed in the following table with L- prefix (L- indicates a lifetime dose)
  - Click OK
- Open /EARLY/Latent Cancer Parameters/Latent Cancer Parameters
  - Convert CFRISK values in following table to the high-dose range by multiplying by corresponding value of DDREFA (DDREFA = 1 for Breast cancer; = 2 for all others)
  - Update or add CFRISK for all cancer types listed in the following table under the column labeled Both
  - Set ACSUSC = 1., CIRISK = 0., and DDREFA = 2. for all new cancer types
- Under General/Properties/Weather tab, switch to Uniform Bin Sampling.
- Open ATMOS/Weather/Samples per Bin and set NSMPLS = 2.
- Run the problem.
- What are the overall numbers of cancer injuries and cancer fatalities within 50 miles? Did they increase or decrease from the previous version
  - Answer: Previous numbers are 2,280 injuries and 999 fatalities; Updated numbers are 2,390 injuries and 1,040 fatalities.

Exercise 5 – Risk Coefficients

Table 2. Age-averaged site-specific cancer mortality risk estimates (cancer deaths per person-Gy) from low-dose, low-LET uniform irradiation of the body.

Site	Males	Females	Both
Esophagus	7.30E-04	1.59E-03	1.17E-03
Stomach	3.25E-03	4.86E-03	4.07E-03
Colon	8.28E-03	1.24E-02	1.04E-02
Liver	1.84E-03	1.17E-03	1.50E-03
Lung (Lungs)	7.71E-03	1.19E-02	9.88E-03
Bone (Bone Surface)	9.40E-05	9.60E-05	9.50E-05
Skin	9.51E-05	1.05E-04	1.00E-04
Breast	-	9.90E-03	5.06E-03
Ovaries	-	2.92E-03	1.49E-03
Bladder Wall	3.28E-03	1.52E-03	2.38E-03
Kidney (Kidneys)	6.43E-04	3.92E-04	5.15E-04
Thyroid	2.05E-04	4.38E-04	3.24E-04
Leukemia (Red Marrow)	6.48E-03	4.71E-03	5.57E-03
Residual[a] (Remainder)	1.35E-02	1.63E-02	1.49E-02
Total	4.62E-02	6.83E-02	5.75E-02

[a] Residual is a composite of all radiogenic cancers that are not explicitly listed in the table.

General Risk Findings

- Populations chronically exposed to elevated natural background or normal occupational exposure do not show consistent or conclusive evidence of an associated increase in cancer risk (BIER V & VII)
- Linear Quadratic model: $Risk = \alpha Dose + \beta Dose^2$
  - *BEIR III*
  - *BEIR VII for leukemia*
  - Relative importance of 2 terms varies for different tissues
  - Dose at which 2 terms equal: 100-1000+ rads in BEIR III
  - Original equation in MACCS; retained but not currently recommended

General Risk Findings (Continued)

- Piecewise Linear Model
  - For Dose > 20 rad or Dose Rate > 10 rad/hr: Risk∝Dose
  - At low dose rates: Stochastic Risk∝(D/DDREF)
    - Recommended by ICRP 60, BEIR V, and BEIR VII for solid cancers
- Genetic Effects
  - Increased non-lethal mutation rate not observed in human populations (nearly all mutations are non-viable)
- Developmental Abnormalities
  - Risk of mental retardation = 4% Per 0.1 Sv (10 rem) of exposure at 8-15 weeks after conception
- High doses (>0.5 Gy) cause increases in multi-factorial diseases of adults (e.g. cardiovascular disease, stroke). Noted in BEIR VII, discussed in UNSCEAR 2006 report.

MACCS Acute Dose Coefficients (FGR-13 and DOSFAC2 Files)

- Radiation exposure is assumed to occur in first day.
- Acute dose coefficients for internal doses are the risk-weighted sum of dose commitments for day 0-1, …, 200-365.

Table 6-1. Effective Acute Dose Reduction Factors (unitless)

	Time Period after Exposure (Days)					
	0–1	**1–7**	**7–14**	**14–30**	**30–200**	**200-365**
	Effective Acute Dose Reduction Factors (α_1 / α_t)					
RED MARR	1.0	0.5	0.5	0.25		
LUNGS	1.0	0.0625	0.0625	0.027	0.027	0.0109
THYROID	1.0	0.2	0.2	0.2		
STOMACH	1.0	0.37				
LOWER LI	1.0	0.43				
SMALL IN	1.0	0.43				

MACCS Early Health Effects Model

D_t = absorbed dose (Gray) delivered to the target organ "T" over time "t"

$D_{50,t}$ = absorbed dose in organ "T" for a given exposure period "t" that would induce the particular effect of interest in 50% of population.

x_T = normalized dose to organ "T" for a particular effect

$$x_T = \left[\sum_t D_t / D_{50,t} \right]$$

Calculate x_T given the absorbed doses to tissue "T" for the time periods "t" using the following table.

MACCS Early Health Effects Model

Values of LD_{50} or D_{50} (Gy)

Early Health Effect – Dose Threshold (Gy)	Time Period (days)							
	0-1	1-7	7-10	10-14	14-21	21-30	30-200	200-365
Early Fatalities								
Hematopoietic Syndrome – 1.5	3.8	7.6	7.6	7.6	15	15	-	-
Pulmonary Syndrome - 5	10	160	160	160	370	370	370	920
Gastro-intestinal Syndrome - 8	15	35	-	-	-	-	-	-
Early Injuries								
Prodromal Vomiting - 0.5	2	5	-	-	-	-	-	-
Diarrhea - 1	3	6	-	-	-	-	-	-
Pneumonitis - 5	10	160	160	160	370	370	370	920
Skin erythrema - 3	6	20	20	-	-	-	-	-
Transepidermal Injury - 10	20	80	-	-	-	-	-	-
Thyroiditis - 40	240	240	240	240	240	-	-	-
Hypothyroidism - 2	60	60	60	60	60	-	-	-

MACCS Early Health Effects Model

$H = cumulative\ \ hazard = 0.693\ x^{\beta}$ *where* β *is called the "shape parameter"*

$e^{-H} =$ *probability of not developing a particular acute health effect*

$1 - e^{-H} =$ *probability of developing a particular acute health effect*

$1 - e^{-\sum H} =$ *probability of developing at least one acute health effect*

- Most early health effects have threshold dose for brief (< 1 day) intense exposures: $H = 0$ if $D < D_{\text{th}}$
- β parameter and thresholds are provided in the following table

Early Health Effects Table

Early Health Effect	End Results		Impaired Organ	Shape Parameter	LD_{th} or D_{th} Threshold (Gy)
	Death	Injury			
Hematopoietic Syndrome	✓		Red marrow	5	1.5
Pulmonary Syndrome	✓		Lungs	7	5
Gastro-Intestinal Syndrome	✓		Lower large intestine	10	8
Prodromal vomiting		✓	Stomach	3	0.5
Diarrhea		✓	Stomach	2.5	1
Pneumonitis		✓	Lungs	7	5
Skin erythrema		✓	Skin	5	3
Transepidermal Injury		✓	Skin	5	10
Thyroiditis		✓	Thyroid	2	40
Hypothyroidism		✓	Thyroid	1.3	2

Early Health Effects Sample Problem

Given the following stomach doses, calculate the probability of: (1) prodromal vomiting, (2) diarrhea, and (3) at least one of these conditions occurring

Time Period	Absorbed Dose for Time Period
Day 1	2 gray
Day 2 through 7	2 gray
Day 8 through ∞	0 gray

Solution to Health Effects Sample Problem

- **Prodromal Vomiting:**

$$x_{PV} = \left[\sum_t D_t / D_{50,t} \right] = \frac{2}{2} + \frac{2}{5} = 1.4$$

$$\beta_{PV} = 3$$

$$H_{PV} = 0.693 \quad (x_{PV})^{\beta_{PV}} = 1.90$$

$$Risk_{PV} = 1 - e^{-H_{PV}} = .85, \quad or \quad 85\%$$

Solution to Health Effects Sample Problem Continued

- **Probability of Diarrhea:**

$$x_D = \left[\sum_t D_t / D_{50,t} \right] = \frac{2}{3} + \frac{2}{6} = 1$$

$$\beta_D = 2.5$$

$$H_D = 0.693 \quad (x_{PV})^{\beta_D} = .693$$

$$Risk_D = 1 - e^{-H_D} = .5, \quad or \quad 50\%$$

Solution to Health Effects Sample Problem Continued

- **Probability of at least one: Prodromal Vomiting or Diarrhea**

$$H_{PV} \text{ was } 1.90$$

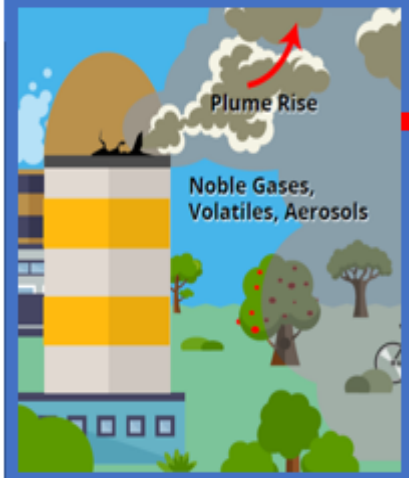
$$H_D \text{ was } 0.693$$

$$1 - e^{-(H_{PV} + H_D)} = 0.93 \text{ or } 93\%$$

Summary of Health Consequences

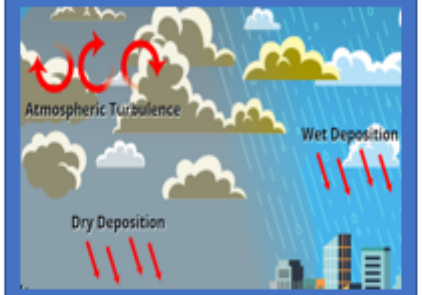
1. Characterize Source Term

- Describes the magnitude and timing of the release
- MELCOR or manual specification



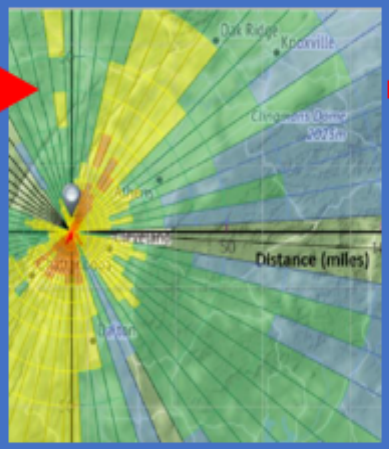
2. Model Atmospheric Transport

- Describes atmospheric transport and dispersion of release
- Gaussian Plume Segment, Gaussian Puff, and Particle Tracking Models



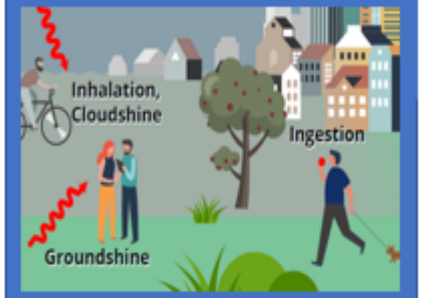
3. Calculate Concentrations

- Describes amount and activity for each radionuclide on a spatial grid over time
- Factors in decay and daughter products



4. Evaluate Exposure Pathways

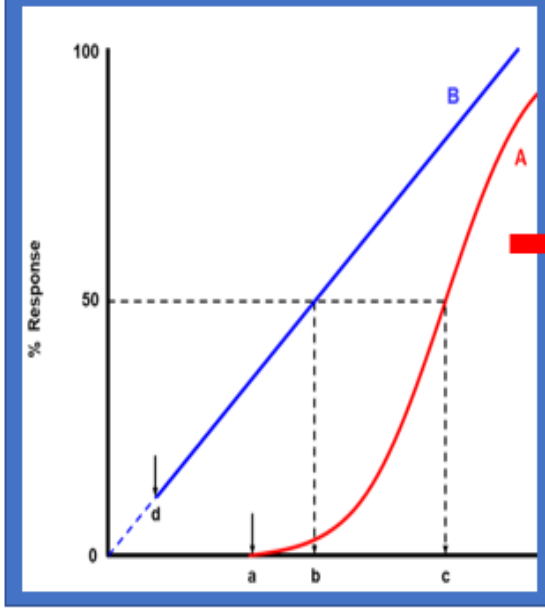
- Describes effective dose to specific organs and whole body from:
  - Inhalation
  - Ingestion
  - Cloudshine
  - Groundshine
  - Resuspension



Transition to Economic Consequences

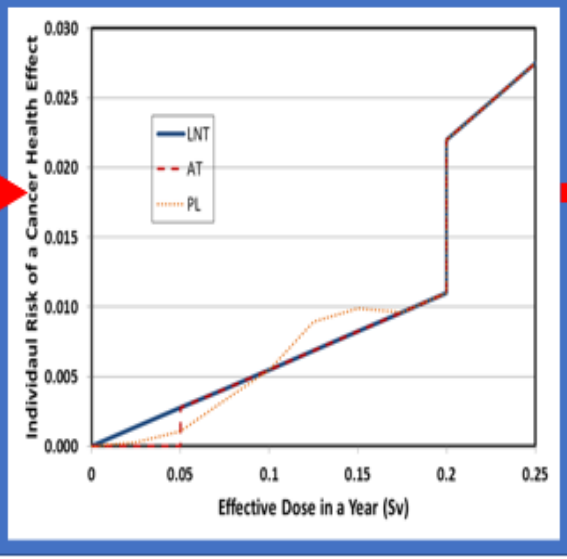
5. Apply Dose Response Models

- Apply dose response models to translate individual doses to dose responses



6. Calculate Risks to Individuals and Population

- Acute: apply hazard functions
- Latent: apply LNT, AT, or PL models for increased cancer risk



7. Apply Protective Actions and/or Emergency Response Planning

- Reduce risk to the public by:
  - Evacuation
  - Relocation
  - Sheltering
  - KI ingestion
  - Food Embargo
  - Interdiction
  - Decontamination
  - Condemnation

Economic Consequence Modeling

MACCS Cost-Based Economic Model

- The original MACCS economic model estimates offsite costs based on the following cost categories
  - Evacuation/relocation costs
    - Per diem basis during emergency and intermediate phases
    - One-time expense during long-term phase
  - Decontamination costs during long-term phase
  - Loss of use for farmland and nonfarmland
    - Expected return on investment (property value)
    - Depreciation on improvements to property
  - Condemnation of property
  - Disposal of contaminated crop and dairy products

Costs Not Included in Economic Model

- Onsite costs
  - Reactor and onsite damage
  - Replacement power
  - Onsite remediation costs
  - Onsite costs related to decontamination worker doses
- Offsite costs
  - Medical and life-shortening (often estimated based on population dose)
  - Psychological
  - Litigation
  - Stigma (lost tourism and trade)
  - Affect on commercial nuclear power industry

Accident Phases from EPA PAGs

- Early (emergency) phase
  - From 1 to 40 days following the start of release
  - 7 days is most commonly used
  - $ Costs are incurred for evacuation and relocation
- Intermediate phase
  - From 0 to 1 year after the completion of the emergency phase
  - $ Costs are incurred for continued relocation
- Long-term phase
  - Up to >300 years after the completion of the intermediate phase
  - $ Costs are incurred for
    - Long-term relocation
    - Decontamination
    - Loss of use
    - Condemnation of property
    - Disposal of contaminated crop and dairy products

Total Accident Cost

$$C_{tot} = C_{epa} + C_{ipa} + C_{ltpa}$$

where

C_{epa} = Cost of early-phase protective actions

C_{ipa} = Cost of intermediate-phase protective actions

C_{ltpa} = Cost of long-term-phase protective actions

Early and Intermediate Phase Costs

$$C_{epa} = n_e \times \Delta t_e \times C_e$$

$$C_{ipa} = n_i \times \Delta t_i \times C_i$$

where

C_{epa} = Cost of early-phase protective actions ($)

C_{ipa} = Cost of intermediate-phase protective actions ($)

n_e = number of early-phase individuals involved (persons)

n_i = number of intermediate-phase individuals involved (persons)

Δt_e = Duration of early-phase action (days)

Δt_i = Duration of intermediate-phase action (days)

C_e = Per diem cost during early phase ($/person-day)

C_i = Per diem cost during intermediate phase ($/person-day)

Long-Term Phase Costs

$$C_{ltpa} = (C_p \times n_{sp}) + (C_A \times A_{sp})$$

where

C_{ltpa} = Cost of long-term protective action

C_p = Cost per person for long-term action for non-farm property

n_{sp} = Population

C_A = Cost per unit area for protective action of farm equipment

A = Farmland area

- Costs per person and per area include:
  - Cost of decontamination
  - Loss of use, depending on the duration of interdiction
  - One time relocation cost (non-farm property)

  OR
  - Cost of condemnation
  - One time relocation cost (non-farm property)

Long-Term Costs for Non-Farm Property

$$C_p = C_d + C_r + C_c$$

where

C_p = Cost of long − term protective action for non − farm property

C_d = Cost per person for decontamination

C_r = Cost per person for relocation

C_c = Cost per person for loss of property usage (expected return on investment + depreciation)

Long-Term Cost from Loss of Use and Depreciation

$$C_c = V_w \cdot \{1 - [(1 - F_{im}) + F_{im} \cdot \exp(-r_{dp} \cdot \Delta t)] \cdot \exp(-r_{ir} \cdot \Delta t)\}$$

where

C_c = Cost from loss of property usage

V_w = Per person value of nonfarm property, including land, buildings, infrastructure, and non − recoverable equipment and machinery

F_{im} = Fraction of property value resulting from improvements

r_{dp} = Depreciation rate

r_{ir} = Inflation adjusted rate of investment return

MACCS GDP-Based Economic Model

- Based on standard input/output model
- Estimates direct, indirect, and induced GDP losses
  - GDP is the net value added by an industrial sector
  - Direct losses are to the affected region
  - Indirect losses are to the remainder of the economy
  - Induced losses result from effect of loss of income on purchasing
- In the MACCS implementation of REAcct, losses also include
  - Decontamination costs
  - Short-term evacuation/relocation costs
  - Long-term relocation cost (one time)
  - Depreciation of improvements to property
  - Condemned property value

GDP-Based Model Parallels Cost-Based Model

Cost-Based Model

- Evacuation/relocation costs
- Long-term relocation
- Decontamination costs
- Value of condemned property
- Loss of use
  - Expected return on investment
  - Depreciation on improvements during interdiction
- Disposal of contaminated crop and dairy products

GDP-Based Model

- Evacuation/relocation costs
- Long-term relocation
- Decontamination costs
- Value of condemned property
- Loss of GDP
  - Direct, indirect, and induced losses
  - Depreciation on improvements during interdiction
- Disposal of crops not included in MACCS 4.0, these were added back in MACCS 4.1

MACCS GDP-Based Economic Model Continued

- GDP-based model estimates direct losses at the county level
  - GDP per industry is at the national level
  - Number of workers employed by industry in each county is used to estimate direct GDP losses for the county
  - GDP-based model adds the contributions by industrial sector for each county in the affected area
  - Partial counties are apportioned either by area or population fractions
- GDP-based model estimates indirect losses at the national level
  - Regional input-output modeling system (RIMS II) multipliers are used to estimate the effect of regional GDP losses on the entire economy
  - An underlying assumption is that only a small portion of the country is affected (i.e., requires interdiction)

MACCS GDP-Based Economic Model Continued

- GDP-based model uses the following formula to sum up direct GDP losses

$$Direct\ lost\ regional\ GDP\ for\ I\ industries\ in\ R\ regions = \sum_{r=1}^{R}\sum_{i=1}^{I} Y_i^{US} \times \frac{E_i^r}{E_i^{US}} \times \frac{d_i^r}{365}$$

where Y_i^{US} = national, annual output for economic sector i

E_i^{US} = national employment for industry i

E_i^r = regional employment for industry i

d_i^r = number of days of disruption for industry i in region r

MACCS GDP-Based Economic Model Continued

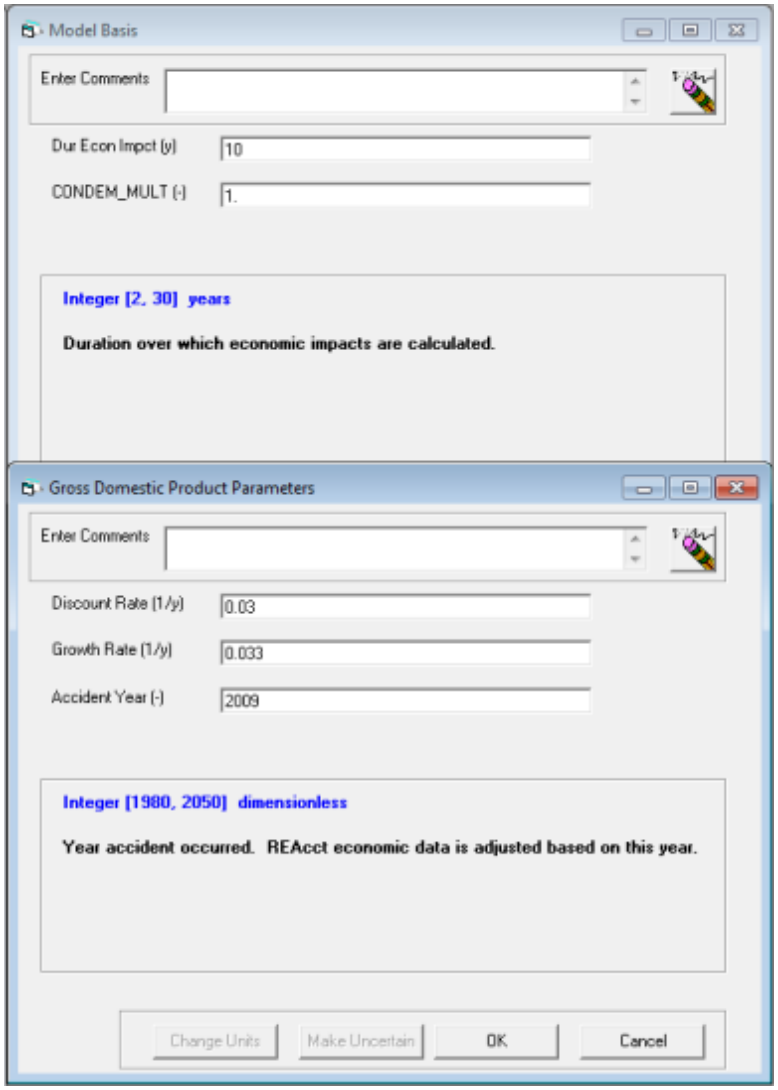
- GDP-based model uses the following formula to estimate total GDP losses (outside the affected region)

$$Total\ lost\ GDP\ for\ Industry\ i = \sum_{j=1}^{I} RIMS\ II_{ij} \times Direct\ lost\ GDP_j$$

where $RIMS\ II_{ij}$ = RIMS II multiplier for the effect of regional losses to industry j on national losses to industry i

Input Parameters for GDP-Based Model

- Six new input parameters were added for the GDP-based economic model
  - Duration of national economic impacts
  - Duration of regional economic impacts
  - A multiplier that affects whether land is condemned or decontaminated
    - A value greater than one means that more money can be spent to decontaminate
    - A value less than one means that less money can be spent to decontaminate
  - Inflation-adjusted social discount rate (discount rate used for social investments)
  - Inflation-adjusted GDP growth rate (change in the GDP per year)
  - Accident year
- Losses are reported in dollars for database year (2011)



Comparison of Decision Process for Decontamination

- GDP-based model: decontaminate when inequality is satisfied

Cost to Decontaminate + Cost of Permanent Relocation + GDP Loss During Interdiction + Depreciation < Property Value * Multiplier + Cost of Permanent Relocation + GDP Loss During Max. Period of Disruption)

- Cost-based model: decontaminate when inequality is satisfied

Cost to Decontaminate + Cost of Permanent Relocation + Expected Rate of Return + Depreciation < Property Value + Cost of Permanent Relocation

Uses for Economic Losses

- New licenses and license extensions (both applicants and NRC)
  - License extensions require a cost/benefit analysis called a SAMA analysis (severe accident mitigation alternatives)
  - New licenses require a similar SAMDA analysis (severe accident mitigation design alternatives)
- Regulatory analyses to support rulemaking
  - Require a cost/benefit analysis
- NRC Research, e.g., Level-3 PRA

Summary

- Stochastic (random) vs. non-stochastic (predictable) health effects
- Acute exposure vs. chronic exposure
- MACCS acute health effects model
- Committee on the Biological Effects of Ionizing Radiation (BEIR)
- Five loss categories modeled by MACCS cost-based economic consequence model
- Two economic models, cost- and GDP-based

References

- *Radiological Assessment: A Textbook on Environmental Dose Analysis*, NUREG/CR-3332, eds. J.E. Till, H.R. Meyer
- Busby, Chris, *Wings of Death: Nuclear Pollution and Human Health*
- Cember, Herman, *Introduction to Health Physics*
- *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation. 1980.* Report III of the Advisory Committee on the Biological Effects of Ionizing Radiation (BEIR).
- *Health Effects of Exposure to Low Levels of Ionizing Radiation. 1990.* BEIR Report V.
- *Health Risks of Exposure to Low Levels of Ionizing Radiation. 2006.* BEIR Report VII phase 2.
- IAEA Report 405 (2001) Cytogenetic Analysis for Radiation Dose Assessment.
- ICRP Database of Dose Coefficients: Workers and Members of the Public, Version 2.01 (1998).
- Preston, D. et al. Studies of Mortality of Atomic Bomb Survivors. Report 13: Solid Cancer and Noncancer Disease Mortality: 1950-1997. Radiation Research, 160, 381-407, 2003.

References

- ICRP Publication 26, Recommendations of the ICRP (1977).
- ICRP Publication 30, Limits for Intakes of Radionuclides by Workers (1979).
- ICRP Publication 49, Developmental Effects of Irradiation on the Brain of the Embryo and Fetus, (1986).
- ICRP Publication 60, 1990 Recommendations of the International Commission on Radiological Protection (1991).
- ICRP Publication 90, Biological Effects after Prenatal Irradiation (Embryo and Fetus) (2003).
- ICRP Publication 103, The 2007 Recommendation on the International Commission on Radiological Protection (2007).
- Strom, D.J., Health Impacts from Acute Radiation Exposure, PNNL-14424, September 2003.
- Boice, J., "Study of One Million U.S. Radiation Workers and Veteran," NRC RIC, March 14, 2013, https://ric.nrc-gateway.gov/docs/abstracts/BOICE-onsite-TH27%20hv.pdf, accessed on April 18, 2013.

References

- Grosch, D. S., *Biological Effects of Radiations.*
- Leggett, R.W. and K.F. Eckerman, *Dosimetric Significance of the ICRP's Updated Guidance and Models, 1989 –2003, and Implications for U. S. Federal Guidance,* ORNL/TM-2003/207.
- MELCOR Accident Consequence Code System (MACCS) Model Description
- FRMAC Radiological Response Manual, Vol. 2. (2003) SAND2003-1072P
- Teresa Neumaier, Joel Swenson, Christopher Pham, Aris Polyzos, Alvin T. Lo, PoAn Yang, Jane Dyball, Aroumougame Asaithamby, David J. Chen, Mina J. Bissell, Stefan Thalhammer, and Sylvain V. Costes, *Evidence for formation of DNA repair centers and dose-response nonlinearity in human cells,*
  PNAS 2011 : 1117849108v1-6.
- Levitt, S.H., et al., *Technical Basis of Radiation Therapy: Practical Clinical Applications,* 4th Edition, Springer *2008.*

References

- Levitt, S.H., et al., Technical Basis of Radiation Therapy: Practical Clinical Applications, 4th Edition, Springer 2008.
- Richardson, David B et al. Risk of Cancer from Occupational Exposure to Ionising Radiation: Retrospective Cohort Study of Workers in France, the United Kingdom, and the United States (INWORKS). British Medical Journal, 2015; 351:h5359.
- Strom, D.J., Health Impacts from Acute Radiation Exposure, PNNL-14424, September 2003.
- Boice, J., "Study of One Million U.S. Radiation Workers and Veteran," NRC RIC, March 14, 2013, https://ric.nrc-gateway.gov/docs/abstracts/BOICE-onsite-TH27%20hv.pdf, accessed on April 18, 2013.

Section 6 Endnotes / Update

- In the current version of the FGR13-based DCF files (FGR13GyEquivDCFxx.INP, file creation date May 13, 2008):
  - Preferred files for risk estimation but not dose estimation.
  - The DCF values for bladder wall have been replaced with values for pancreas to accommodate MACCS limitations.
  - DCF values for breast are based on an RBE value of 10 for alpha radiation.
  - DCF values for red marrow are based on an RBE of 1 for alpha radiation.
  - Previous version (FGR13DCFxx.INP, file creation date July 13, 2007) can still be used for dose equivalent estimation purposes.