ACCIDENT CONSEQUENCE ANALYSIS
P-301

May 2-6, 2016

United States
Nuclear Regulatory Commission

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Sandia National Laboratories

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1. Purpose and Scope of Level-3 PRA Analysis

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Objectives

- Discuss the 3 levels of PRA (PSA) and how Level 3 fits in
- Learn the relationship between consequence and risk
- Discover the characteristics of consequence analysis
- Discuss the overall course scope
- Consider some applications of consequence modeling
- Summarize the course schedule

Overview of PRA Applications

- Used to assess the relative risks posed by various types of operations and facilities
- Used to understand the relative importance of the risk contributors
- Used to obtain insights on potential safety improvements
- The primary goal(s) is to
  - Lessen the chance (probability) of an accident
  - Minimize the impact of an accident

PRA vs. PSA

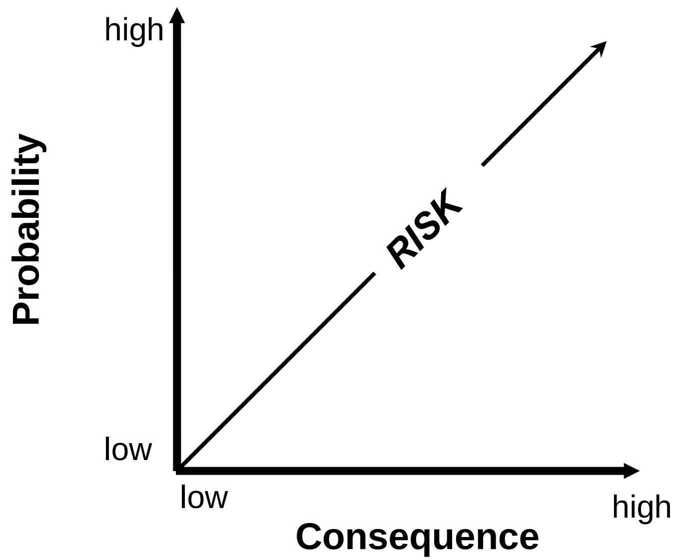
- PRA = Probabilistic Risk Assessment
- PSA = Probabilistic Safety Assessment
- Used interchangeably – no standard

Three Levels of PRA/PSA

- *Level 1* - The assessment of plant failures that lead to core damage and the determination of **core damage frequency (CDF)**.
- *Level 2* - The assessment of fission product release/transport and containment response that, together with the results of Level 1 analysis, leads to the determination of **release frequencies**.
- ➔ *Level 3* - The assessment of off-site consequences that, together with the results of Level 2 analysis, leads to estimates of **risk to the public**.

Measure of Safety

- Consequence = The undesired outcomes or losses resulting from an accident.
- Probability = The likelihood of an outcome per event.
- (Frequency = The likelihood of an outcome per unit time.)
- Risk = Consequence × Probability (or Frequency)



Level-3 PRA (Consequences)

- Health and Economic Consequences

Release from Plant (end of Level 2)

↓

Transport to Public

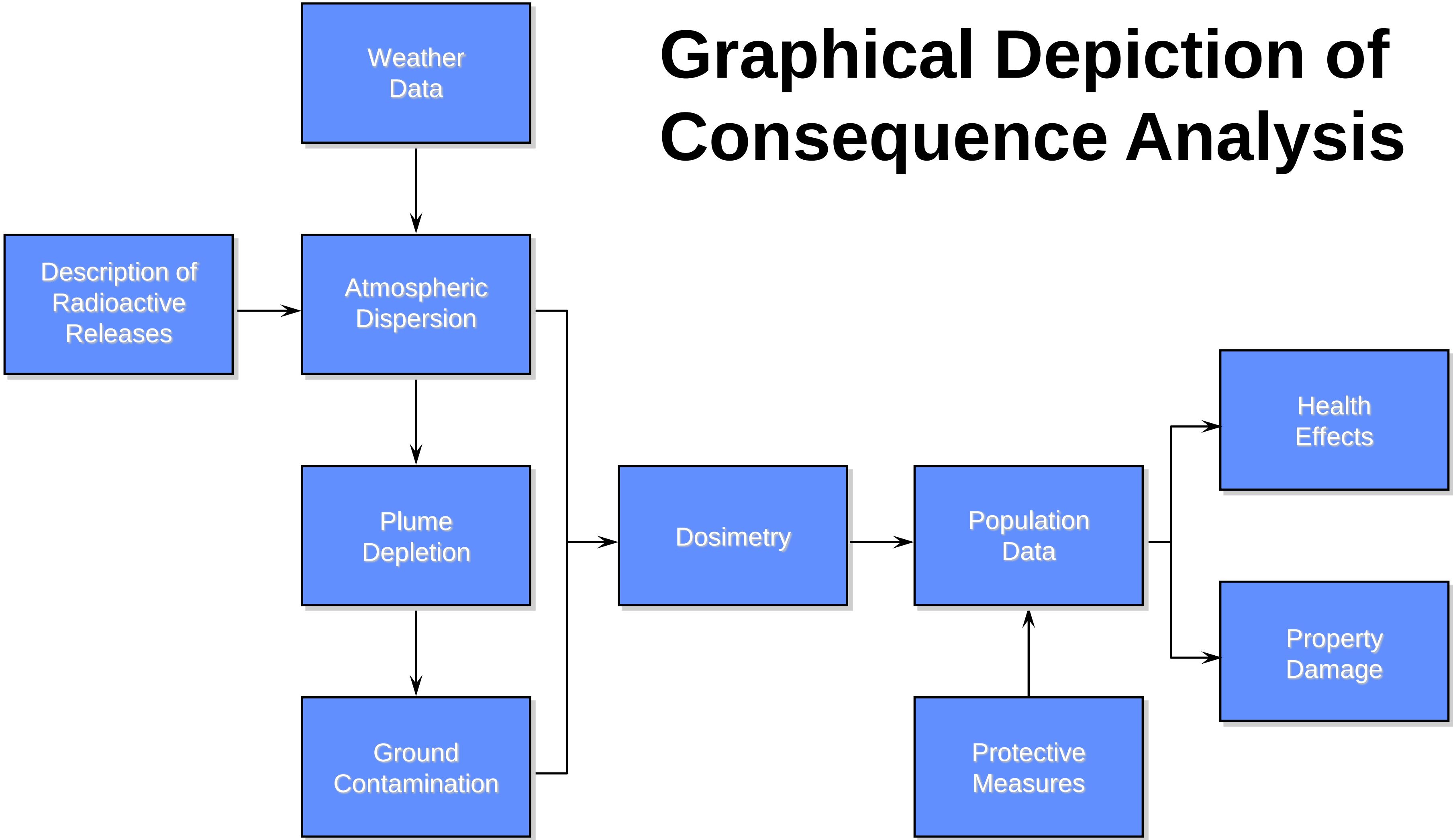
↓

Effect of Transported Release on Public

Characteristics of Level-3 Consequence Analysis

- Limited to atmospheric releases
- Conditional on the release occurring
- The major calculation steps are incorporated into computer codes:
  - ✓ MACCS and MACCS2 (US and worldwide)
  - ✓ COSYMA (European Commission)
  - ✓ OSCAAR (Japan)
  - ✓ PACE (UK)
  - ARANO (Finland)
  - LENA (Sweden)
  - MECA2 (Spain)
- Ongoing interest generated by
  - Security investigations following 9/11
  - Evaluation of safety of US plants after Fukushima
  - License extension for existing reactors (Pilgrim, Indian Point, etc.)
  - Certification and licensing of new reactors
  - Fukushima accident

Graphical Depiction of Consequence Analysis



Scope of Course

- Source terms
- Atmospheric dispersion and deposition
- Dose pathways to man
- Protective measures
- Health effects
- Economic consequences
- Calculations and codes
- Current status

General Applications of PRA

- Predictions of public risk
  - Generic or site specific
  - Societal or individual
- Environmental impact assessment
  - Part of license application and license extension processes
  - SAMA (severe accident mitigation alternatives)
  - SAMDA (severe accident mitigation design alternatives)
- Rulemaking and regulatory procedures

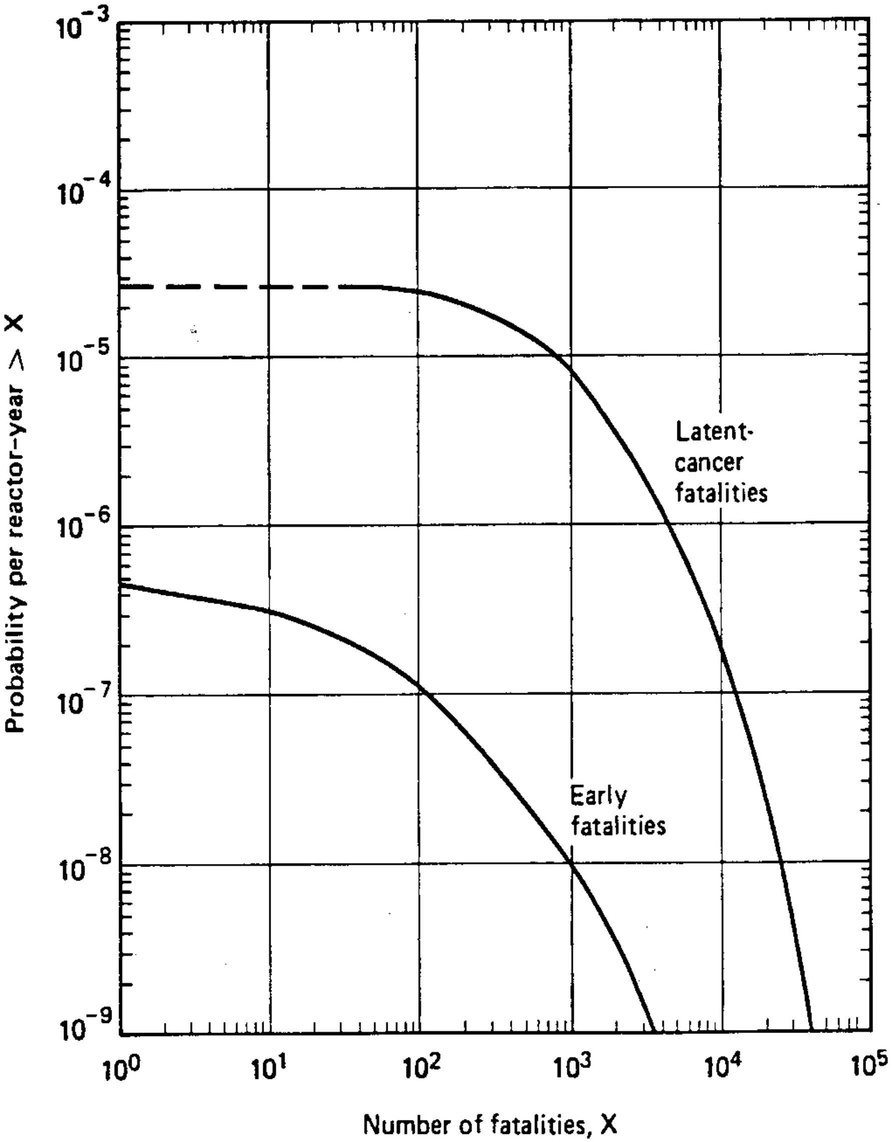
General Applications of PRA (cont.)

- Confirmation of safety goals
- Emergency planning and response
- Evaluation of risk metrics for licensing
- Guidance for research priorities

Complementary Cumulative Distribution Function (CCDF)

- A distribution function calculated from a set of input parameters.
- With respect to PRA, it is a function that shows the relationship between Probability and Consequence.

CCDF for Early and Latent-cancer Fatalities



Notes:

- From the Reactor Safety Study (USNRC, 1975)

Class Schedule

- May 2, Monday AM
  - Section 1 – Purpose and Scope of Level-3 Analysis
  - Section 2 - History of Consequence and Risk Analysis
- May 2, Monday PM
  - Section 3 - Interface with Level-2 Analysis
  - Section 4 - Overview of MACCS
- May 3, Tuesday AM and PM
  - Section 5 - Atmospheric Transport and Dispersion
- May 4, Wednesday AM and PM
  - Section 5 - Atmospheric Transport and Dispersion (Cont'd)
  - Section 6 - Health Effects and Economic Consequences
- May 7, Thursday AM
  - Section 6 - Health Effects and Economic Consequences (Cont'd)
  - Section 7 - Protective Measures
- May 7, Thursday PM
  - Section 8 - Uncertainties, V&V, and Research
  - Section 9 - Course Summary and Exam Preparation
  - Exam
- May 8, Friday AM
  - SecPop and MELMACCS Demonstrations
  - Additional Consequence Analyses

2. History of Consequence and Risk Analysis

Overview of Historical Section

- Historical Timeline
- WASH-740
- WASH-1400
- NUREG-1150
- Consequence Code Evolution

Early History: Pre-1940's

- Wilhelm Roentgen discovers x-rays - [1895]
- Marie Curie discovers the radioactive elements radium and polonium - [1898]
- International Commission on Radiological Protection (ICRP) is founded in Stockholm by the International Society of Radiology (ISR) - [1928]
  - Rolf Sievert was a founding member
  - Originally entitled "International X-ray and Radium Protection Committee"
- Radiation effects are studied and become qualitatively understood
- Otto Hahn and Fritz Strassman demonstrate nuclear fission - [Germany, 1938]
- Initial step towards Manhattan Project - [1939]
  - Albert Einstein's letter to President Roosevelt informing him of German atomic research

1940's

- Manhattan Project formed to build the atomic bomb - [1942]
  - Research was secret
  - Los Alamos was selected as the atomic bomb laboratory site
- Enrico Fermi (University of Chicago) - [1942]
  - First major investigation of a *controlled* nuclear fission chain reaction
  - SCRAM - Safety Control Rod Axe Man, Safety Cut Rope Axe Man, Scram (as in run away)….the truth according to Warren Nyer:
    - *Nyer's job that day was to be Hilberry's backup. If all safety systems failed, he and the other members of the "suicide squad" were to dump a liquid cadmium solution on CP-1 to poison the reaction. The axe-man story is, he recalls, "a bunch of baloney." But he did offer another explanation for the word. His recollection was that Wilson was assembling a panel that included a big red button. According to Nyer, someone asked Wilson the reason for the red knob. Wilson replied you'd hit it if there was a problem. "Well, then what do you do?" he was asked. Wilson reportedly replied "You scram … out of here." – Tom Wellock (NRC Historian)*
- Hanford Site was built to produce plutonium for the Manhattan Project - [1943]
  - Meteorological Reconnaissance Tower (1944)
    - to prepare for production reactors
    - 125 m tower, diffusion experiments
  - Hanford fuel processing
    - noble gases and iodine released
    - ruthenium also lost in large quantities

1940's (cont.)

- Study of radium dial painters - [1945]
- Atomic Energy Act was passed - [1946]
  - Atomic Energy Commission (AEC) is established
  - AEC replaces the Manhattan Project
- AEC built first reactor (Clementine) - [1946]
  - Los Alamos
  - Miniature
- AEC establishes the Reactor Safeguards Committee [1947-1948]
  - Later become the Advisory Committee on Reactor Safeguards (ACRS)
  - Recommends risk-informed approaches to regulatory problems
  - Review and resolve key technical issues relating to NPP regulation

Fig. 5. Clementine fuel rod cage, constructed of mild steel. Mercury coolant circulated through the cage.

1950's

- "Atoms for Peace" (President Eisenhower) - [1953]
  - Considered the birth of *commercial* nuclear power
  - Establishment of the International Atomic Energy Agency (IAEA)
- Atomic Energy Act - [1954]
  - Permitted atomic energy use for peaceful purposes
  - Supported the growth of private, commercial nuclear industry
- Exposure dose formula published - [throughout the 50's]
  - Publication of maximum permissible dose limits
  - National Bureau of Standards (NBS) $\longrightarrow$ Becomes NIST in 1988
- USAEC publishes WASH-740, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants" - [1957]
- ACRS establishes the "Maximum Credible Accident" Methodology - [1958]

1960's

- 10CFR100, "Reactor Site Criteria" - [1962]
  - MCA used to evaluate site acceptability
  - Engineered safeguards allowed to offset less favorable characteristics
  - 2-hour dose to a phantom person at the exclusion area boundary (EAB) using 95-percentile meteorology:
    - less than 25 rems - whole body
    - 300 rems - thyroid
  - 30-day dose to low population zone (LPZ) using average meteorology
- TID-14844, "Calculation of Distance Factors for Power and Test Reactors", USAEC - [1962]
  - "TID Source Term" instantaneous release to containment
    - 100% of noble gases
    - 50% of radioiodines
    - 1% of other particulate matter (non-gases)
  - Containment assumed to be fully effective at design leak rate
- Focus on emergency core cooling system (ECCS)
  - Fluid flow
  - Heat transfer

1960's (cont.)

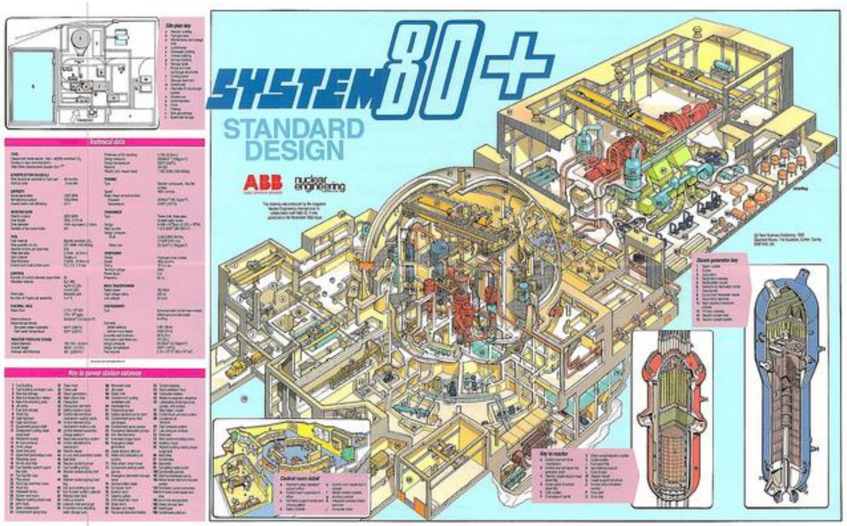
- Core integrity investigation during a LOCA
  - Thermal-hydraulic safety related computer codes
  - Two-phase flow
  - LOFT (Loss of Fluid Tests)
- TID release assumptions used in safety system design
  - Iodine releases recognized as conservative
  - Assumed to compensate for uncertainty
- National Council on Radiation Protection and Measurements (NCRP) - [1964]
  - A congressionally chartered independent body of scientific experts
  - Recommends limits for occupational exposure
- Regulatory Guides 1.3 and 1.4 - [1964]
  - Reduced iodine source term by factor of two (deposition)
  - Distribution of radioiodines in elemental, particulate, and organic forms
  - Iodine release recognized as "stylized non-mechanistic," meaning 50% plated out in containment and not 100% release

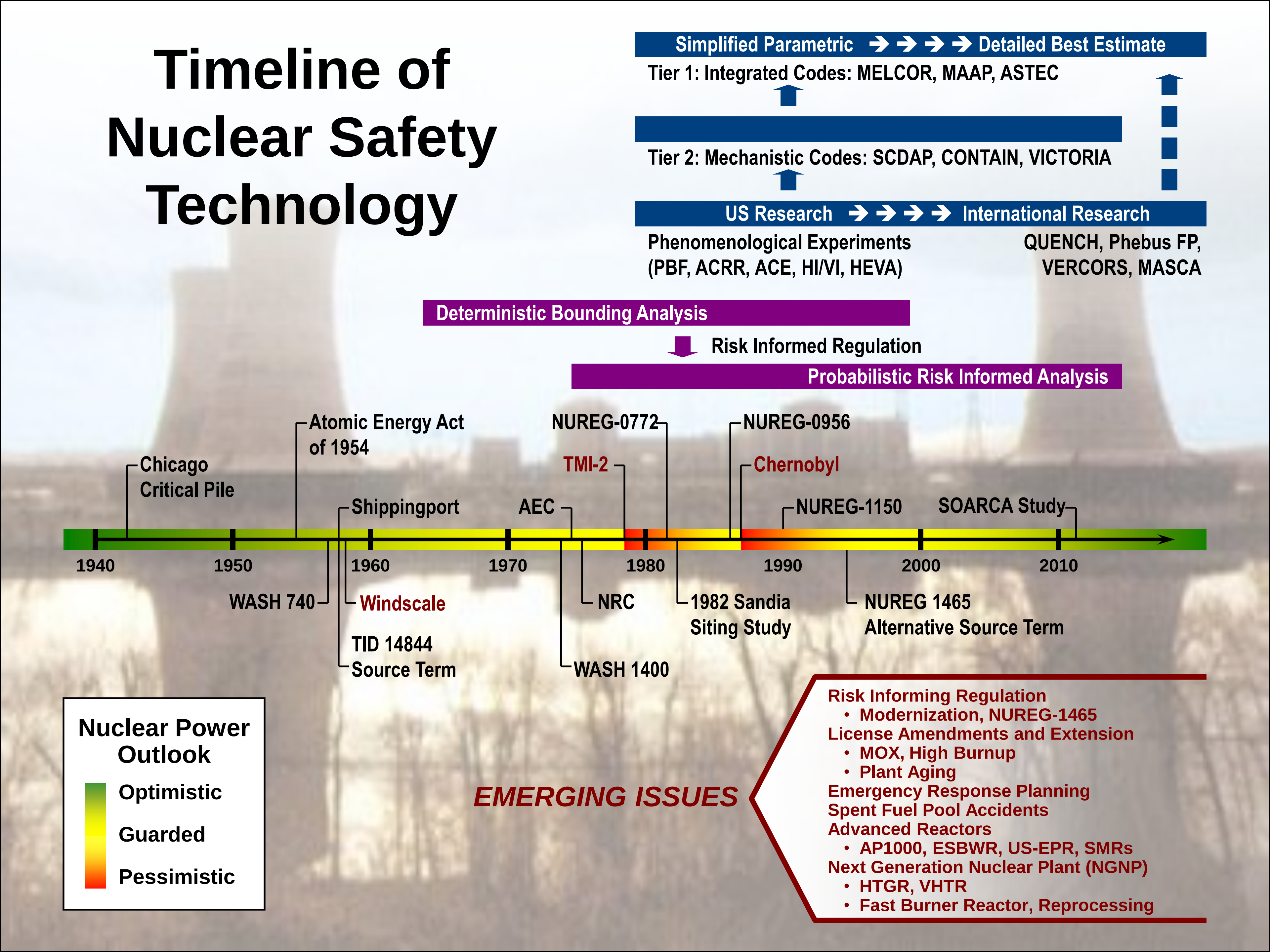
1970's

- ECCS Concerns
  - Semi-scale
  - AEC publishes "interim acceptance criteria"
- US AEC "realistic" assessment assumptions (NEPA) - [1971]
  - Appendix D 10CFR50 - staff judgments
  - Nine accident classes
  - Class 9 was "very serious", with potential for severe consequences
  - Class 9 accidents not analyzed as probability of occurrence considered too low
  - Class 9 is beyond design basis
- Energy Reorganization Act - [1974]
  - NRC
  - ERDA (DOE)
- WASH-1400, "Reactor Safety Study" - [1975]
- TMI - [1979]

1980's - 1990's

- R&D Response to TMI
  - Human factors
  - Small-break LOCA
  - Fission product release
  - Hydrogen generation
- USNRC, "The Development of Severe Reactor Accident Source Terms: 1957-1981", NUREG-0773 - [1982]
- Advance Light Water Reactor (ALWR) Program - [mid 80's-90's]
  - AP600
  - ABWR
  - System 80+
- NUREG-1150 - [1991]




Timeline of Nuclear Safety Technology
Simplified Parametric → → → → Detailed Best Estimate
Tier 1: Integrated Codes: MELCOR, MAAP, ASTEC
Tier 2: Mechanistic Codes: SCDAP, CONTAIN, VICTORIA
US Research → → → → International Research
Phenomenological Experiments (PBF, ACRR, ACE, HI/VI, HEVA)
QUENCH, Phebus FP, VERCORS, MASCA
Deterministic Bounding Analysis
Risk Informed Regulation
Probabilistic Risk Informed Analysis
Chicago Critical Pile
Atomic Energy Act of 1954
Shippingport
AEC
TMI-2
NUREG-0772
NUREG-0956
Chernobyl
NUREG-1150
SOARCA Study
1940
1950
1960
1970
1980
1990
2000
2010
WASH 740
Windscale
TID 14844 Source Term
WASH 1400
NRC
1982 Sandia Siting Study
NUREG 1465 Alternative Source Term
Nuclear Power Outlook
Optimistic
Guarded
Pessimistic
EMERGING ISSUES
Risk Informing Regulation
• Modernization, NUREG-1465
License Amendments and Extension
• MOX, High Burnup
• Plant Aging
Emergency Response Planning
Spent Fuel Pool Accidents
Advanced Reactors
• AP1000, ESBWR, US-EPR, SMRs
Next Generation Nuclear Plant (NGNP)
• HTGR, VHTR
• Fast Burner Reactor, Reprocessing

WASH-740

- USAEC, “Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants”, March 1957, aka “Brookhaven Report”
- Three typical cases for a 500 MWe Reactor:
  - Contained - no release but a “gamma shine” dose
  - Volatile Release - significant fractions of noble gases, halogens, etc., released
  - 50 Percent Release - 50% of all fission products in reactor released to atmosphere
- Probabilities discussed but not estimated - ($1E^{-5}$/Yr -$1E^{-9}$/Yr)
- Consequences estimated as:
  - 0 to 3400 prompt fatalities (over 3 calculations evaluated)
  - 43,000 injuries (max.)
  - $7 billion damage to property (max.)

Reactor Safety Study (RSS)

- "Reactor Safety Study", WASH-1400, October 1975
  - first U.S. systematic attempt to search out large spectrum of accidents
  - first to use quantitative techniques to estimate the following in an integrated manner:
    - probabilities: 1/20,000 core melt per reactor per year
    - source terms
    - public consequences
- Models developed: (MARCH, CORRAL, CRAC)
  - physical accident processes
  - consequence models
    - dispersion and impact of radioactive material releases
    - assess distribution of risks
- Nine PWR and five BWR release categories defined and frequencies quantified

Reactor Safety Study (cont.)

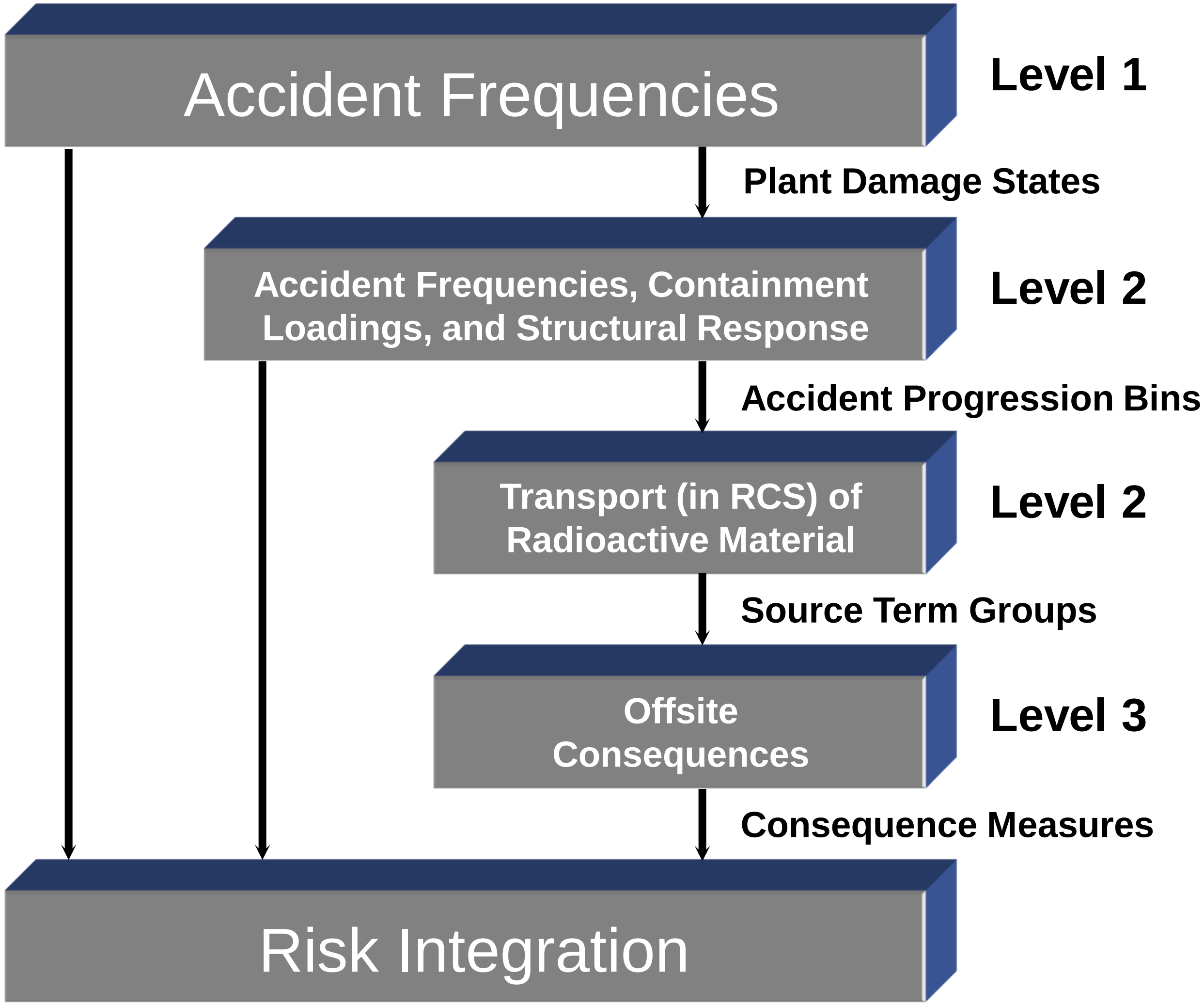
- Calculation of Reactor Accident Consequences (CRAC)
  - Assign probability distribution to key variables
    - release magnitude
    - weather conditions
    - population

Statistics	WASH-740	RSS	
		Peak	Average
Prompt Fatalities	3400	92	.05
Prompt Injuries	43000	200	0.1
Total Damage (Billions of $)	7	1.7	0.51

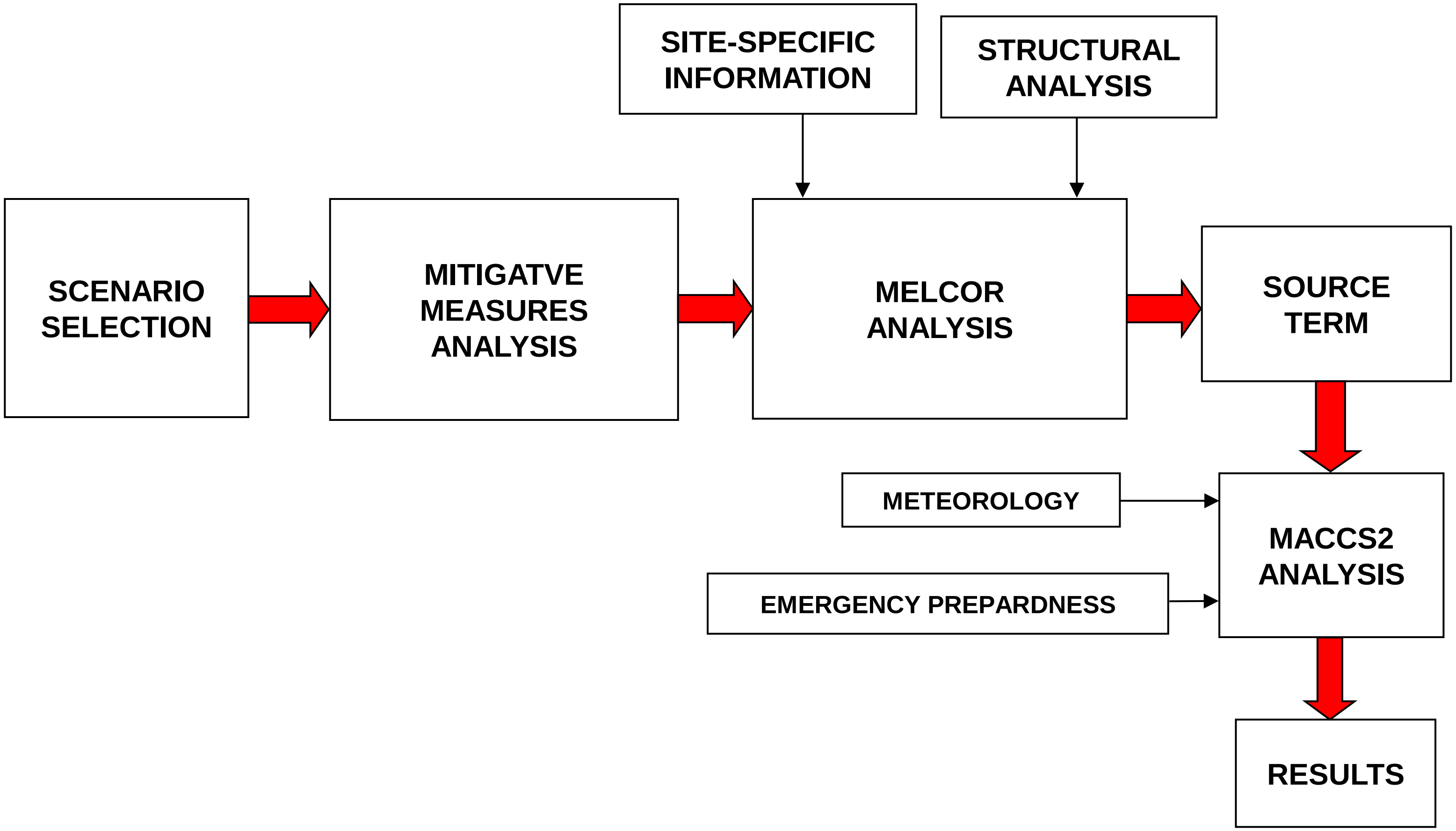
NUREG-1150

- "Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants"
  - Completed in October, 1990
  - Five assessed plants were:
    - Surry
    - Sequoyah
    - Peach Bottom
    - Grand Gulf
    - Zion
- Five principle steps of risk analysis:
  - Accident (frequency) analysis
  - Accident progression, containment loadings, and structural response analysis
  - Radioactive material transport (source term) analysis
  - Offsite consequence analysis
  - Risk Integration - combines and analyzes the first four steps

NUREG-1150 Risk Analysis Process



SOARCA Approach



Evolution of NRC Consequence Tools

- **CRAC** — **1975: WASH-1400 (Reactor Safety Study)**
- **CRAC2** — **1982: Early PRAs, Sandia Siting Study**
- **MACCS1.5.11** — **1990: NUREG-1150 and LaSalle PRAs**
- **MACCS2** — **1998: Improvements in dose conversion data base, decay chains, emergency response model, and food pathway model**
- **WinMACCS** — **2002-2005: Security studies for 6 nuclear power plants**

2005-2007: Protective Action Recommendation Study

2006-2012: State of the Art Reactor Consequence Analysis

2011-2013: Spent Fuel Pool Scoping Study

2012-2014: SOARCA Uncertainty Analysis

2012-2014: Filtered Vent Study

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MACCS (MELCOR Accident Consequence Code System)

Source Term File
- Plume start times and durations
- Release fractions
- Release heights
- Heat content
- Aerosol size distribution

Weather File
- Wind speed & direction
- Precipitation
- Stability class
- Mixing layer heights

ATMOS Module
- Atmospheric transport using Gaussian plume segment model
- Plume depletion
- Dry and wet deposition
- Radioactive decay
- Ground contamination
- Weather sampling

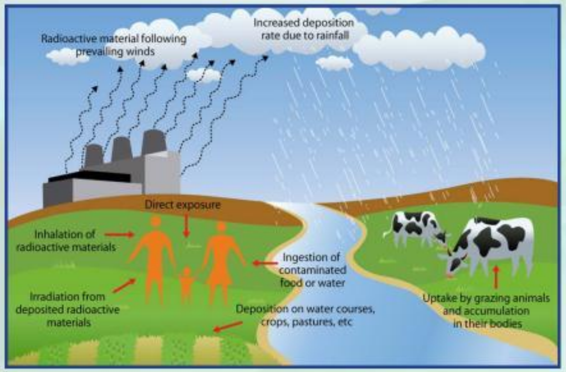
EARLY Module

	Emergency Phase
Duration	~ 1 week
Protective Actions	• Sheltering • Evacuation • Relocation
Exposure Pathways	• Cloudshine • Groundshine • Inhalation • Skin Deposition

CHRONC Module

	Intermediate Phase	Long-Term Phase
Duration	0-1 year	30-50 years
Protective Actions	• Relocation • Interdiction	• Interdiction • Decontamination • Condemnation
Exposure Pathways	• Groundshine • Inhalation of resuspended materials	• Groundshine • Inhalation of resuspended materials • Food and water ingestion

Outputs
- Health Effects
- Economic Costs
- Land Contamination



Site File
- Population
- Land/Water fraction
- Farm/Non-farm fraction
- Economic values

Dose Conversion Factor File
- Dose conversion factors for each pathway, organ, and radionuclide (Sv/Bq-s/m³, Sv/Bq-s/m², Sv/Bq)

Food Chain File
- Radionuclide concentrations in nine foodstuff types for different seasons of the year
- Food category consumption rates for an average adult

Key Applications of MACCS:
- State-of-the-Art Reactor Consequence Analyses (SOARCA) – NUREG-1935, NUREG/CR-7110 and NUREG/BR-0359 (ML12332A057, ML12332A058, ML13150A053, ML13240A242, ML12347A049)
- SECY-13-0112, "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor" (ML13256A334)
- SECY-12-0157, "Consideration of Additional Requirements for Containment Venting Systems for Boiling Water Reactors with Mark I and Mark II Containments," Enclosure 5B (ML12345A030)

3. Interface With Level-2 PRA Analysis

Interfaces Between the Levels of PRA

- *Level 1 -* The assessment of plant failures leading to core damage and the determination of core damage frequency (CDF).

⇩

- *Level 2 -* The assessment of fission product release/transport and containment response that, together with the results of Level-1 PRA analysis, leads to the determination of release frequencies (including LERF).

⇩

- *Level 3 -* The assessment of off-site consequences that, together with the results of Level-2 PRA analysis, leads to estimates of risk to the public.

Objectives

- Learn the interfaces and results from Level-1 and -2 analyses that are important to Level-3 PRA analysis.
- Understand the significance of the amounts and types of releases.
- Define source terms.
- Become familiar with NUREG-1150 data and methods.
- Learn about IPEs and SOARCA.

Outline

- Level-1/Level-2 interface (plant damage states)
- Level-2 PRA
- Introduction to source terms
- Importance of released radionuclides
- Source term release categories (source term groups)
- Structure of the NUREG-1150 analyses
- Structure of the NUREG-1560 analyses (IPEs)
- SOARCA

Level-1/Level-2 Interface

- Plant-Damage-State (PDS) characterization
  - Physical state of the reactor coolant system (RCS) and containment
  - Availability of functions to mitigate accident progression after core damage
- PDSs are chosen to bound the level-1 accident sequences
  - Essential discrimination of accident response
  - Information needed for the level-2 analyses
- Level of discrimination between states is designed to
  - Significantly reduce the number of level-2 analyses
  - Retain important sequence characteristics for accident progression

Plant Damage State Characteristics

- Status of the containment and reactor coolant system pressure boundaries
- Availability and possible recovery of AC power
- Availability of various pumped water flows to the vessel and to containment
- Availability of containment heat removal
- Implied characteristics such as the reactor coolant system (RCS) pressure at vessel failure may be included

Example NUREG-1150 Plant Damage State Grouping Characteristics

- Status of RCS at onset of core damage (8 modes)
  - No break
  - Break size (very small, small, medium, large)
  - SGTR (break, break with loss of secondary system integrity)
  - Event V (Interfacing systems LOCA)
- Status of emergency core cooling system (ECCS) (5 modes)
  - Injection then recirculation, Injection only, recoverable, not recoverable, LPIS available
- Containment heat removal (4 modes)
  - Operating, recoverable, not recoverable, sprays only
- AC power (4 modes)
  - Available, partially available, recoverable, not recoverable

NUREG-1150 Plant Damage State Grouping Characteristics (cont.)

- Contents of reactor water storage tank (RWST) (4 modes)
  - Injection into containment, available when power is recovered, not available, injection into upper compartment
- Heat removal from steam generators (6 modes)
  - Auxiliary feedwater system (AFWS) status - steam and electric
  - Steam generator pressurization
  - Recoverability
- Cooling for reactor coolant pump seals (3 modes)
  - Operating, recoverable, not recoverable
- There are potentially 46080 PDSs, but only a few dozen are of interest

Components of a Level-2 PRA

- Characterization of the core-melt accident progression
- Estimation of conditional probability of containment failure
- Calculation of source term
- Assessment of ***uncertainties***
  - Severe-accident phenomenology
  - Containment challenge
  - Source term

Typical Core-Melt Accident Sequence

- Initiating event
- In-vessel:
  - Core uncovery
  - Core heatup
  - Core oxidation and melting
  - Core slump and relocation into lower plenum
  - Fuel/coolant interactions (FCIs) in lower plenum
- Vessel and/or RCS failure:
  - Over-temperature/overpressure failure of RCS piping, valves, steam generator tubes
  - Vessel penetration or vessel failure depending on in-vessel and/or ex-vessel cooling

Typical core-melt accident sequence (cont.)

- Ex-vessel:
  - Release of melt and debris from vessel
  - Venting of remaining vessel contents (steam, hydrogen, and fission products)
  - Debris relocation
  - Melt/concrete interactions
- Containment response to challenges and mitigation:
  - Temperature and pressure rise from mass and energy additions
  - Hydrogen combustion
  - Steam explosion
  - Mitigative systems: sprays, coolers, venting
  - Containment failure

Typical core melt accident sequence (cont.)

- Release of Fission Products
  - From fuel rods due to oxidation or melting
  - From vessel/RCS (breach or valve)
  - Release into the environment via
    - Containment breach
    - Failure to isolate
    - Bypass of containment (SGTR, ISLOCA)

Level-2 Analysis

- Level-2 analysis extends the in-plant probabilistic and deterministic descriptions of the severe accident sequence
  - From impending core melt (Level 1)
  - To fission product release to the environment
- Level-1 segment of the accident
  - Depicted probabilistically on an event tree
    - Called **accident sequence tree** if containment systems excluded
    - Called **extended accident sequence tree** if containment systems included
- Level-2 segment of the accident
  - Usually depicted probabilistically on **containment event tree** (CET)
  - Depicted on **accident-progression event tree** (APET) in NUREG-1150
  - Guided by deterministic source term calculations

Level-2 Probabilistic Analysis (cont.)

- Binning of sequences is performed at several levels
  - Plant damage state grouping in Level 1
  - Source term category grouping in Level 2
- Binning (or “grouping”) causes loss of information detail
  - A bin is often represented by a single description
  - Description may be conservative or best estimate
- Uncertainty is intrinsic in Level-2 predictions

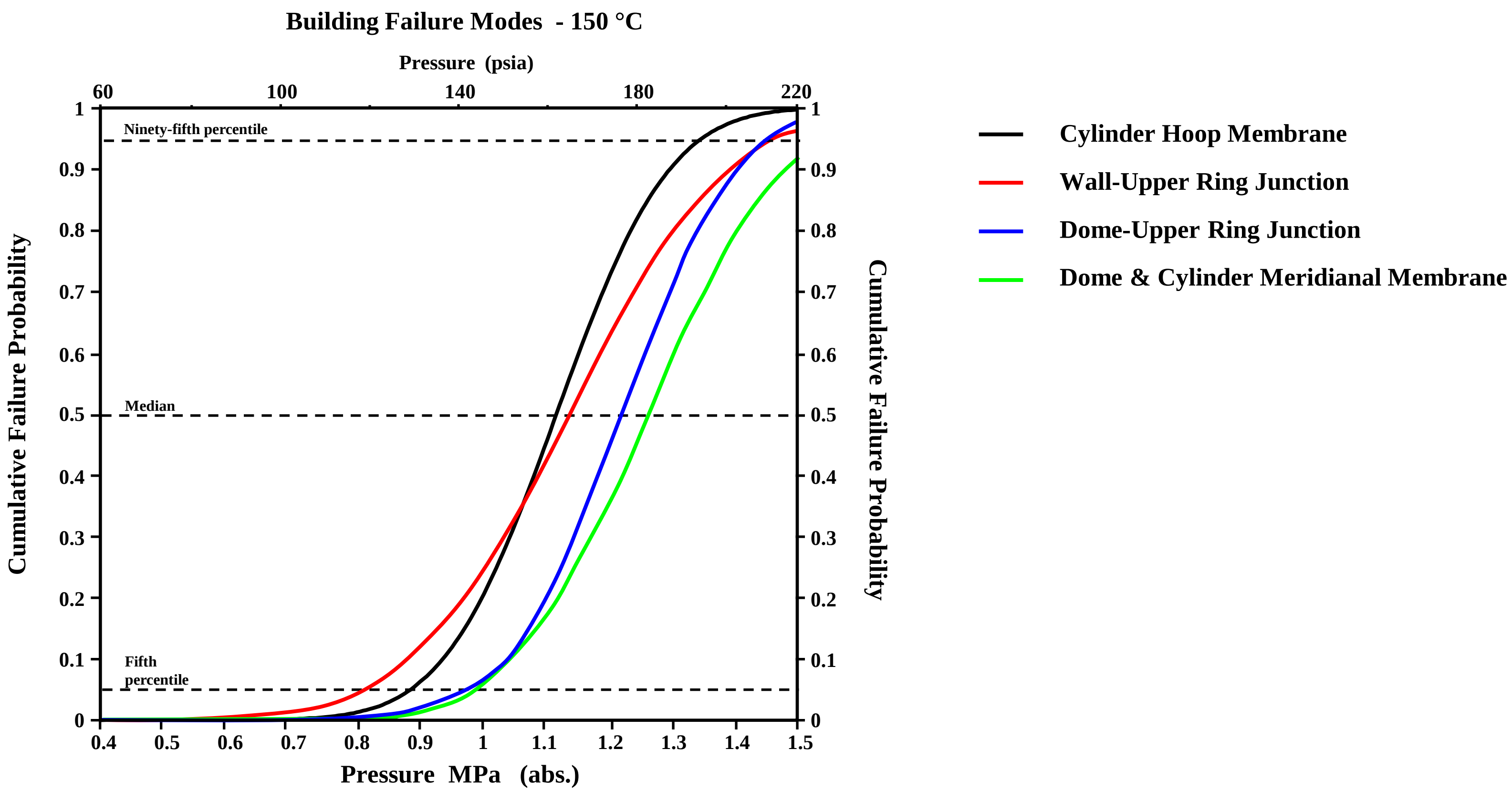
Accident-Progression Analysis

- Progression of core-melt accidents and plant conditions are analyzed deterministically to provide
  - Verification of appropriateness of event-tree descriptions of the accident
  - Detailed physical picture of the phases of the accident
  - Characteristic fission product source terms

Containment Failure Locations (Determines Release Height)

- Shell
  - Mid-height
  - Apex
- Large openings and hatches
- Discontinuities
  - Basemat/shell
  - Ring girder
  - End anchorage zone
  - Base slab
- Liner plate
  - Floor/wall junction
  - At hatch and locks
  - Hatch and locks (seals)
  - Penetrations

Containment Fragility for Overpressure Conditions (example)



Level-2 PRA Results

- Timing of significant events (e.g., core melt, vessel breach, containment failure) for the various accident progressions
- Conditional probabilities of containment failure and source terms
- Release of fission products to environment
  - Radionuclide quantities
  - Time history of release
  - Elevation and energy of release
- Significance of Level-1 sequences, systems, etc.
- Insights, vulnerabilities, improvement evaluation

Introduction to Source Terms

- The “Source Term” represents the magnitude, timing, and other characteristics an environmental release
  - Isotopic activities (Bq)
  - Timing of release
  - Chemical and physical forms
  - Thermal energy and initial height
- Chernobyl Example (very large accidental release)
  - Initial intense phase of release during core disruption
    - fragments of fuel, aerosol particles, gases, and vapors
    - high energy release lifted heated plume high into atmosphere
  - Release continued at lower level, with a secondary peak, for 10 days
  - Large release of more volatile elements
    - 50% of core inventory of I
    - 33% of core inventory of Cs and Te
  - 3.5% of low volatility elements released due to core debris oxidation
  - Ruthenium and molybdenum released in late phase probably because of oxidation to volatile forms

Characteristics Affecting Source Term

- Release path through RCS
- Containment failure modes:
  - Pre-existing leakage/isolation failure
  - Bypass with/without submergence
  - Early containment failure
  - Late failure
  - Late leakage (precludes rupture)
  - No failure (design leakage)
- Natural and engineered removal mechanisms
  - Suppression pool in BWR
  - Spray systems
  - Deposition in auxiliary building

Source-Term Release Categories

- Too many important sequences to perform the consequence analysis for each
- Only important and distinguishable combinations are characterized
- Similar sequences are grouped into release categories, e.g.
  - Potential for released activities to induce cancers
  - Potential for released activities to induce prompt fatalities
  - Release timing (compared with evacuation)

Factors Determining Importance of Radionuclides Released

- Total core inventory
  - Fission yields
  - Operating history
  - Half-lives
  - Decay products
- Physical and chemical properties
  - Nature of radioactivity (alpha, beta, gamma)
  - Volatility
- Atmospheric transport factors (e.g., deposition properties)
- Biological impact
  - Uptake
  - Biological half-life
  - Specific organ effects

Current Radionuclide Grouping

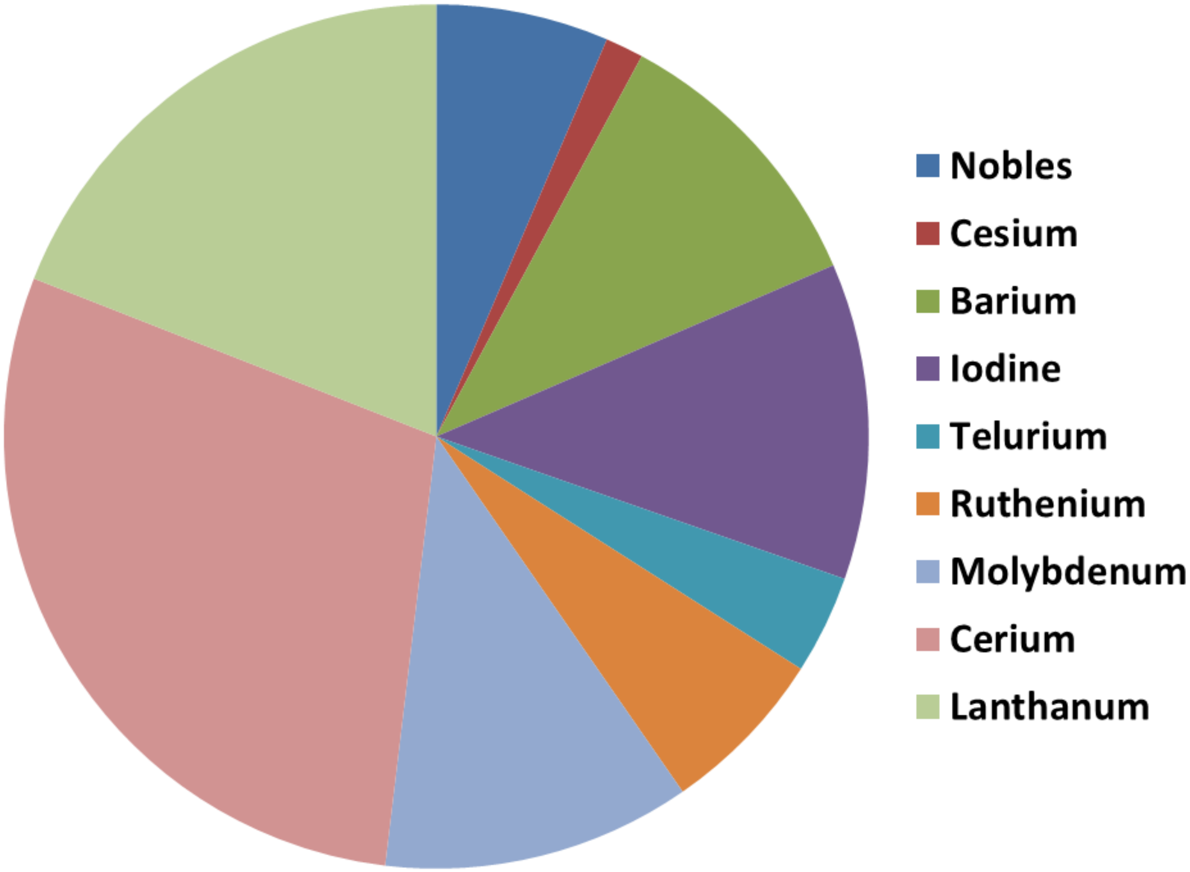
1. **Noble Gases (Kr, Xe)** - Do not interact chemically
2. **Alkali Metals (Cs, Rb)** – Reactive, volatile, form compounds with most other elements in fuel
3. **Alkaline Earths (Sr, Ba)** - Present as simple oxides (most stable), molybdates, and zirconates
4. **Halogens (I, Br)** - React immediately with several metals. CsI tends to dominate. There is 10 times more cesium formed than iodine in fission process.
5. **Chalcogens (Te, Se)** - Present in fuel in metallic form, alloys with zirconium, which may delay release
6. **Ruthenium (Ru, Rh)** - Form volatile oxides, strong tendency to form alloys
7. **Molybdenum (Mo, Tc, Nb, Co)** - Form volatile oxides, strong tendency to form alloys
8. **Rare Earths and Refractory Metals (Ce, Np, Pu, Zr)** – Very low volatility, form **dioxides**, account for significant portion of fission yield
9. **Rare Earths and Refractory Metals (La, Pr, Y, Nd, Cm, Am)** – Very low volatility, **valence of three**, account for significant portion of fission yield

Groups 8 and 9 account for almost 50% of initial core activity.

NUREG-1150 Classification (60 Isotopes in 9 Classes)

- Noble Gases: Kr-85, Kr-85m, Kr-87, Kr-88, Xe-133, Xe-135
- Iodine: I-131, I-132, I-133, I-134, I-135
- Cesium: Rb-86, Cs-134, Cs-136, Cs-137
- Tellurium: Sb-127, Sb-129, Te-127, Te-127m, Te-129, Te-129m, Te-131m, Te-132
- Strontium: Sr-89, Sr-90, Sr-91, Sr-92
- Ruthenium: Co-58, Co-60, Mo-99, Tc-99m, Ru-103, Ru-105, Ru-106, Rh-105
- Lanthanum: Y-90, Y-91, Y-92, Y-93, Zr-95, Zr-97, Nb-95, La-140, La-141, La-142, Pr-143, Nd-147, Am-241, Cm-242, Cm-244
- Cerium: Ce-141, Ce-143, Ce-144, Np-239, Pu-238, Pu-239, Pu-240, Pu-241
- Barium: Ba-139, Ba-140

Relative Activities at Shutdown (for SOARCA Sequoyah)



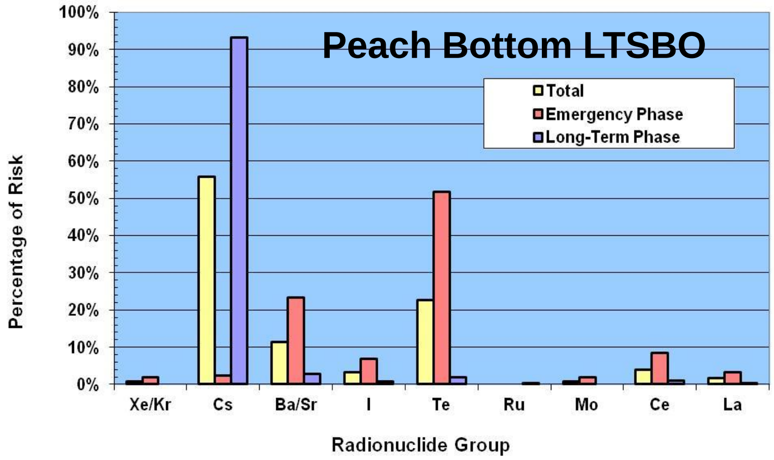
WASH-1400 First Day Doses at 0.5 Miles (Example to indicate important groups)

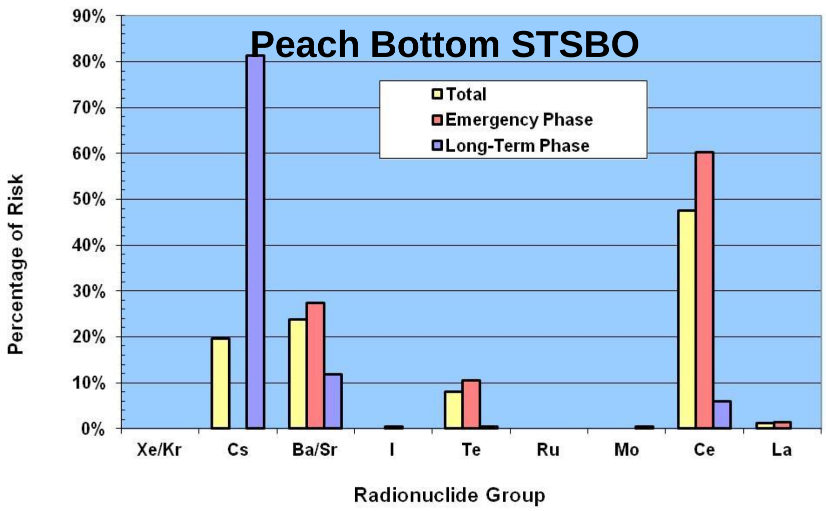
Radionuclide Group	Curies (3000 MWt)	Baseline Relative Dose[1]	Relative Dose with Indicated Attenuation	
			Fraction Released	Dose
Noble Gases[2]	3.4E+8	0.8	1.0	0.8
Iodines[3]	7.2E+8	54.8	0.1	5.5
Telluriums	1.8E+8	28.8	0.1	2.9
Cesiums	0.2E+8	1.0	0.1	0.1
Ceriums	3.7E+8	6.2	0.1	0.6
Rutheniums	2.1E+8	1.0	0.1	0.1
Others[4]	33.3E+8	7.4	0.1	0.7

1. Normalized to Cs.
2. The noble gases are not as important as their activity would suggest.
3. The iodines are the most important group even though their total activity is not the highest.
4. "Others" consist of mostly low volatility materials which do not get transported far.

SOARCA Results for Peach Bottom (BWR) Contribution to Latent Cancer Fatalities

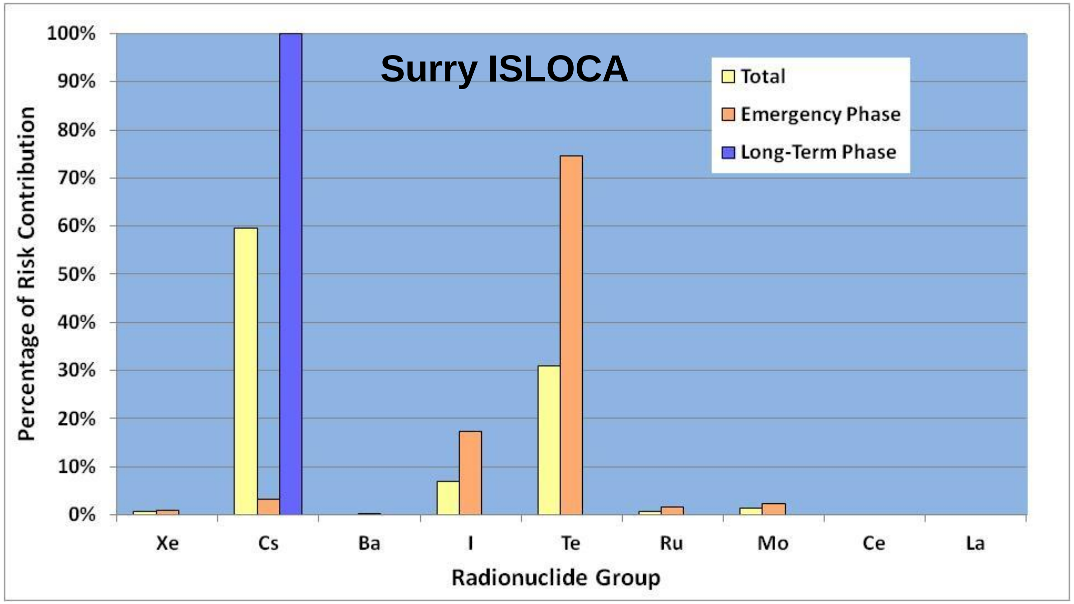
- Gamma radiation from the Cs group, primarily Cs-137, dominates long-term phase
- Emergency phase is dominated by combination of Te, Ce, and Ba/Sr
- Iodine is less important than expected when release is delayed
- Difference between the two sequences is largely from ex-vessel phase





SOARCA Results for Surry (PWR) Contribution to Latent Cancer Fatalities

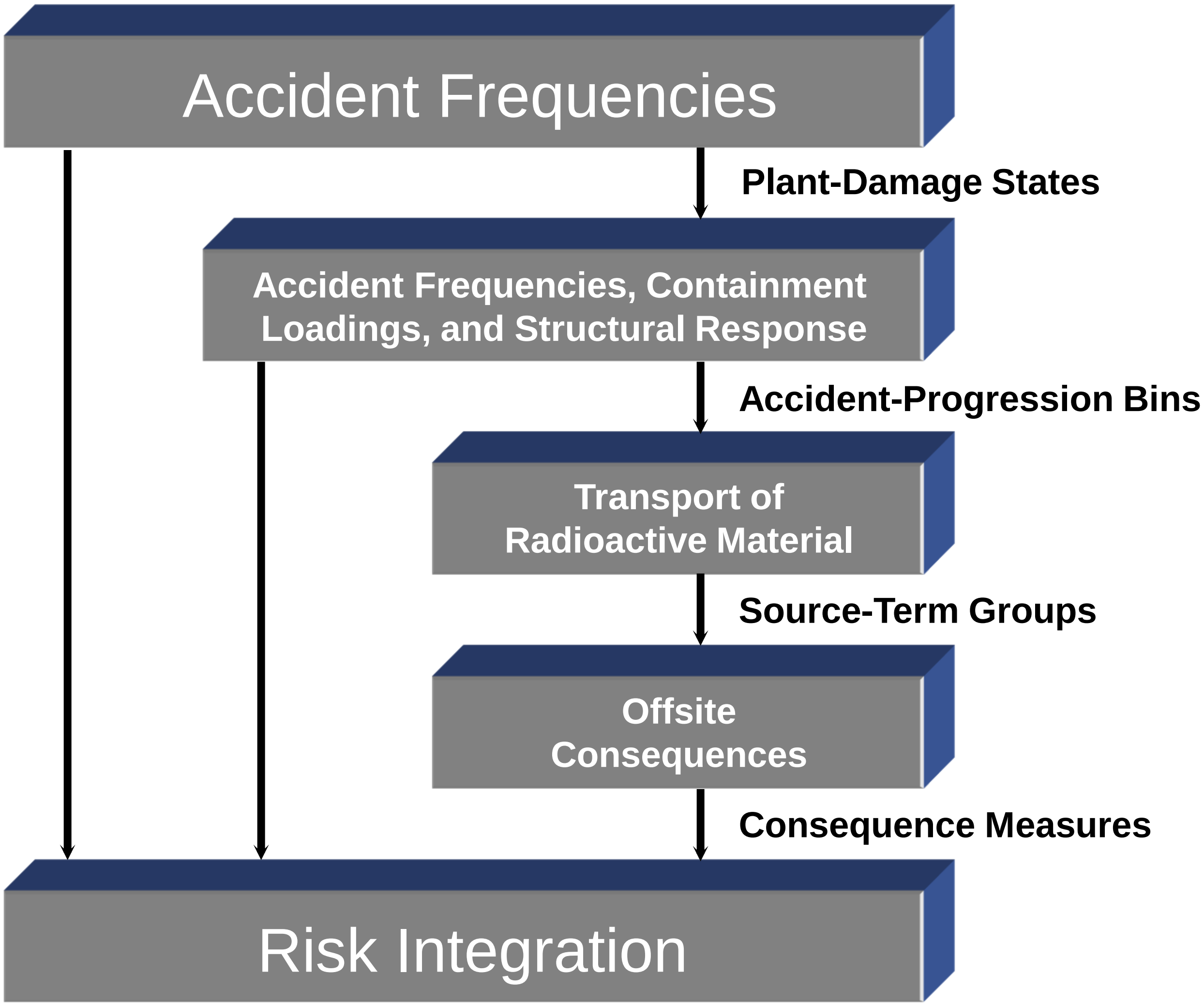
- Gamma radiation from the Cs group, primarily from Cs-137, dominates long-term phase
- Emergency phase is dominated by combination of Te and I
- Cs followed by Te are the major contributors to total



STRUCTURE OF THE NUREG-1150 ANALYSIS (Level-3 PRAs)

- Systems Analysis (Level 1)
  - Estimates Core-Damage Frequency (CDF)
  - SETS and TEMAC codes
- Accident-Progression Analysis (Part of Level 2)
  - Determines possible accident evolutions given core damage
  - EVNTRE code
- Source-Term Analysis (Part of Level 2)
  - Estimates environmental releases for specific accident conditions
  - XXSOR codes, using STCP and MELCOR data
- Consequence Analysis (Level 3)
  - Estimates health/economic impacts of the individual source terms
  - MACCS code using PARTITION to group source terms

NUREG-1150 Risk Analysis Process



NUREG-1150 PRAs are Characterized as Fully Integrated

- Both probability and outcome calculated through all levels of PRA
- Measures of uncertainty in risk are calculated by repeating risk calculations with different values for important parameters and using the distribution of risk estimates as a measure
- The calculations of each step are represented as a product of matrices

NUREG-1150 Accident-Progression Analysis (Level 2)

- Level-1 – Level-2 Interface
  - Plant-Damage States (PDSs) formed by grouping System Analysis minimal cut sets
  - The PDSs can be represented as a vector of frequencies for the PDS groups
- Accident-Progression Analysis
  - An accident-progression event tree (APT) is developed for each plant
  - Typically thousands of paths through the APT
- Accident-Progression Results
  - Grouped into Accident-Progression Bins (APBs)
  - Each bin is a group of paths through APT that define a similar set of conditions for source term analysis
- Accident-Progression Bin Frequencies
  - The accident-progression analysis results in the production of a transition matrix $P(PDS \rightarrow APB)$ such that

where is a vector of the frequencies of the APBs.

NUREG-1150 Source Term Analysis

- Source Term Analysis Interface
  - Input is descriptions of the the Accident-Progression Bins characteristics and their frequencies
- Source Term Analysis
  - Parametric models based on linear correlations of STCP/MELCOR calculations
  - Models contained in XXSOR codes (SURSOR, PBSOR, etc.)
  - Source term estimated for each APB
  - Source terms are grouped into <u>Source Term Groups (STGs)</u> where each group is a collection of source terms that define similar conditions for consequence analysis
  - Transition matrix representation is

where is vector of frequencies of APBs, and $P(APB \rightarrow STG)$ is the matrix of transition probabilities from APBs to STGs.

Generation of Source Terms from Surry NUREG-1150 Analyses

- Grouped into source term groups defined to have similar health effect impacts
- Grouping done with PARTITION code based on
  - Early health effects (equivalent ^{131}I release)
  - Chronic health effect (linear effect between release of each radionuclide released and cancer fatalities as calculated by MACCS for a fixed release fraction)
  - Release timing
- Grouped into 17 groups and further into 51 subgroups using three evacuation time bands
- Example Surry Group Source Terms
  - SUR-14 (dominant risk) mostly SGTRs
  - SUR-10 (largest consequences) mostly Event V
  - SUR-16 (most frequent) no bypass and no early containment failure

Example Surry Source Term Groups

SOURCE TERM		RELEASE FRACTIONS				
		NG	I	Cs	Te	La
SUR-14	"Puff Release"	.93	.49	.44	.17	2.5E-4
	Continuous Release	.041	.027	.019	.007	1.2E-5
SUR-10	"Puff Release"	.99	.70	.65	.22	1.8E-3
	Continuous Release	.005	.01	.003	.13	5.1E-4
SUR-16	"Puff Release"	.0015	1.4E-8	1.8E-9	7.1E-9	4.7E-11
	Continuous Release	.016	1.9E-4	3.5E-8	2.5E-8	6.4E-10

SOURCE TERM		FREQ/YR	ENERGY (W)	START (s)	DURATION (s)
SUR-14	"Puff Release"	1.1E-7	1.0E+6	5.1E+4	1.4E+3
	Continuous Release		2.1E+2	5.4E+4	1.7E+4
SUR-10	"Puff Release"	4.9E-8	3.5E+6	6.0E+6	1.9E+3
	Continuous Release		1.6E+5	4.0E+4	4.9E+4
SUR-16	"Puff Release"	1.9E-5	1.8E+3	4.7E+4	3.1E+0
	Continuous Release		8.4E+1	4.8E+4	8.5E+4

NUREG-1150 CONSEQUENCE ANALYSIS

- Consequence Analysis Interface
  - Input is the source term description in MACCS terms of each Source-Term Group (STG)
- Consequence Analysis
  - Analysis is performed with MACCS for each STG to produce various consequence measures
  - Results include estimates for mean consequences and distributions of consequences
- Risk Measures
  - The mean consequence results can be combined with the source-term group frequencies to produce overall measures of risk

where is a vector of risk measures, and

$P(STG \rightarrow C)$ is a matrix of conditional consequence measures that result from a STG. They are given as means over the weather.

- Overall Matrix Representation of Risk

OFFSITE CONSEQUENCE RISK

$$rC_m = \sum_{j=1}^{nPDS} \sum_{k=1}^{nAPB} \sum_{l=1}^{nSTG} fPDS_j \, pAPB_{jk} \, pSTG_{kl} \, cSTG_{lm}$$

where

rC_m = annual risk (per year) for consequence measure m (e.g. early fatalities),

$fPDS_j$ = frequency (per year) of plant damage state j,

$pAPB_{jk}$ = conditional probability that PDS_j will result in APB_k,

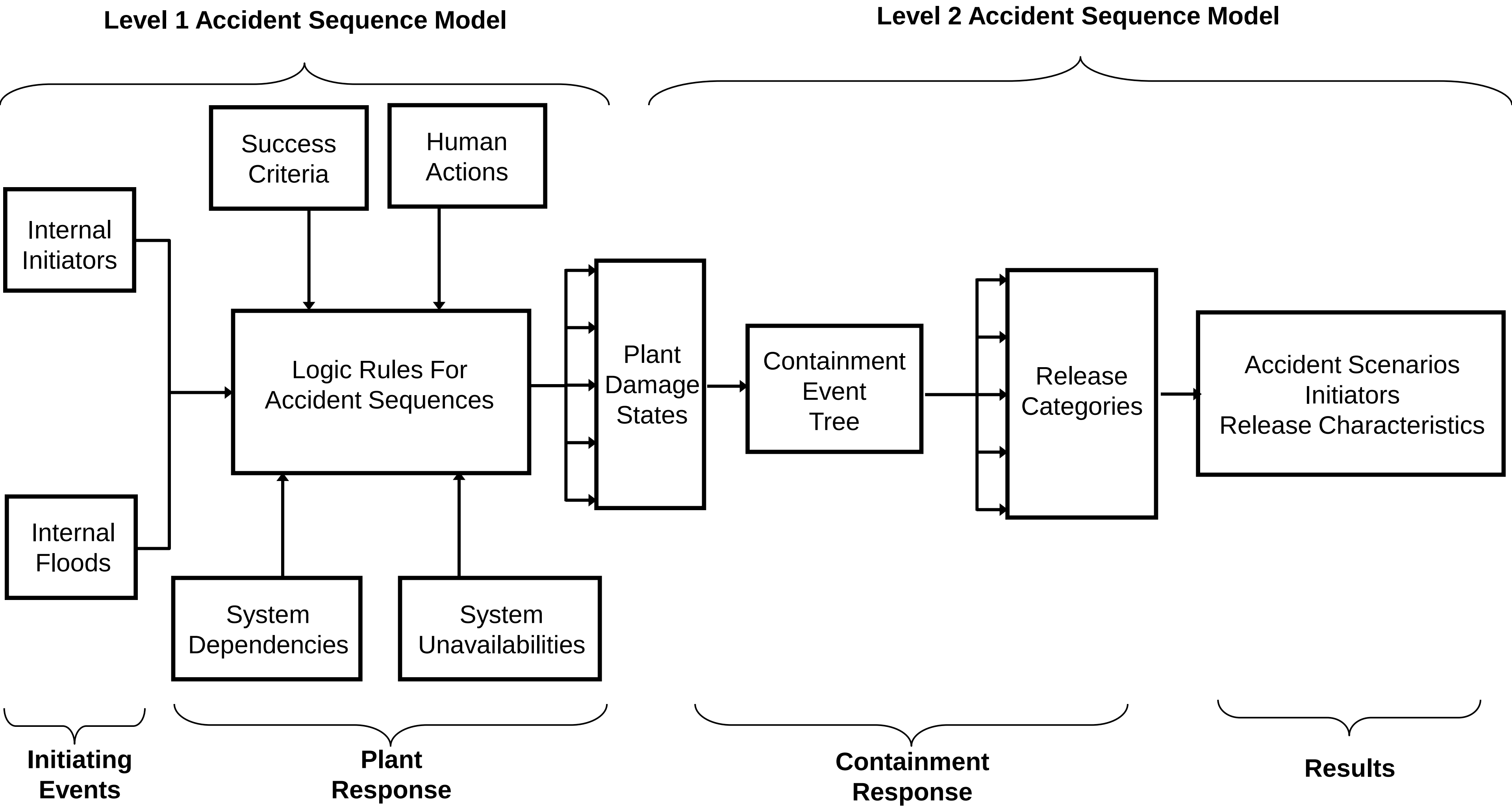
$pSTG_{kl}$ = conditional probability that APB_k will be assigned to STG_l,

$cSTG_{lm}$ = mean (over weather variability) for consequence measure m conditional on the occurrence of STG_l

Individual Plant Examinations (IPEs)

- The next step (after NUREG-1150) in the PRA methodology
- NRC issued a request (Generic Letter 88-20) that all operating NPPs systematically examine their plants for any plant-specific vulnerabilities. (November, 1988)
- The IPE would serve the following purposes:
  - Develop an appreciation of severe accident behavior
  - Understand the most likely severe accident sequences
  - Gain a more quantitative understanding of the overall probabilities of core damage and fission-product releases
  - If necessary, reduce the overall probabilities of core damage and fission-product releases by modifying (where appropriate) hardware and procedures to help mitigate severe accidents

IPE Risk Model



Comparison of NUREG-1150 & IPE Methodologies

- Both start with large numbers of potential accident sequences and reduce those of interest by:
  - Determining which plant challenges are the most likely to occur
  - Determining if those that are likely to occur have a high probability of mitigation
  - The reduction results in ~ a few dozen PDSs of interest
- The PDSs carry the important information from Level 1 to Level 2:
  - Primary pressure at time of core damage
  - Status/potential for containment heat removal
- Differences include:
  - IPEs are a much higher level (source term info etc.)
  - IPEs do NOT consider consequence analysis

What Is SOARCA?

- SOARCA was initiated to develop a body of knowledge on the realistic outcomes of severe reactor accidents
- Plants examined in pilot study:

Peach Bottom

Surry

- Analysis of Sequoyah is nearly finished

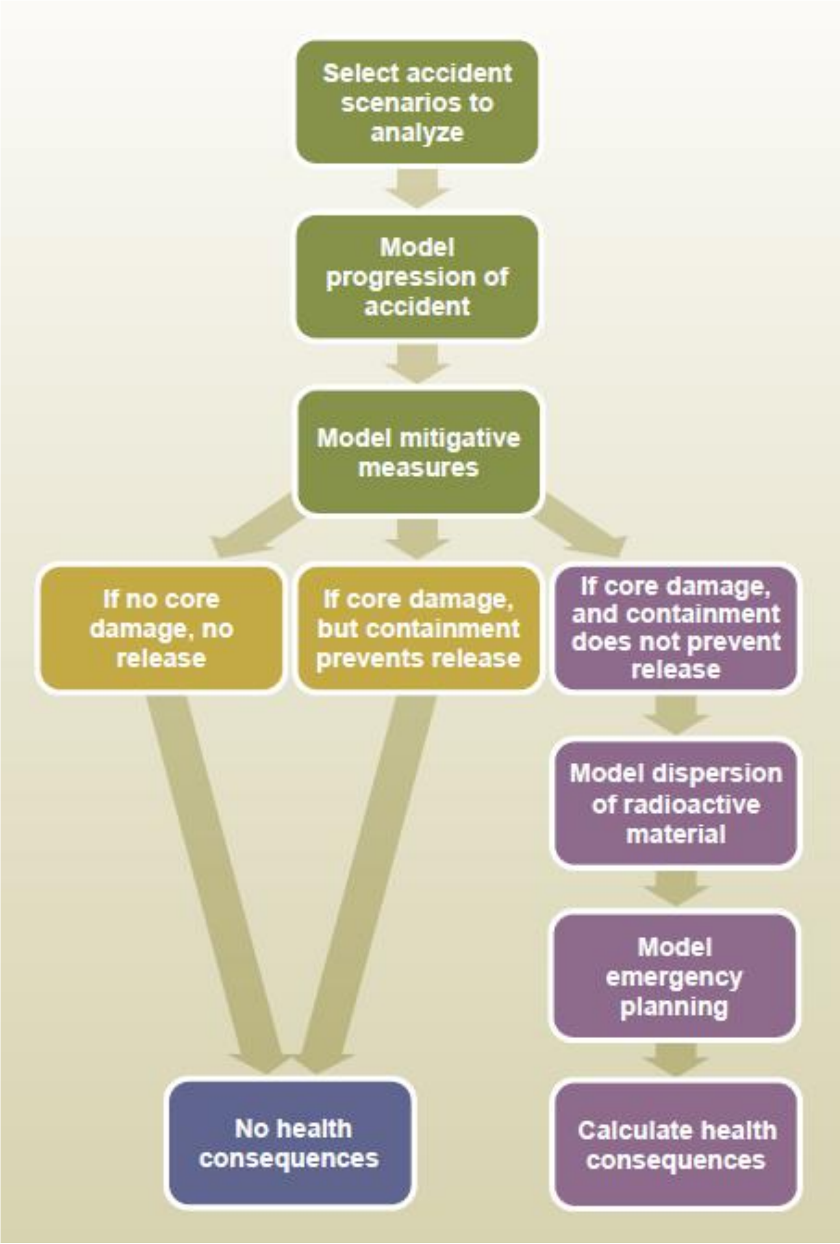
Why Was SOARCA Done?

- Update the quantification of offsite consequences accounting for
  - Plant changes not reflected in earlier assessments
  - Security-related improvements
  - State-of-the-art modeling (MELCOR/MACCS)
- Enable the NRC to communicate severe accident aspects of nuclear safety

How Is SOARCA Different?

- Focus on important severe accident scenarios
- Realistic assessments and detailed analyses
- Integrated analyses
- Incorporated recent physical experiments
- Treatment of seismic impacts on evacuation
- Range of health effects modeling

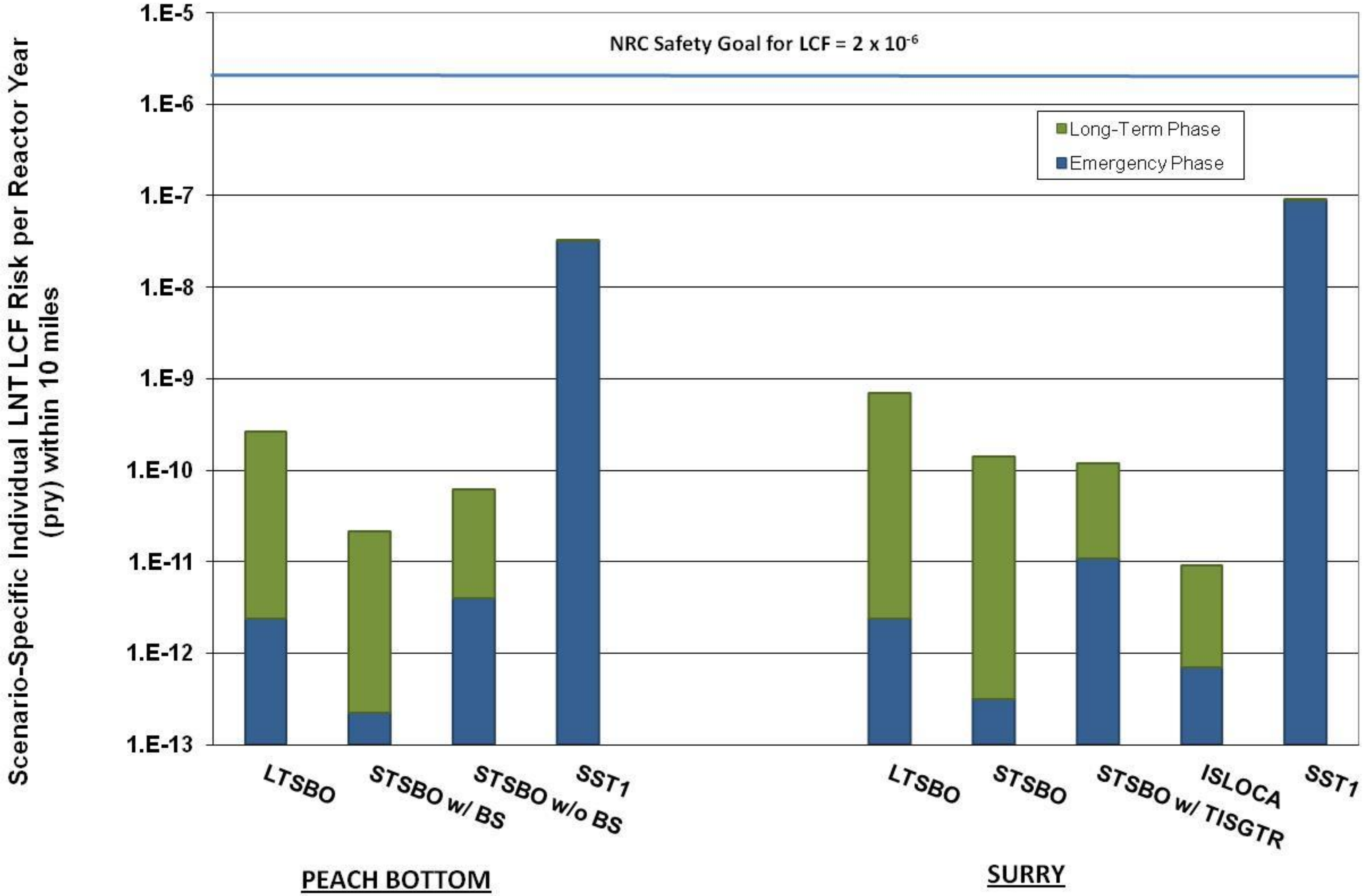
How Did We Do SOARCA?



What Scenarios Were Analyzed?

Reactor Site	Accident Scenario	Description
Peach Bottom, Surry	Long-Term Station Blackout	Seismic event; loss of AC power; batteries available initially
Peach Bottom, Surry	Short-Term Station Blackout	Seismic event; loss of AC power; batteries unavailable
Surry	Short-Term Station Blackout with Thermally Induced Steam Generator Tube Rupture	Variation of STSBO. A steam generator tube ruptures resulting in a pathway for radioactive material to potentially escape
Surry	Interfacing Systems Loss-of-Coolant Accident	A random failure of valves ruptures low-pressure system piping outside containment

SOARCA Results



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- E. D. Gorham, et al., “Evaluation of Severe Accident Risks: Methodology for the Containment, Source Term, Consequence, and Risk Integration Analyses,” NUREG/CR-4551, Vol.. 1, Rev. 1, Dec. 1993.
- Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants, NUREG/CR-1150
- State-of-the-Art Reactor Consequence Analysis (SOARCA) Report, NUREG-1935
- Sandia National Laboratories, “State-of-the-Art Reactor Consequence Analysis Project, Vol. 1: Peach Bottom Integrated Analysis,” NUREG/CR-7110
- Sandia National Laboratories, “State-of-the-Art Reactor Consequence Analysis Project, Vol. 2: Surry Integrated Analysis,” NUREG/CR-7110

4. MACCS Overview

Objectives

- **Develop a basic understanding of**
  - **Atmospheric radioactive transport and related potential for exposure**
  - **Dose pathways**
  - **Phases of an accident**
  - **Preprocessor codes in MACCS suite**
  - **Code structure and applicability**
  - **Code outputs**

Basic Concepts I

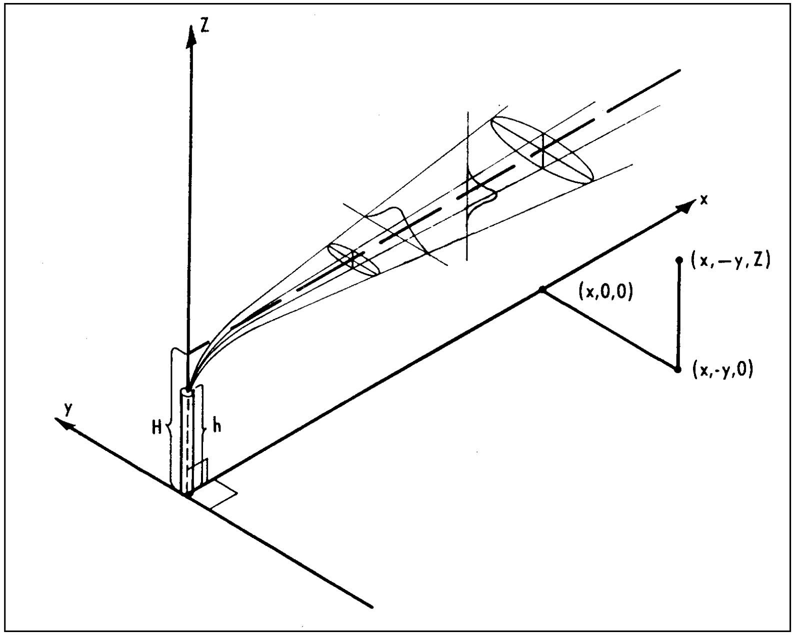
- **Source term**
  - **Defines the magnitude and timing of release of radionuclides**
  - **Characterized by the following parameters**
    - **Initial time of release**
    - **Release rate as a function of time (by radionuclide)**
    - **Initial height**
    - **Buoyancy (heat content)**
    - **Aerosol size distribution (by radionuclide)**
    - **Chemical composition**
  - **Hypothetically occurs at some indeterminate future time**
    - **Implies weather conditions are unknown at time of release**
    - **Suggests need to treat uncertainty in weather conditions**

Basic Concepts II

- **Atmospheric transport and dispersion (ATD)**
  - **Describes how released material moves through the atmosphere**
  - **Governed by the following mechanisms**
    - **Buoyancy (tendency to rise because of lower density)**
    - **Advection (material moves downwind at the mean speed of the wind)**
    - **Dispersion (stochastic motion from diffusion and turbulence)**
    - **Aerosol deposition onto the ground or other surfaces**
    - **Washout by falling rain drops**
    - **Agglomeration (coalescence of aerosol particles to form larger ones)**

Basic Concepts III

- **Gaussian plume**
  - **Very good approximation to a steady, point source in a steady, plug flow**
  - **Approximate solution for a turbulent, nonuniform flow**
  - **Model neglects the following phenomena**
    - **Irregular terrain**
    - **Spatial variations in wind field**
    - **Temporal variations in wind direction**



Basic Concepts IV

- **Dose pathways include**
  - **Direct exposure pathways**
    - **Inhalation from plume**
    - **Cloudshine (mainly gamma radiation from plume)**
    - **Groundshine (mainly gamma radiation from deposited material)**
    - **Deposition onto skin**
  - **Indirect exposure pathways**
    - **Ingestion of food and water**
    - **Inhalation of resuspended aerosols**

Basic Concepts V

- Dose pathways include
  - External pathways
    - Cloudshine
    - Groundshine
    - Deposition onto skin
  - Internal pathways
    - Inhalation (direct and resuspension)
    - Ingestion
- External doses are concurrent with exposure period
- Internal doses continue after exposure period

Basic Concepts VI

- **Activity**
  - **Measures disintegrations per unit time**
  - **Units are becquerel (Bq) or curie (Ci)**
  - **1 Ci = activity of 1 g of Ra-226 = $3.7 \cdot 10^{10}$ Bq**
  - **1 Bq = 1 decay/s**
- **Absorbed dose or total ionizing dose**
  - **Energy deposited per unit mass**
  - **Units are Gray (Gy) or rad**
  - **1 Gy = 1 J/kg = 100 rad**
- **Equivalent dose**
  - **Measurement of biological effect**
  - **Absorbed dose times a radiation weighting factor**
    - **1 for photons, electrons, and muons (low LET)**
    - **20 for alpha particles**
  - **Units are Sievert (Sv) or rem**
  - **1 Sv = 100 rem**

Basic Concepts VII

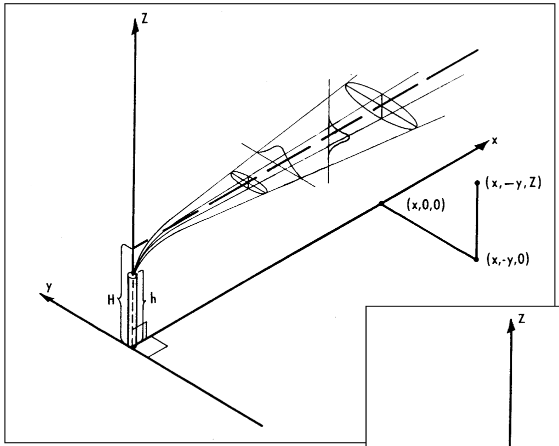
- **Types of dose**
  - **Absorbed dose – energy deposited in a specific organ (Gy)**
  - **Equivalent dose or dose equivalent – biological effect of dose to a specific organ (Sv)**
  - **Effective dose – weighted average of doses to a set of organs (represents entire body)**
  - **Committed dose – time integral (usually over 50-yr period) of internal dose**
- **Acronyms**
  - **CEDE – Committed effective dose equivalent (internal)**
  - **TEDE – Total effective dose equivalent (internal + external)**

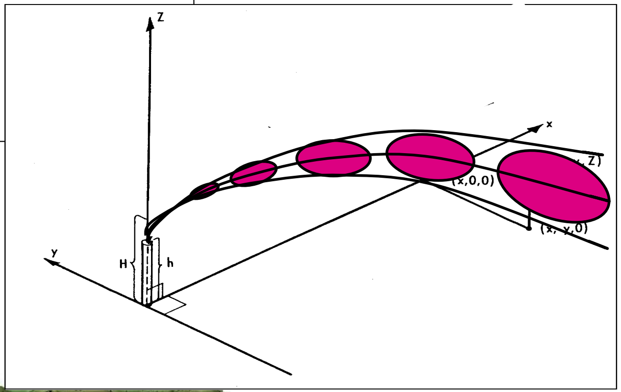
Basic Concepts VIII

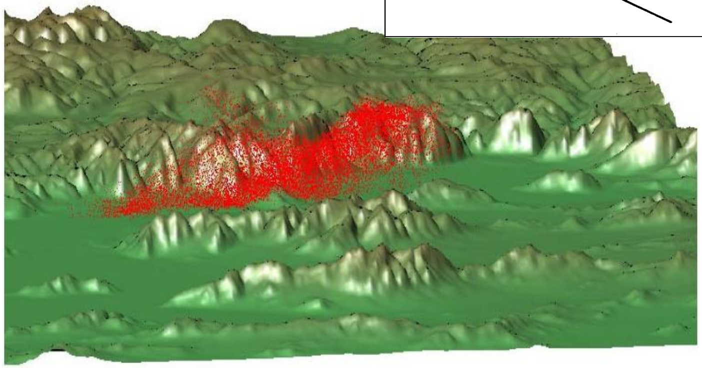
- **Dose conversion factors (dose coefficients in newer ICRP documents) are used to calculate doses from exposures**
  - **Exposure is a measure of the rate times the duration to which a receptor is exposed for each**
    - **Radionuclide**
    - **Pathway**
    - **Organ**
  - **Exposures are expressed in terms of intake (Bq) or time-integrated surface or airborne concentrations (Bq-s/m^2 or Bq-s/m^3)**
  - **Exposure values are multiplied by dose conversion factors (DCFs) to calculate doses (Sv or rem)**
- **Cancer risk factors are used to calculate health effects from doses**

Basic Concepts IX

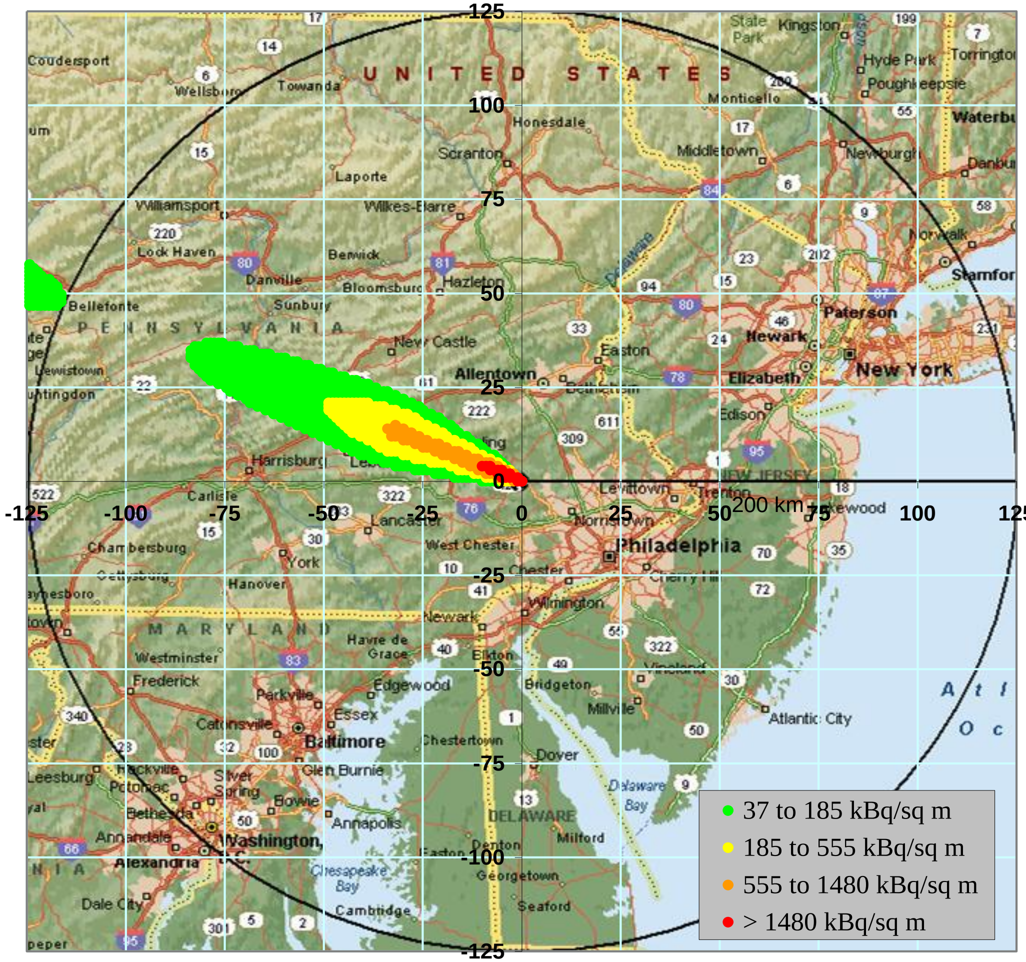
- Types of ATD models
  - Gaussian plume (MACCS)
    - One-dimensional wind field (x)
    - Empirical dispersion model in two dimensions
    - Very fast (seconds to minutes)
  - Gaussian puff (RASCAL)
    - Two- or three-dimensional wind field (x, y) or (x, y, z)
    - Empirical dispersion model in three dimensions
    - Intermediate speed (minutes to hours)
  - State-of-the-art models (LODI from NARAC)
    - Three-dimensional wind field (x, y, z)
    - Monte-Carlo particle tracking model
    - Slow (hours to days)



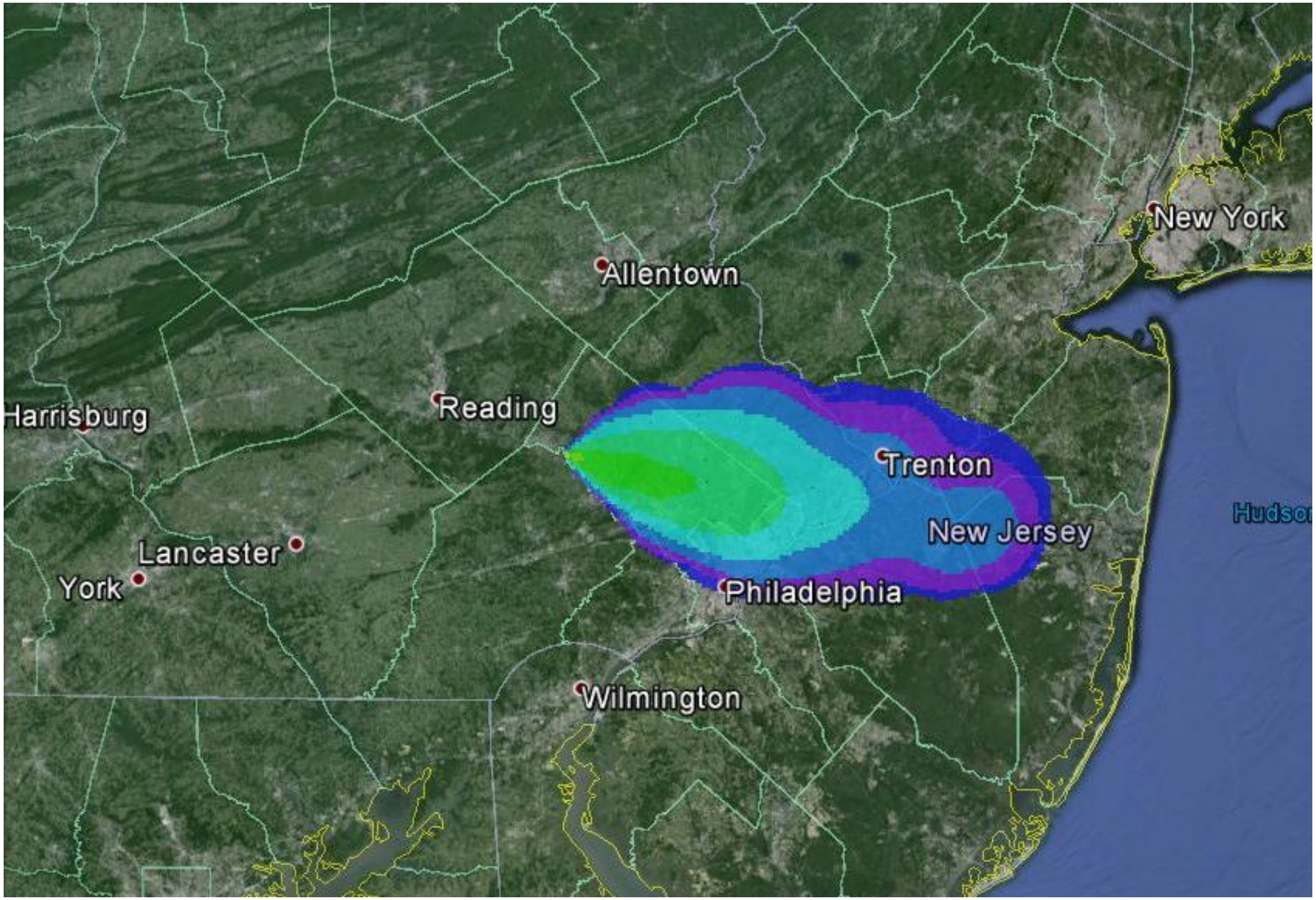




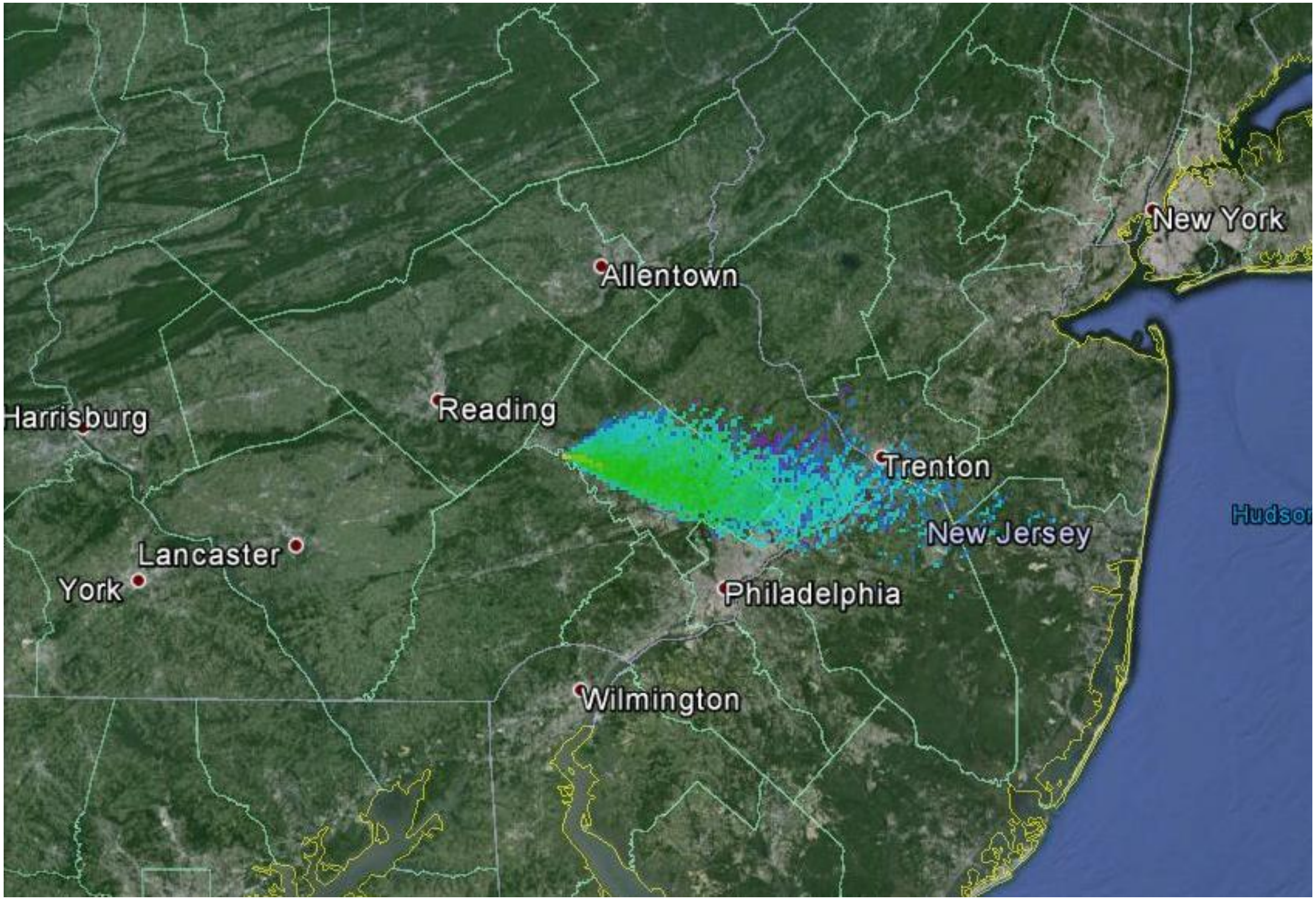
Deposition Under a Gaussian Plume (MACCS)



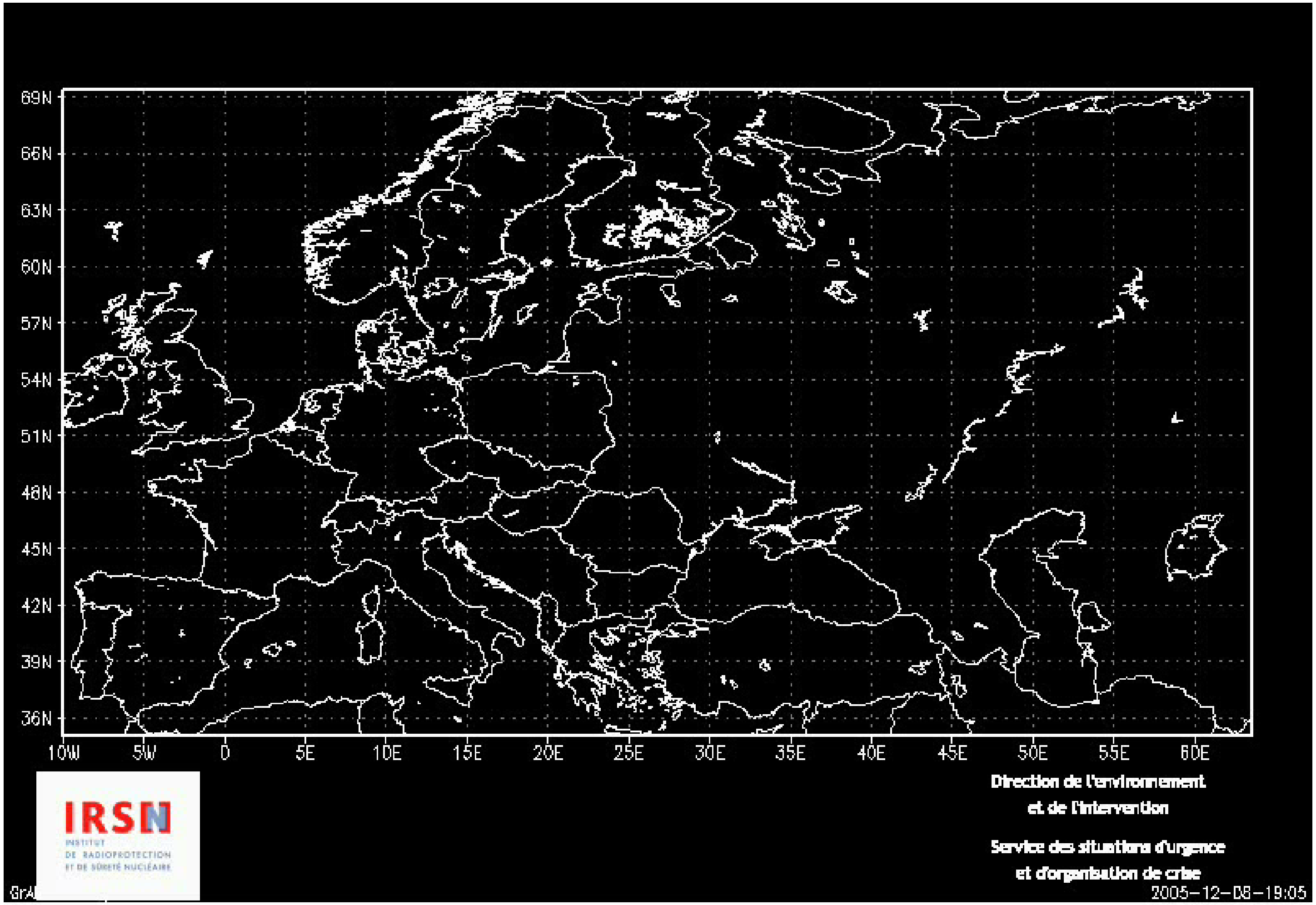
12-hr Averaged Air Concentration Using a Gaussian Puff Model (HYSPLIT)



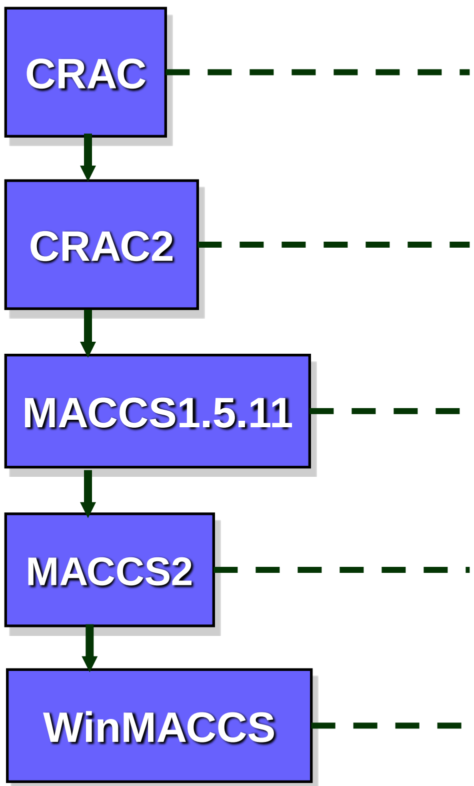
12-hr Averaged Air Concentration Using a Lagrangian Particle Tracking Model (HYSPLIT)



Simulation of Chernobyl Accident



Evolution of NRC Consequence Tools



1975: WASH-1400 (Reactor Safety Study)

1983: Early PRAs, Sandia Siting Study

1990: NUREG-1150 and LaSalle PRAs

1998: Improvements in dose conversion data base, decay chains, emergency response model, and food pathway model

2002-2005: Security studies for 6 nuclear power plants

2005-2007: Protective Action Recommendation Study

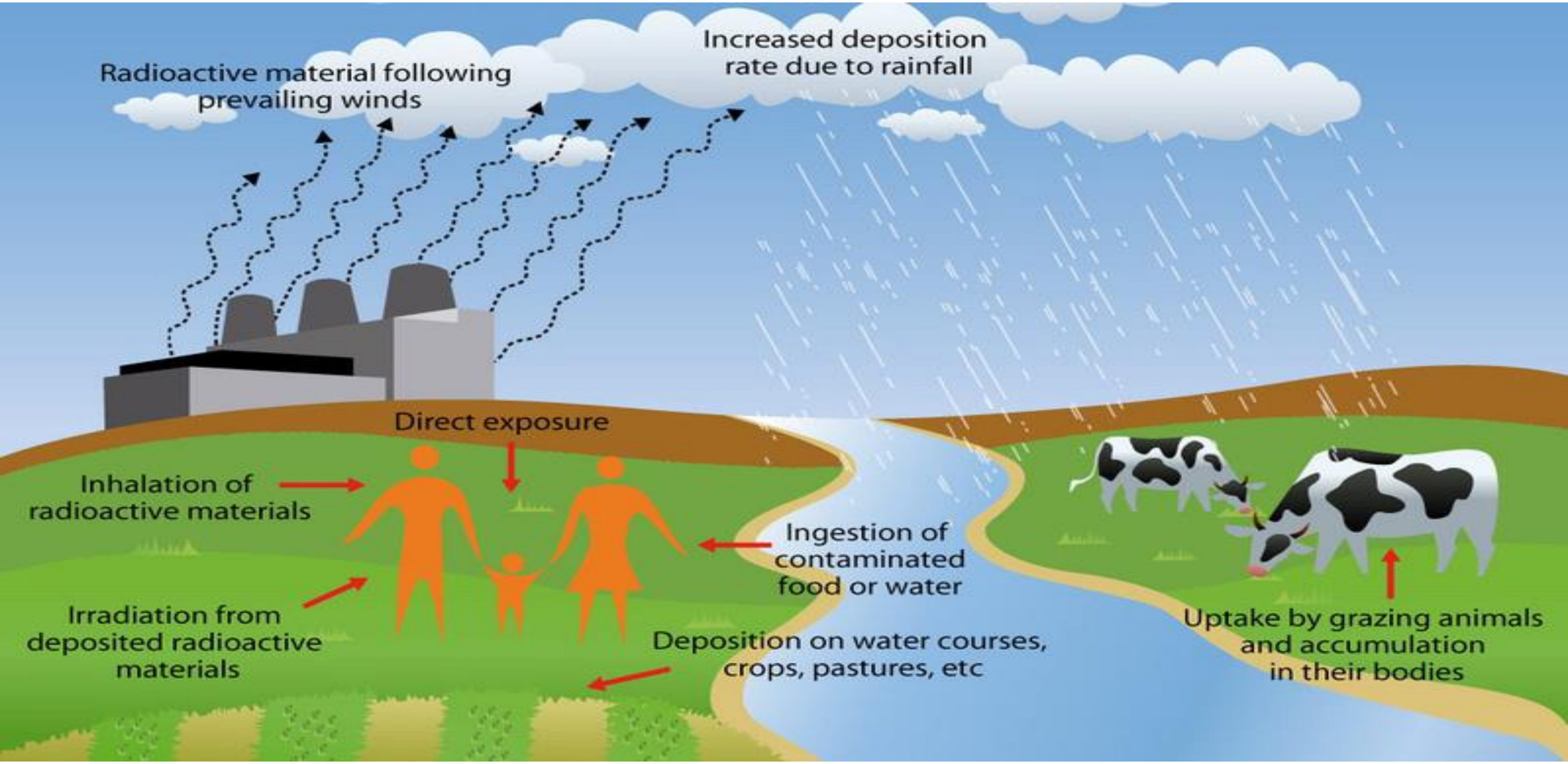
2006-2012: State of the Art Reactor Consequence Analysis

2011-2013: Spent Fuel Pool Scoping Study

2012-2014: SOARCA Uncertainty Analysis

2012-2014: Filtered Vent Study

Pathways to Receptors From Atmospheric Release



MACCS Estimates Consequences of Airborne Radioactive Releases

- **Consequences considered by MACCS (MELCOR Accident Consequence Code System)**
  - **Doses**
  - **Health effects**
  - **Land contamination**
  - **Economic impacts**
- **Consequences altered by mitigative actions including**
  - **Sheltering, evacuation, and relocation**
  - **Decontamination, interdiction, and condemnation**

Key Features of MACCS

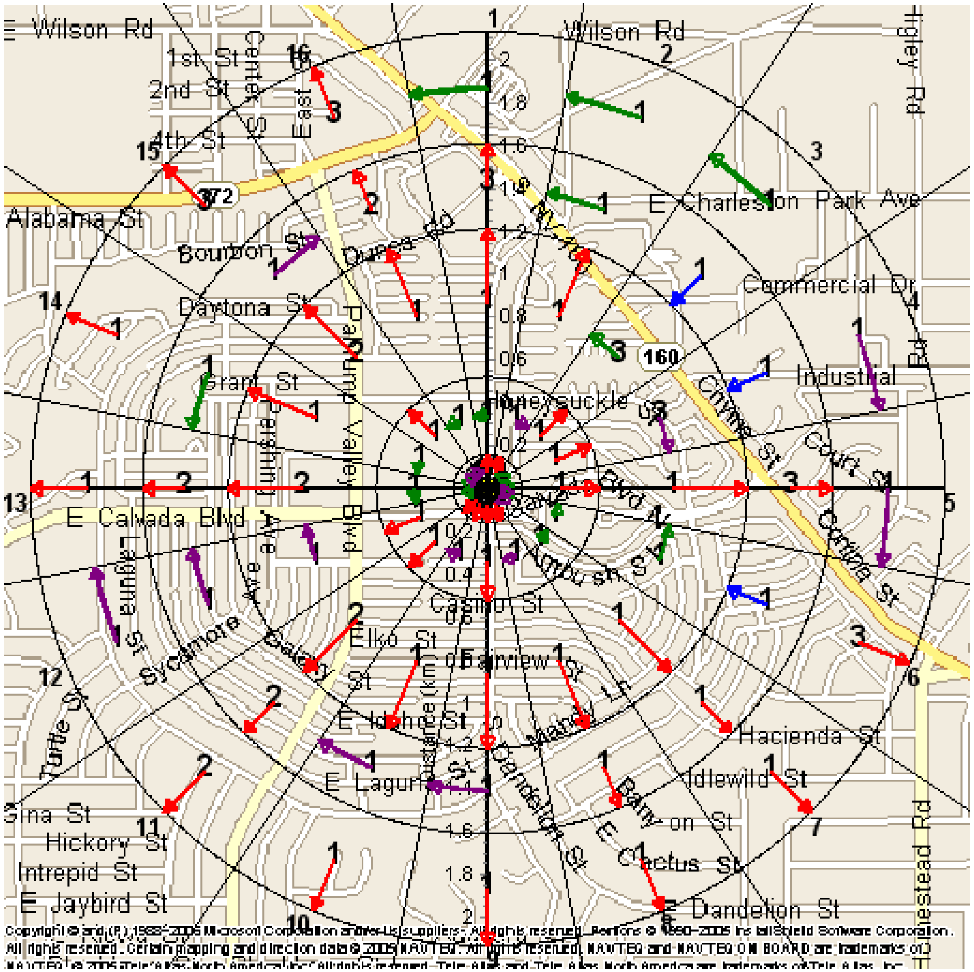
- **Polar coordinate spatial discretization**
  - **Up to 35 radii**
  - **16, 32, 48, or 64 compass directions**
- **Phases consistent with existing EPA protective action guides (PAGs)**
- **Architecture allows user to invoke the following modules as needed (to determine results of interest)**
  - **ATMOS – atmospheric transport and dispersion**
  - **EARLY – emergency-phase response and consequences**
  - **CHRONC – intermediate and long-term consequences**

Atmospheric Dispersion Approximated with Gaussian Plume Model

- Contaminants assumed to disperse producing normal distributions in the vertical and cross-wind directions
- Dispersion rate increases with atmospheric turbulence
- Downwind distribution (x-axis) ignored because associated turbulence small compared to mean wind speed
- Horizontal (y-axis) and vertical (z-axis) dispersion
  - Defined by standard deviations (σ_y and σ_z) of normal distributions
  - Functions of atmospheric stability (related to turbulence)
  - Increase with downwind distance
  - Differ because of temperature gradients in atmosphere

Spatial Division Based on Compass Sectors

- Illustration shows 16 22.5º-sectors numbered clockwise from north
- Origin is at point of release
- Up to 64 compass directions
- Up to 35 radial endpoints
- Allowable radial range from 50 m to 9999 km



First Phase

- **Emergency phase**
  - **1 to 40 days (typically 7 days)**
  - **Dose pathways**
    - **Direct inhalation**
    - **Cloudshine**
    - **Groundshine**
    - **Resuspension inhalation**
    - **Deposition onto skin**
  - **Possible mitigative actions**
    - **Sheltering**
    - **Evacuation**
    - **Relocation**

Second Phase

- **Intermediate phase**
  - **After end of emergency phase up to 1 year**
  - **Dose pathways**
    - **Groundshine**
    - **Resuspension inhalation**
    - **Ingestion of contaminated food/water not considered**
  - **Mitigative actions limited to relocation**

Third Phase

- **Long-term phase**
  - **After end of intermediate phase up to 317 years**
  - **Dose pathways**
    - **Groundshine**
    - **Resuspension inhalation**
    - **Ingestion of contaminated food and water**
  - **Possible mitigative actions**
    - **Decontamination**
    - **Interdiction (implies relocation)**
    - **Condemnation**
  - **Mitigative actions are based on “habitability” and “farmability” criteria with “habitability” decisions taking precedence**

ATMOS Module
ATD Models I

- **ATMOS module required**
- **ATMOS calculates**
  - **Radioactive decay and ingrowth**
    (limited to 150 radionuclides in a maximum of 6 generations)
  - **Effects of building wake**
    (MACCS not recommended within 0.5 km of release location)
  - **Buoyant plume rise**
  - **Dry deposition**
    (user supplied velocities for up to 20 particle-size groups)
  - **Wet deposition**
    (all deposited nuclides subject to one set of user-supplied factors)
  - **Atmospheric dispersion**

ATMOS Module
ATD Models II

- **Atmospheric dispersion can be calculated for multiple plume segments (i.e., up to 500)**
- **Dispersion based on**
  - **Gaussian plume segment model (with provisions for meander and surface roughness effects)**
  - **Plume sensible heat content**
  - **Plume release duration**
  - **Plume release height**
  - **Meteorological conditions**

ATMOS Module
ATD Models III

- **Meteorological conditions needed include wind direction and speed, Pasquill stability category, precipitation rate, and seasonal mixing layer heights**
- **User selectable meteorology sampling options include**
  - **Single weather sequences**
    - **Constant meteorological conditions**
    - **120 h of user supplied meteorological data**
    - **Fixed start time from a meteorological data file**
  - **Multiple weather sequences**
    - **Stratified random sampling (user sets number of samples randomly selected from each day)**
    - **Weather bin sampling (user selects number of samples randomly selected from each bin)**

ATMOS Module Contains Basic Phenomenological Modeling (cont.)

- Weather bin sampling categories include:
  - 16 predefined bins based on initial wind speed and stability
  - 12 to 24 additional bins based on user specifications for
    - Rain intensity breakpoints (either 2 or 3 allowed)
    - Rain distance intervals (from 4 to 6 allowed)

METBIN	STABILITY	WIND SPEED - u (m/s)
1	A/B	$0 < u \leq 3$
2	A/B	$3 < u$
3	C/D	$0 < u \leq 1$
4	C/D	$1 < u \leq 2$
5	C/D	$2 < u \leq 3$
6	C/D	$3 < u \leq 5$
7	C/D	$5 < u \leq 7$
8	C/D	$7 < u$
9	E	$0 < u \leq 1$
10	E	$1 < u \leq 2$
11	E	$2 < u \leq 3$
12	E	$3 < u$
13	F	$0 < u \leq 1$
14	F	$1 < u \leq 2$
15	F	$2 < u \leq 3$
16	F	$3 < u$

EARLY Module
Emergency Phase I

- **EARLY module is optional**
- **EARLY calculates emergency phase**
  - **Acute and lifetime doses (pathway, organ, and nuclide specific)**
    - **Inhalation (direct and resuspension)**
    - **Cloudshine**
    - **Groundshine**
    - **Skin deposition**
  - **Associated health effects**
    - **Early injuries/fatalities from acute doses**
    - **Cancers/latent health effects from lifetime doses**
- **Calculations subject to effects of user specified**
  - **Sheltering, evacuation, and dose-dependent relocation**
  - **Shielding (dose scaling for sheltering, evacuation, and normal activity)**

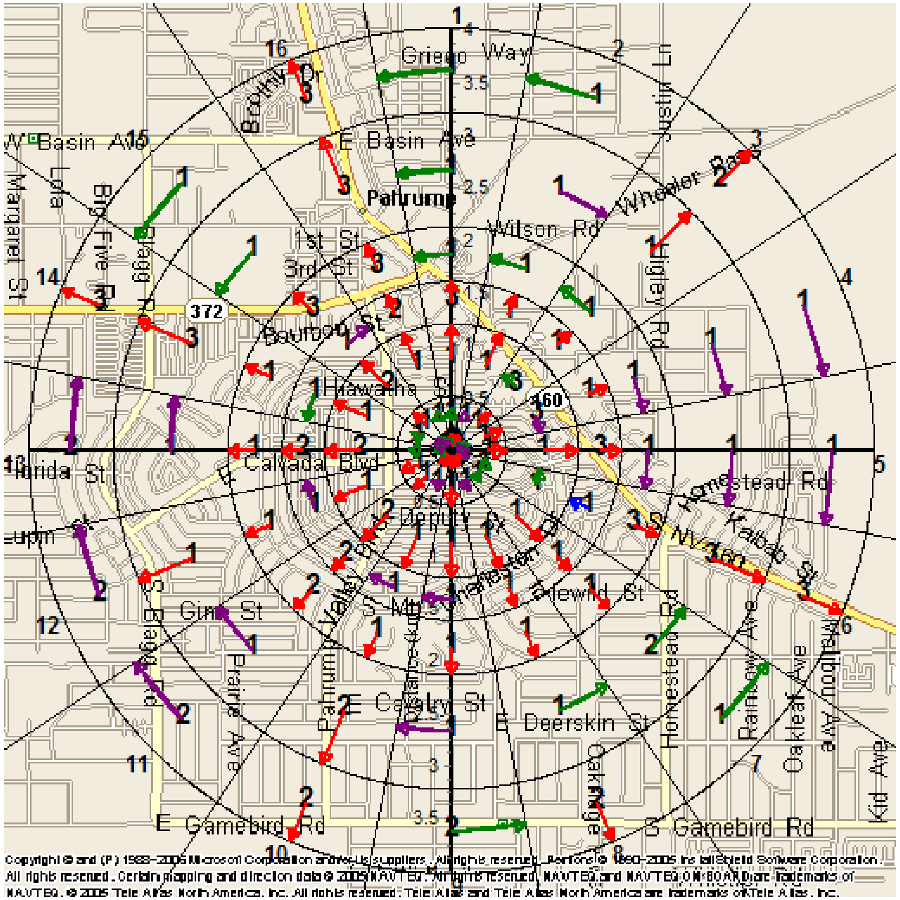
EARLY Module
Emergency Phase II

- Dose-dependent relocation
  - Applies to all non-evacuees
  - Based on user-specified dose criteria
- Sheltering/evacuation mitigative actions
  - Circular region (surrounding release point)
  - Sheltering period (0 is allowed) always precedes evacuation
  - Evacuation speeds can vary by
    - Subphase: early, middle, and late portion of emergency phase
    - Grid element, to reflect road type and congestion
    - During adverse weather
  - Radial and network evacuation schemes allowed

Network Evacuation Approximates Complex Transportation Routes

Valid evacuation networks:

- ✓ **Cannot move through origin of coordinate system**
- ✓ **Have at least one outbound path (leaving the grid)**
- ✓ **Do not have infinite loops (closed paths)**



CHRONC Module
Intermediate and Long-Term Phases I

- **CHRONC module is optional**
- **CHRONC calculates**
  - **Lifetime doses (pathway, organ, and nuclide specific)**
    - **Groundshine**
    - **Resuspension inhalation**
    - **Ingestion of contaminated food and water (long-term phase)**
  - **Associated health effects (cancers/latent fatalities)**
  - **Costs associated with mitigative actions from all phases**

CHRONC Module
Intermediate- and Long-Term Phases II

- **CHRONC calculations subject to effects of user specified**
  - **Dose-dependent relocation during intermediate phase**
  - **Decontamination/interdiction/condemnation during long-term phase**
- **Decontamination accounts for**
  - **Scaling factor for reduction of contamination**
  - **Effects of decay and weathering**
  - **Up to 1-year to perform decontamination**
- **Decay and weathering continue during interdiction**
  - **Up to 8 years for farmland**
  - **Up to 30 years for residential regions**

CHRONC Module
Intermediate- and Long-Term Phases III

- **Condemnation invoked if**
  - **Dose criteria cannot be achieved by decontamination/interdiction**
  - **Costs exceed value of property**
- **Economic costs include**
  - **Food, lodging, lost income associated with evacuation/relocation (early and intermediate phases)**
  - **One-time moving expense (long-term phase)**
  - **Losses associated with crop/property destruction**
  - **Decontamination labor and materials**
  - **Loss of building/land use and any corresponding depreciation associated with decontamination/interdiction**
  - **Value of condemned land and improvements**

Preprocessors Provide Flexibility

- **Preprocessors assist with compilation of input files for**
  - **Source-term data (MelMACCS)**
  - **Site data (SecPop)**
  - **Food-chain data (COMIDA2)**
- **Source-term data needed by ATMOS (user can define simple source terms by hand)**
- **Site data optionally needed by EARLY to define population and regional economic data**
- **Food-chain data optionally used by CHRONC**

SecPop
Based on Census Data

- **For each MACCS grid section (within continental US)**
  - **Block-level data (2010 census) used to estimate population**
  - **County-level data for (2007 BEA, USDA, etc.) used to estimate (2012 in progress)**
    - **Land/water fractions**
    - **Fraction of land devoted to farming**
    - **Fraction of farm revenue from dairy**
    - **Total farm revenue**
    - **Farmland values (land, buildings, machinery)**
    - **Non-farm values (land, buildings, infrastructure)**

Dose Conversion Factor Files

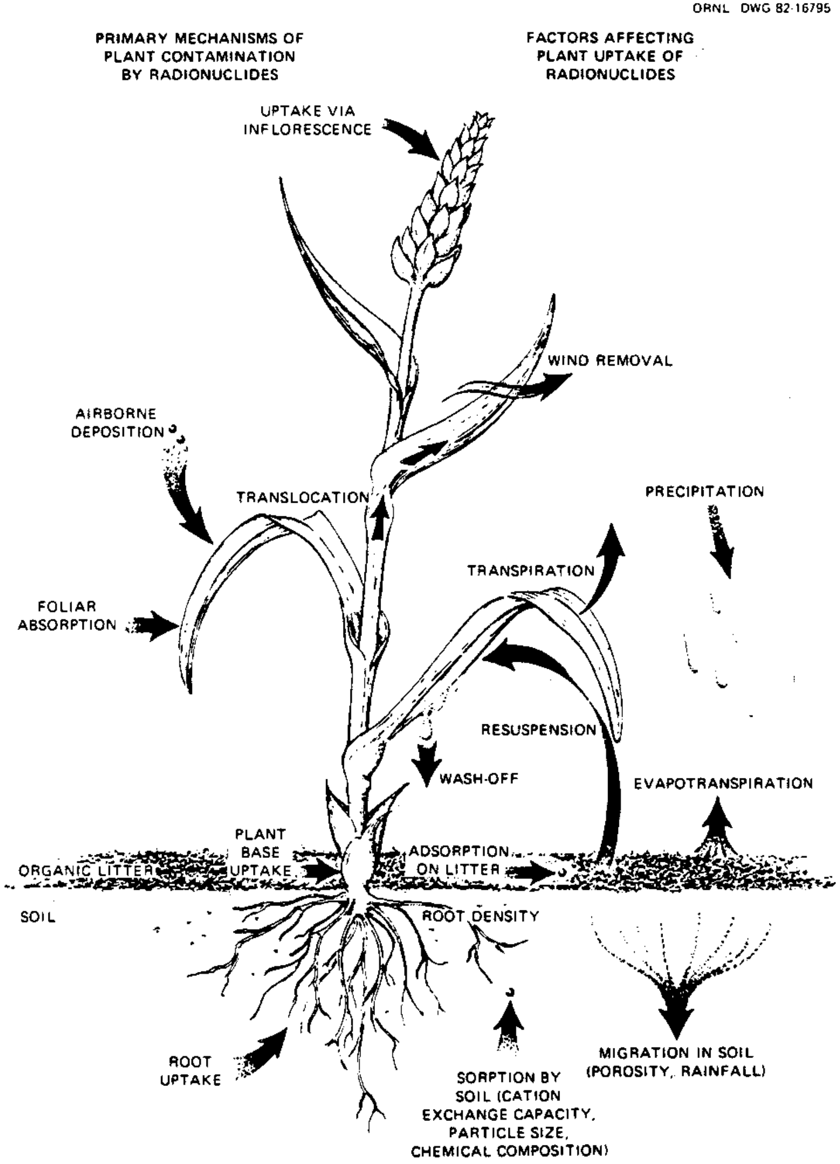
- **Dose conversion factor (DCF) files accompany MACCS release (adequate for most applications)**
  - **dosdata20organs – based on DOSD87 & DOE/EH-0070**
    - **60 nuclides for internal and external pathways**
    - **Lifetime and acute dose coefficients**
  - **FGRDCF – based on Federal Guidance Reports 11 and 12**
    - **500 nuclides for internal pathways**
    - **825 nuclides for external pathways**
    - **No acute capabilities**
  - **fgr13DCF – based on Federal Guidance Reports 12 and 13**
    - **825 nuclides**
    - **Most nuclides have acute dose coefficients**

Three Options for Food Chain Modeling

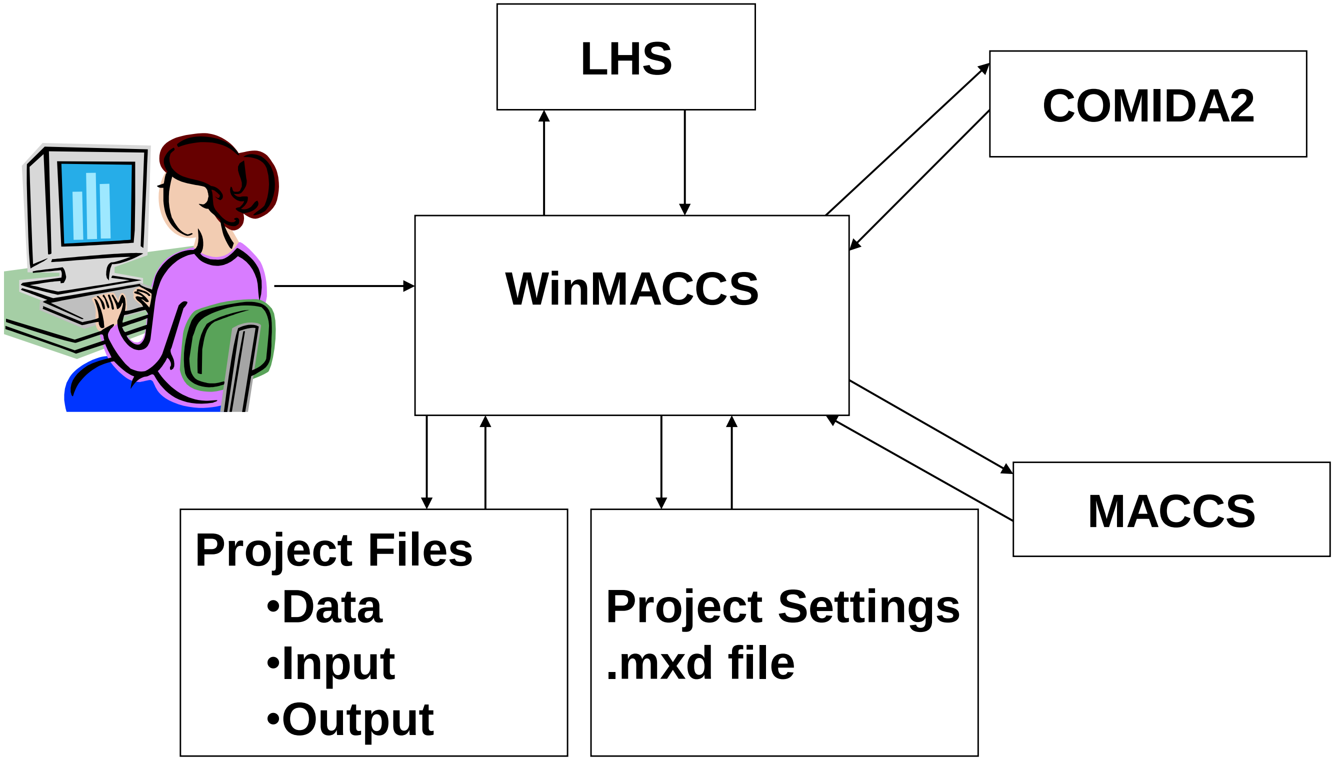
- **Options include:**
  - **Transfer-factor model (MACCS model used in NUREG-1150)**
  - **COMIDA2**
  - **No ingestion pathway**
- **Transfer-factor model**
  - **Doesn’t account for time during growing season**
  - **Neglects radioactive decay and ingrowth**
  - **Limited to 6 nuclides**
- **COMIDA2**
  - **Provides dose conversion factors (based on published information)**
  - **Capable of multiple release dates**
  - **Includes decay and ingrowth (up to 4 generations for up to 50 nuclides)**

Food Chain Models Address Numerous Contaminant Paths

- Contamination begins with plants
- Contaminated plants can be processed for humans
- Contaminated plants can be consumed by animals
- Contaminated animal and animal products can be consumed by humans



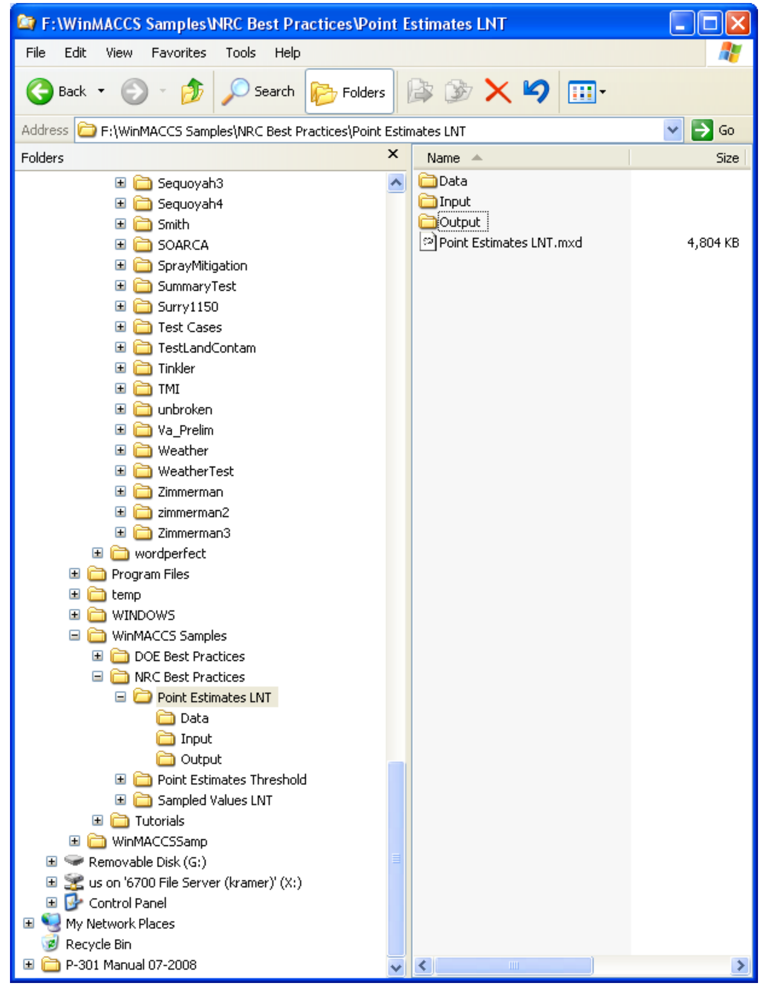
Architecture of WinMACCS Components



Input → **MACCS** → **Output**

Project Folder Structure

- Project folder is a self-contained problem description
- .mxd file contains project settings
- Data contains auxiliary files selected by user
- Input contains files are created by WinMACCS and its components as inputs to MACCS
- Output contains results created by primarily by MACCS

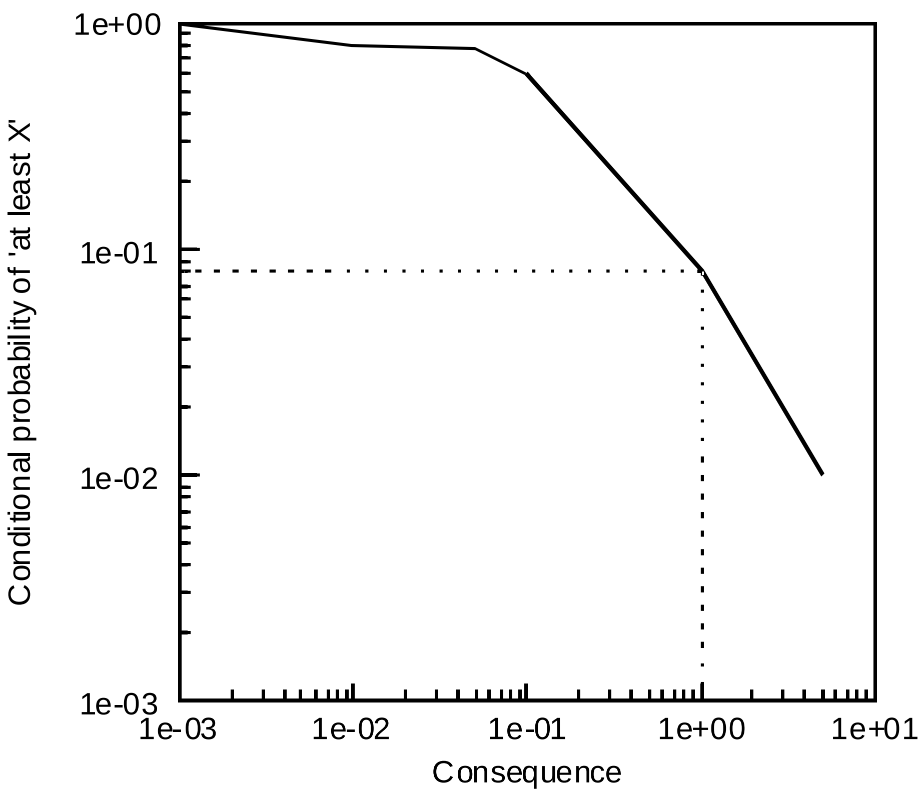


Extensive Output Available

- **ATMOS dispersion results**
  (contaminant concentrations, σ_y, σ_z, χ/Q, plume arrival times, etc.)
- **Acute and lifetime doses**
  (by organ and pathway)
- **Early health effects**
  (injuries and fatalities by organ)
- **Latent health effects**
  (injuries and fatalities by organ)
- **Costs of mitigative actions**
  (by action and phase for farm and non-farm regions)

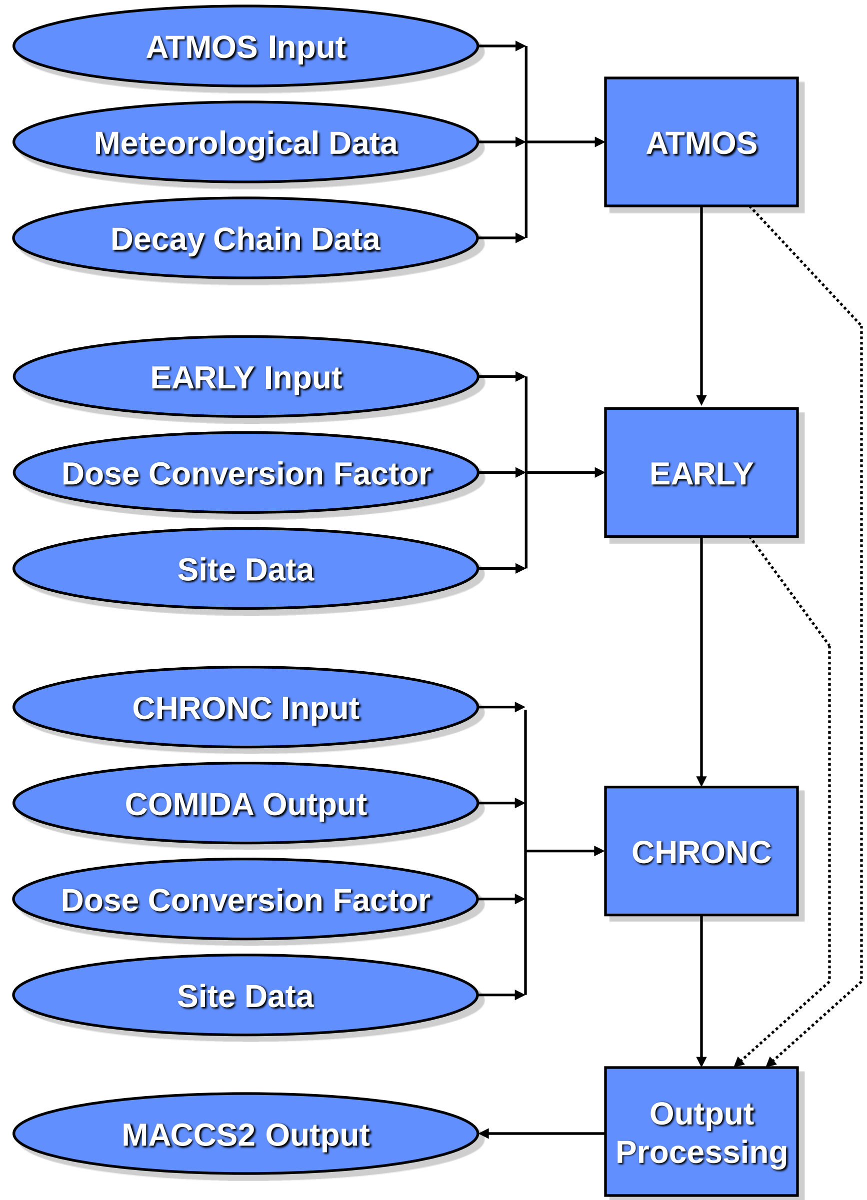
Any Result can be Outputted as a CCDF

- **A CCDF (complementary cumulative distribution function) shows conditional probability that a consequence of 'at least X' occurs**
- **E.g., there is a conditional probability of $8 \cdot 10^{-2}$ that the consequence will be 1 or more**



MACCS Data Flow

- User activates modules only as needed to determine results of interest
- Activated modules determine input files that are required
- Some required input files may be used as transmitted with MACCS (without user modification)



Summary

- **MACCS estimates doses, health effects, and economic costs associated with airborne radioactive releases**
  - **External and internal dose pathways considered with calculation of acute and lifetime committed doses**
  - **Health effects include early and latent injuries/fatalities arising from calculated doses**
  - **Economic costs due to mitigative actions**
- **Radioactive dispersion based on Gaussian plume model with capabilities for sampling annual meteorological data**
- **Preprocessors provided for development of source terms, site data, and food-chain data**

References

- Jow, H-N, J. L. Sprung, J. A. Rollstin, L. T. Ritchie, D. I. Chanin (1990), MELCOR Accident Consequence Code System (MACCS): Model Description, NUREG/CR-4691, Volume 2, Sandia National Laboratories, Albuquerque, NM
- Chanin, D., M. L. Young, J. Randall, K. Jamali (1998), Code Manual for MACCS2: Volume 1, User's Guide, NUREG/CR-6613, Sandia National Laboratories, Albuquerque, NM
- Chanin, D., M. L. Young, J. Randall, K. Jamali (1998), Code Manual for MACCS2: Volume 2, Preprocessor Codes COMIDA2, FGRDCF, IDCF2, NUREG/CR-6613, Sandia National Laboratories, Albuquerque, NM
- Bixler, N. E., S. A. Shannon, C. W. Morrow, B. E. Meloche, and J. N. Ridgely (2003), SECPOP2000: Sector Population, Land Fraction, and Economic Estimation Program, NUREG/CR-6525 Rev. 1, Sandia National Laboratories, Albuquerque, NM

5. Atmospheric Dispersion

Objectives

- **Learn the mechanisms that describe *atmospheric dispersion***
- **Calculate the *air concentration* at a downwind location from a release**
- **Learn the mechanisms that describe *deposition***
- **Calculate *deposition rate***
- **Learn the basic concepts concerning *dose pathways***
- **Become familiar with WinMACCS**

Complex Processes That Affect a Released Contaminant

- **Buoyant plume rise**
- **Dilution and transport**
- **Chemical reactions (not modeled in MACCS)**
- **Radioactive decay**
- **Wet deposition - rainout by interaction with cloud droplets and washout by falling precipitation**
- **Dry deposition – gradual loss of reactive vapors and aerosols by deposition onto the surface cover**

Source-Term Models Estimate Environmental Releases

- **Input for consequence analysis**
- **Emission of contaminants**
  - **Quantity of each contaminant**
  - **Rate**
  - **Height**
  - **Energy content**

Dispersion and Deposition Modeling

- **Source term inputs**
- **Basic weather inputs**
  - **Wind speed**
  - **Wind direction**
  - **Atmospheric stability**
  - **Precipitation rate**
- **Basic outputs**
  - **Air concentrations**
  - **Surface contamination (deposition)**

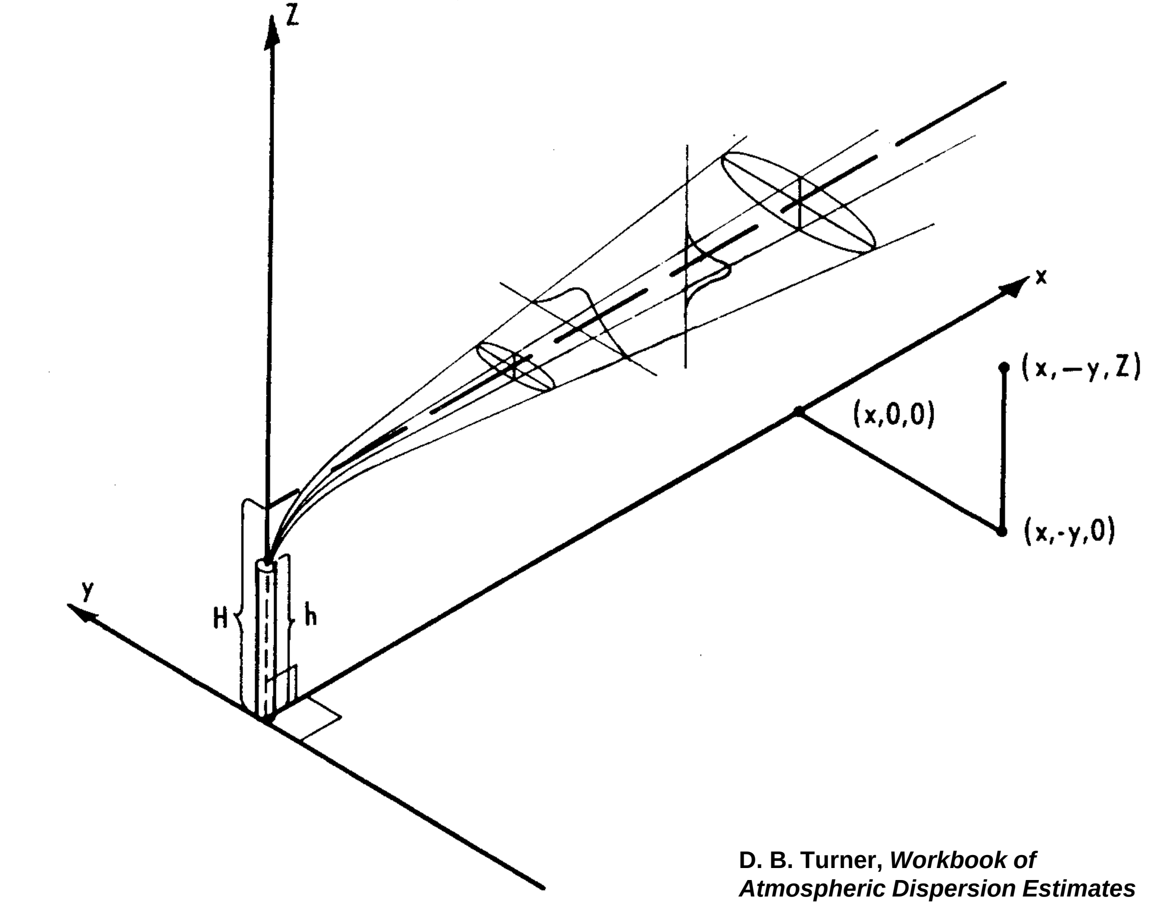
Straight-Line Gaussian Model (Standard Model)

- **Derived from Fick's diffusion equation**

$$\frac{\partial C}{\partial t} = K\nabla^2 C$$

- **Simple domain**
- **Good approximation when**
  - **Terrain is relatively flat compared with plume dimensions**
  - **Far from large water bodies**
  - **Winds are not calm**
  - **Winds are steady during the period of release**

Coordinate System for Atmospheric Transport and Dispersion



D. B. Turner, *Workbook of Atmospheric Dispersion Estimates*

Basic Concentration Equation

- **Continuous release**
- **Point source**
- **No boundaries**

$$C = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z u}\exp\left\{-\frac{1}{2}\left[\left(\frac{y}{\sigma_y}\right)^2 + \left(\frac{z}{\sigma_z}\right)^2\right]\right\}$$

C = Plume concentration (Bq/m^3)

$\dot{Q}$ = Release rate of contaminant (Bq/s)

y = Cross-wind (lateral) distance from plume centerline (m)

z = Vertical distance from plume centerline (m)

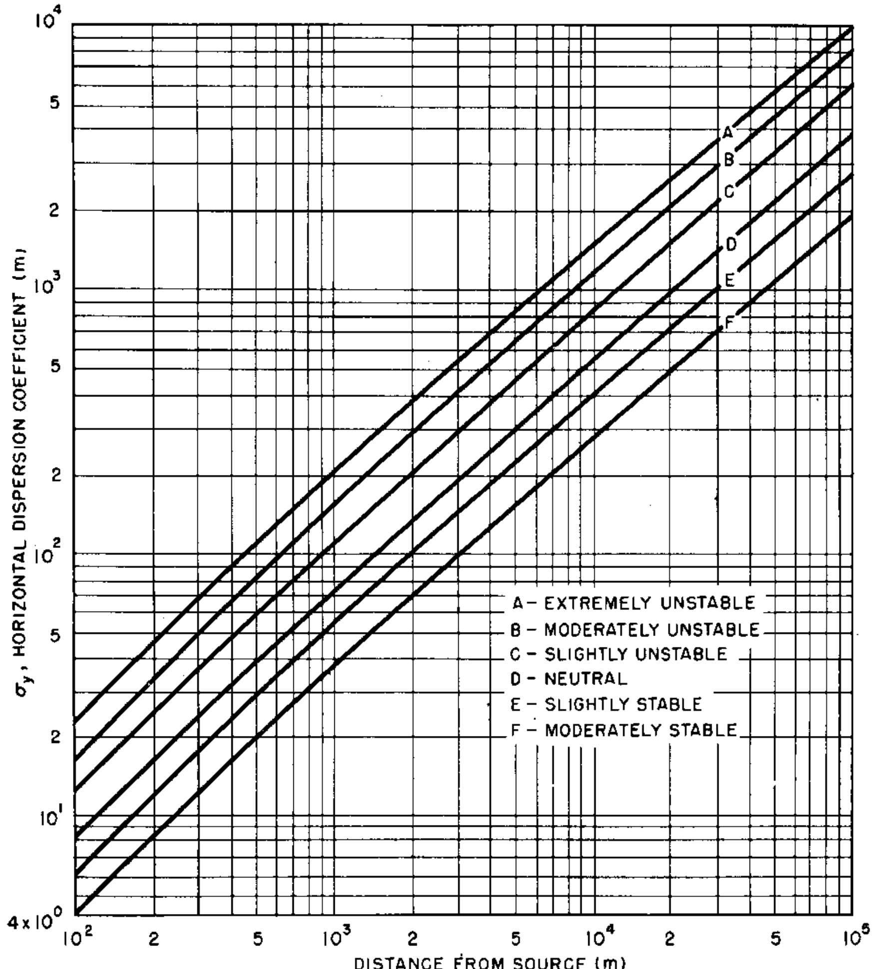
σ_y = Standard deviation of plume in the y direction as a function of x (m)

σ_z = Standard deviation of plume in the z direction as a function of x (m)

u = Average wind speed along plume centerline

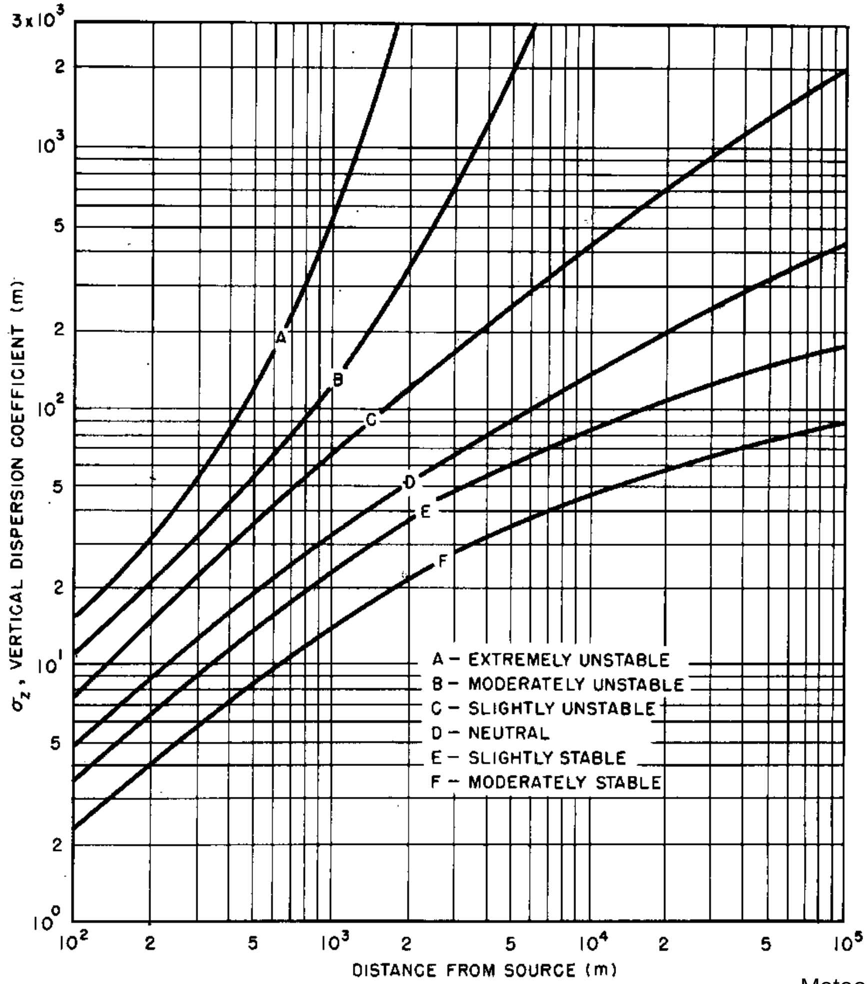
$$\frac{\int C dt}{\int \dot{Q} dt} = \frac{\chi}{Q}$$

Lateral Dispersion, σ_y, vs. Downwind Distance From Source



Meteorology and Atomic Energy, 1968

Vertical Dispersion, σ_z, vs. Downwind Distance From Source (Pasquill-Gifford)



Meteorology and Atomic Energy, 1968

Power-Law Representation of Dispersion

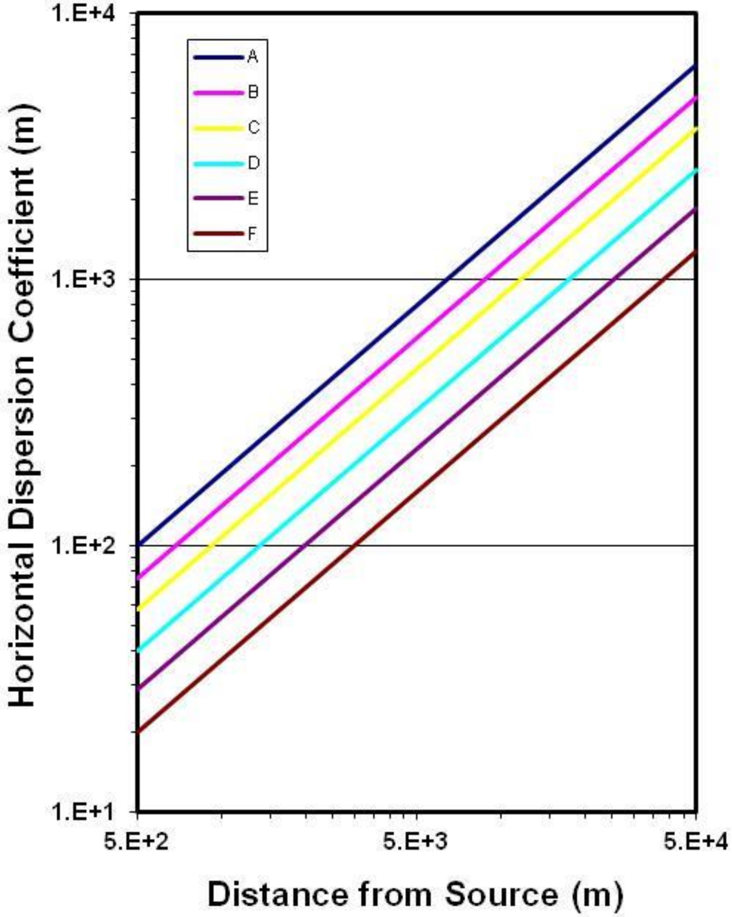
- **Power-law representation from Tadmor and Gur**

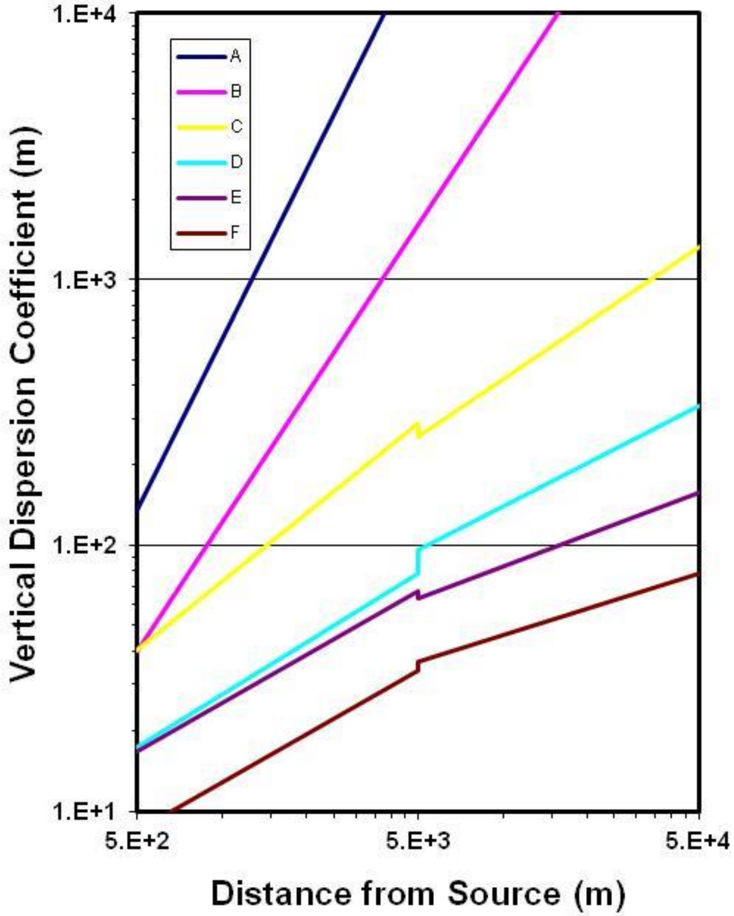
$$\sigma_y = a \cdot x^b \qquad \sigma_z = c \cdot x^d$$

- **Excellent representation for σ_y**
- **Two-piece, less accurate, representation for σ_z**

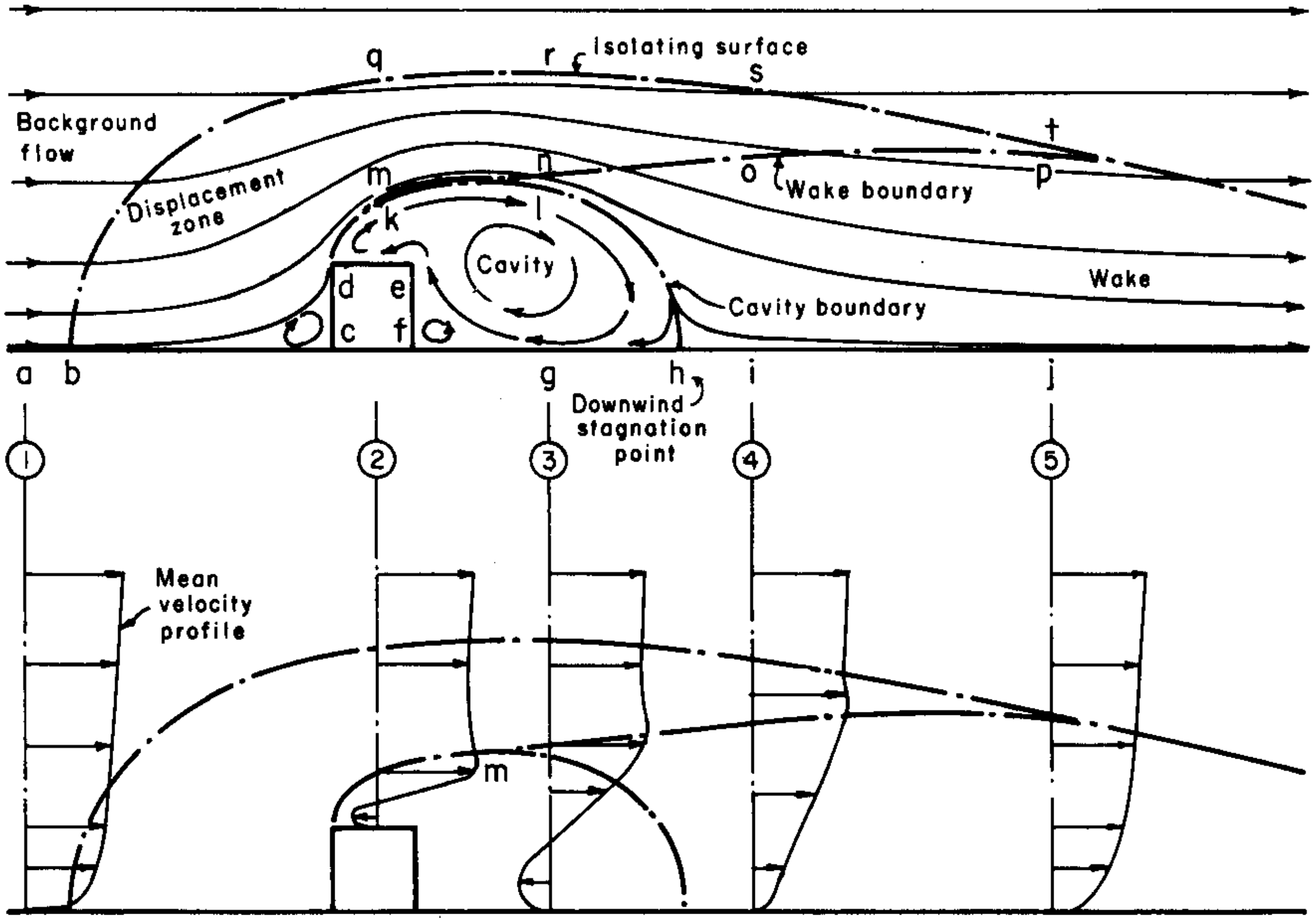
Parameter	Distance Range (km)	Stability Class A	B	C	D	E	F
a	0.5 - 50	0.36580	0.2751	0.2089	0.1474	0.1046	0.0722
b	0.5 - 50	0.90310	0.9031	0.9031	0.9031	0.9031	0.9031
c	0.5 - 5	0.00025	0.0019	0.2000	0.3000	0.4000	0.2000
	5 - 50			0.5742	0.9605	2.1250	2.1820
d	0.5 - 5	2.12500	1.6021	0.8543	0.6532	0.6021	0.6020
	5 - 50			0.7160	0.5409	0.3979	0.3310

Plots of Power-Law Functions for Tadmor and Gur Parameters





General Arrangement of Flow Zones Near a Sharp-edged Building



Meteorology and Atomic Energy, 1968

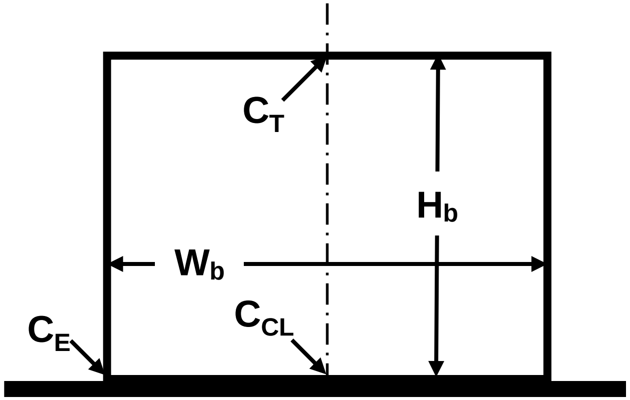
Wind-Tunnel Test of Scaled Plant

Building Wake - Area Source

- **Assume fraction, f, of centerline concentration at building edge and top**

$$f = \frac{C_E}{C_{CL}} = \exp\left(\frac{-(W_b/2)^2}{2\sigma_{y_0}^2}\right)$$

$$f = \frac{C_T}{C_{CL}} = \exp\left(\frac{-H_b^2}{2\sigma_{z_0}^2}\right)$$

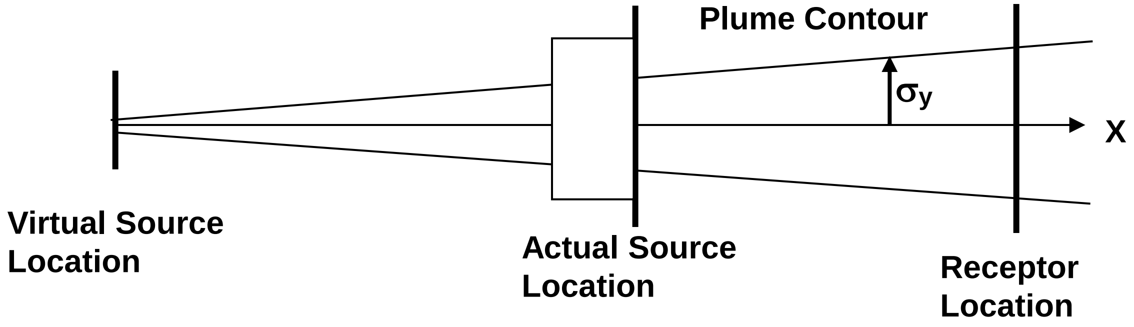


For f = 0.1, $\sigma_{y_0} = 0.23\ W_b$ and $\sigma_{z_0} = 0.47\ H_b$

Where W_b and H_b are the width and height of the building, respectively

Virtual Sources

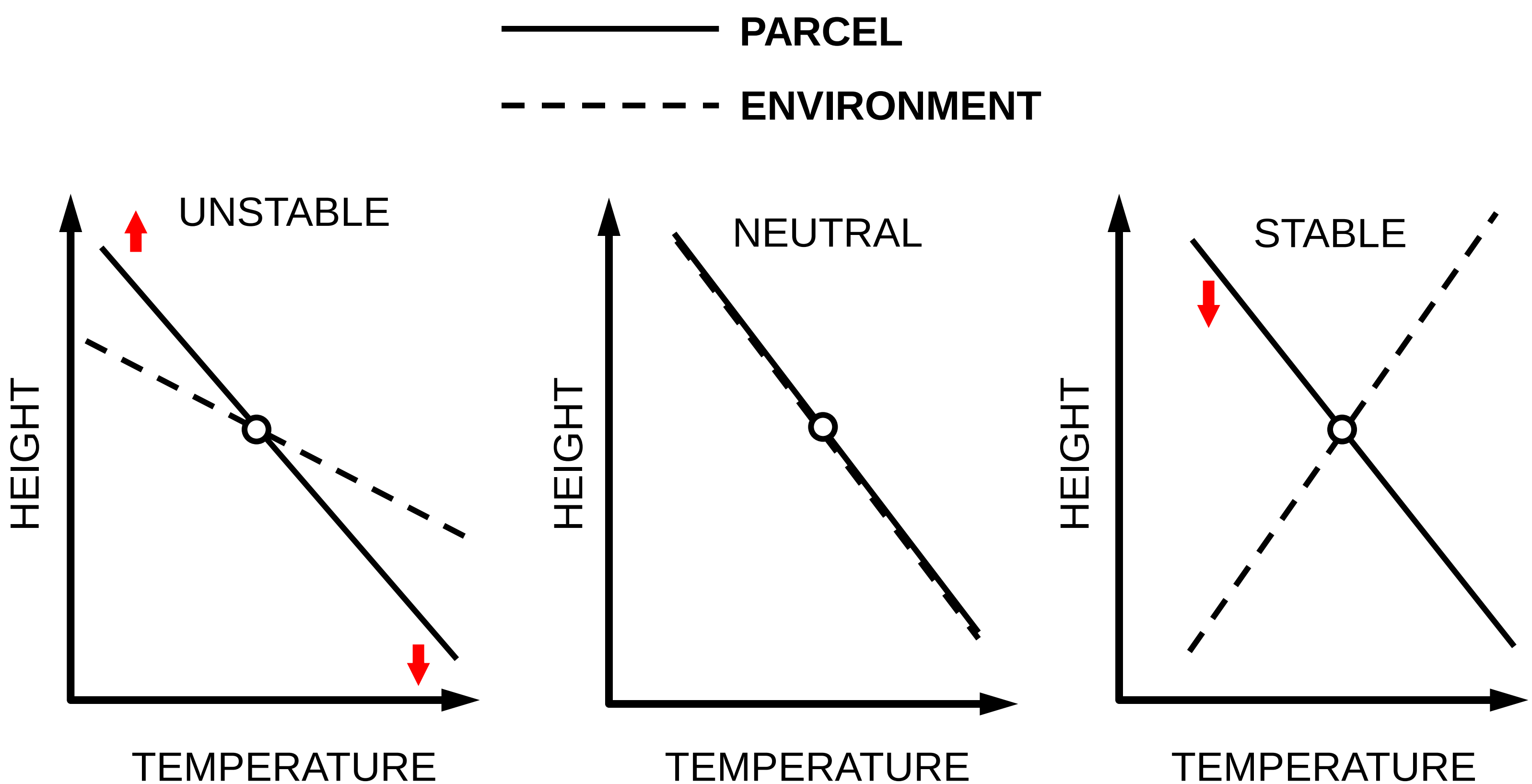
- **Virtual source is the location of a "point" source that produces an equivalent plume size**
- **Actual source location corresponds to a finite distance downwind from the virtual source**
  - **X_{y0} for crosswind dispersion**
  - **X_{z0} for vertical dispersion**
- **Receptor locations are relative to actual source location**



Planetary Boundary Layer

- **Region of atmosphere between earth's surface and an upper region of nonturbulent, geostrophic flow**
- **Ranges in height from 50 m – height of troposphere (10 to 18 km)**
- **Consists of three parts**
  - **Surface layer (first 10%, turbulence is created)**
  - **Core (up to 70% of PBL, turbulence is dissipated)**
  - **Top (remainder)**
- **Principal types are convective and stably stratified**
- **Wind speed and direction tend to vary with height in surface layer**
- **Stability of atmosphere within PBL determines turbulence intensity (dispersion effects)**
- **Radioactive materials are assumed to be trapped in this layer**
- **Here we assume it is the same as the mixing layer**

Illustrations of PBL Stability Conditions



ORNL-DWG 83-10939

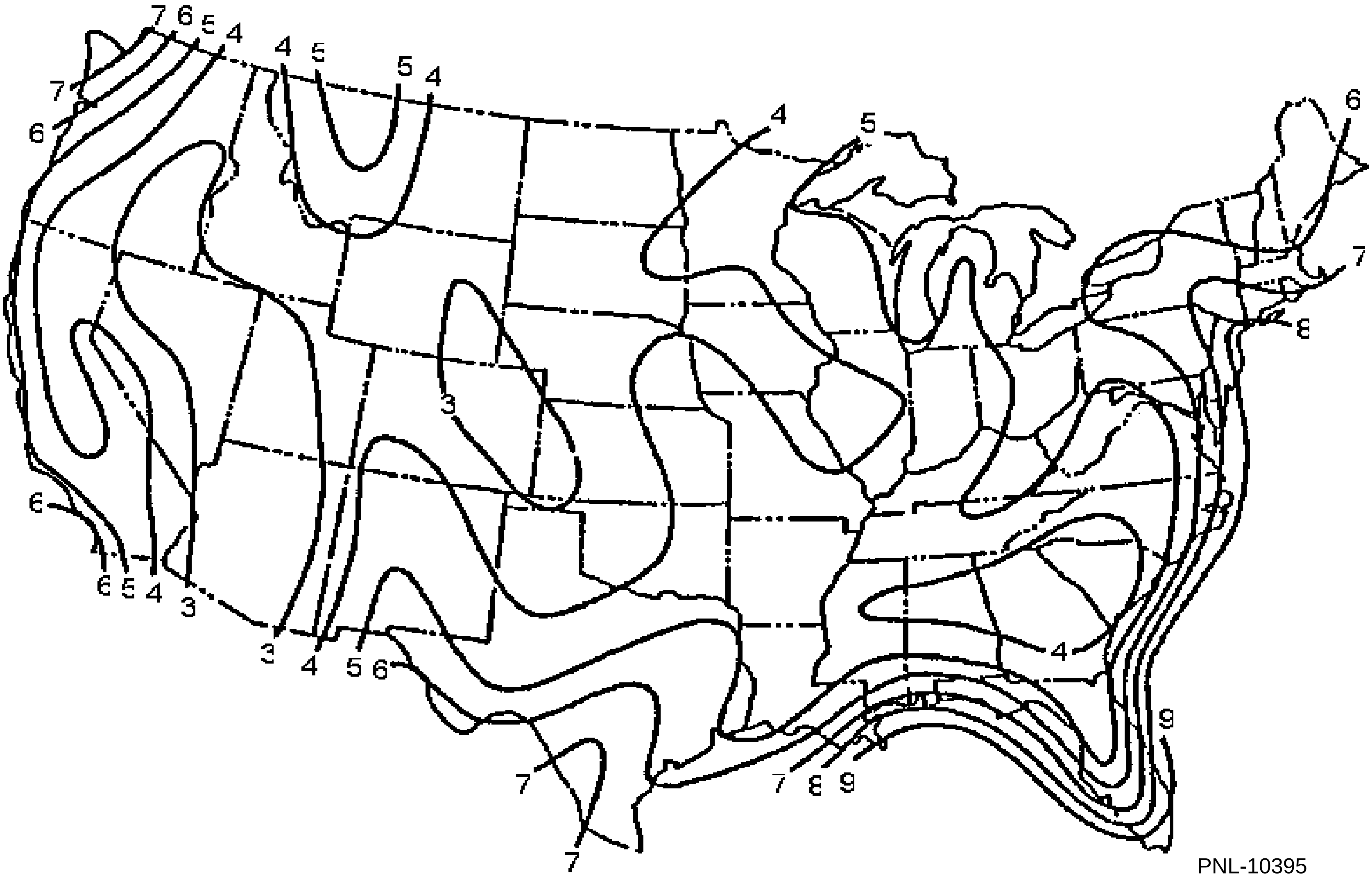
Atmospheric Stability Classifications by Vertical Temperature Gradient (Lapse Rate)

Stability classification	Pasquill categories	Temperature change with height (°C/100 m)
Extremely unstable	*A*	$\Delta T/\Delta z \leqslant -1.9$
Moderately unstable	*B*	$-1.9 < \Delta T/\Delta z \leqslant -1.7$
Slightly unstable	*C*	$-1.7 < \Delta T/\Delta z \leqslant -1.5$
Neutral	*D*	$-1.5 < \Delta T/\Delta z \leqslant -0.5$
Slightly stable	*E*	$-0.5 < \Delta T/\Delta z \leqslant 1.5$
Moderately stable	*F*	$1.5 < \Delta T/\Delta z \leqslant 4.0$
Extremely stable	*G*	$4.0 < \Delta T/\Delta z$

Mixing Height

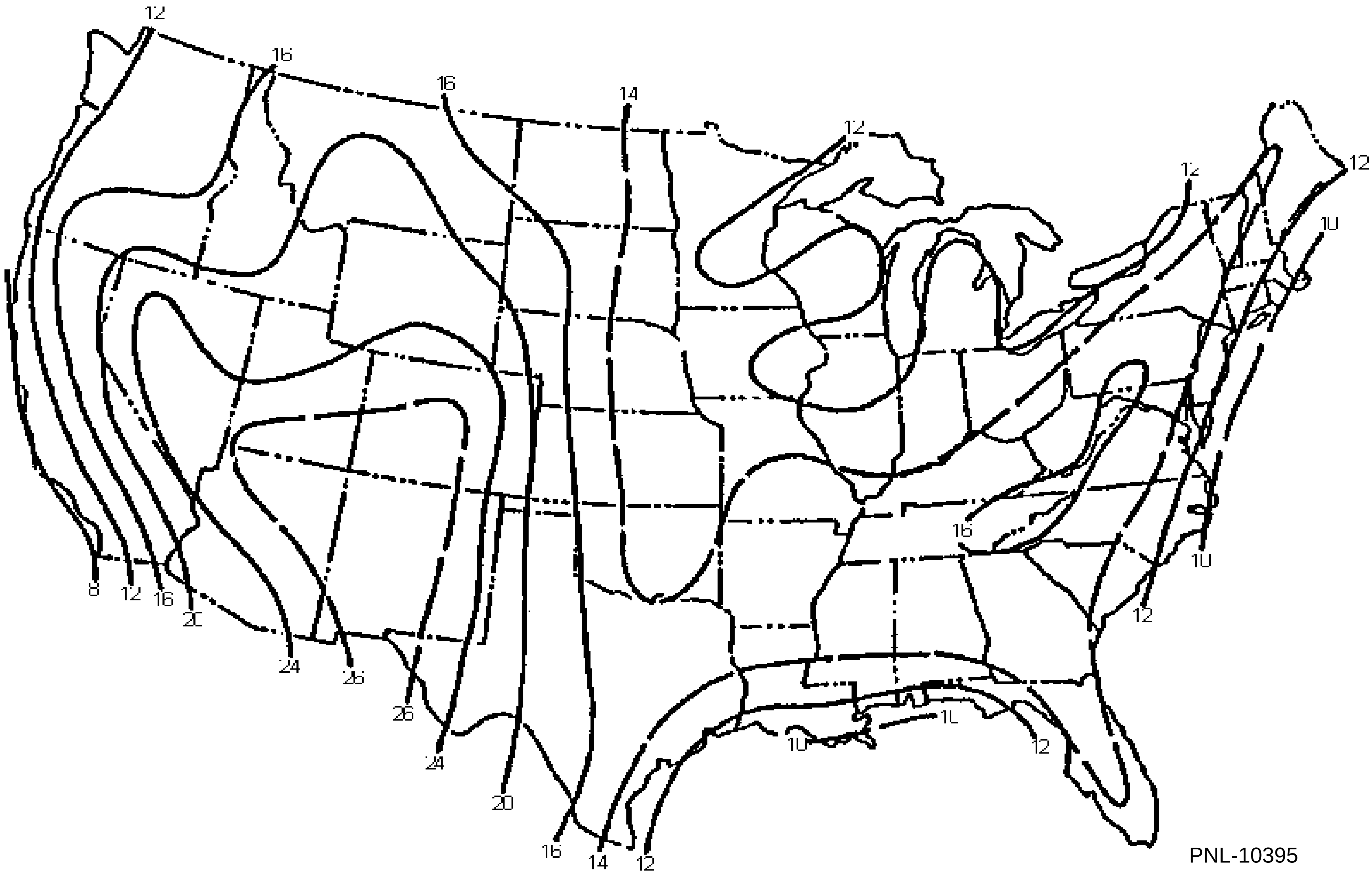
- **Mixing height is usually determined by**
  - **Thermal mixing (convection) during daytime**
  - **Mechanical mixing during nighttime**
- **Varies continuously (hour to hour, day to day, season to season)**
- **Usually lowest at night and early morning**
- **Usually highest in late afternoon**
- **Inhibits plume rise (here we assume that it is an absolute barrier)**

Mean Annual Morning Mixing Heights (m x 10^2)



PNL-10395

Mean Annual Afternoon Mixing Heights (m x 10^2)

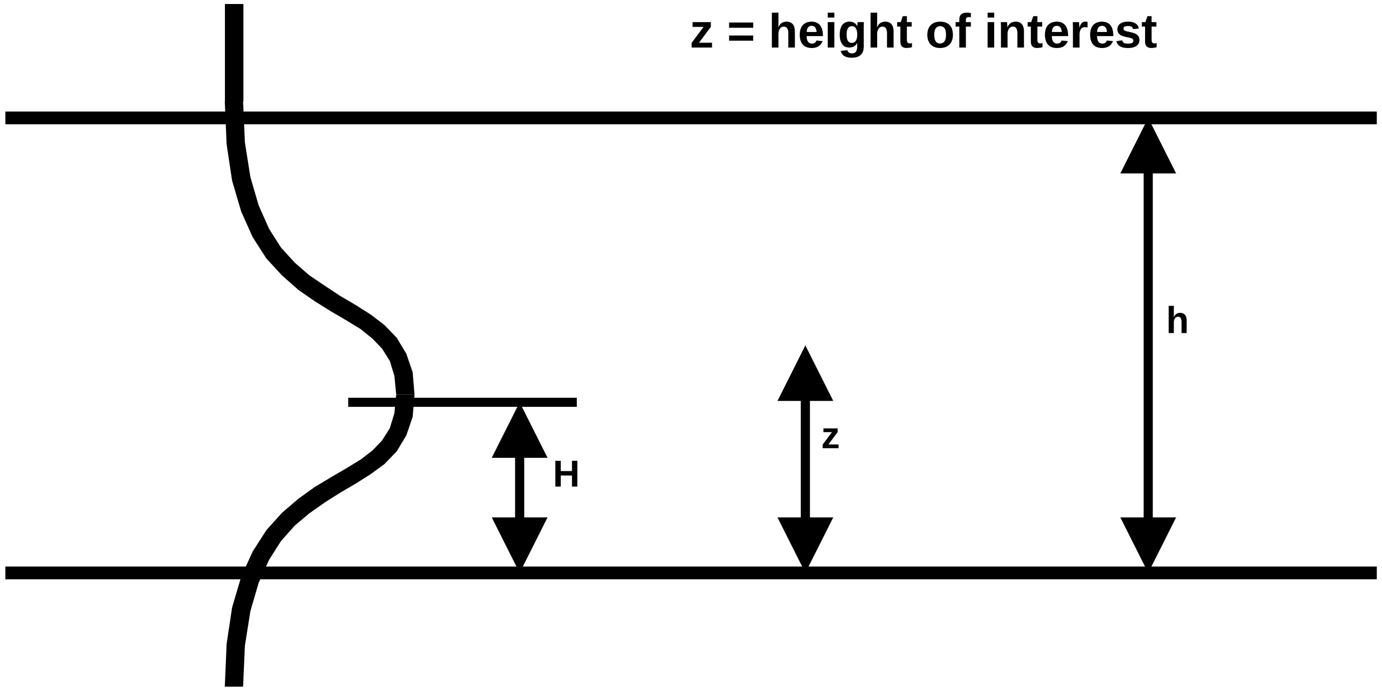


Vertical Boundaries
Ground and Mixing Layer

H = release height (or lofting height) above ground

h = height of mixing layer

z = height of interest



General Gaussian Plume Equation With Reflective Boundaries

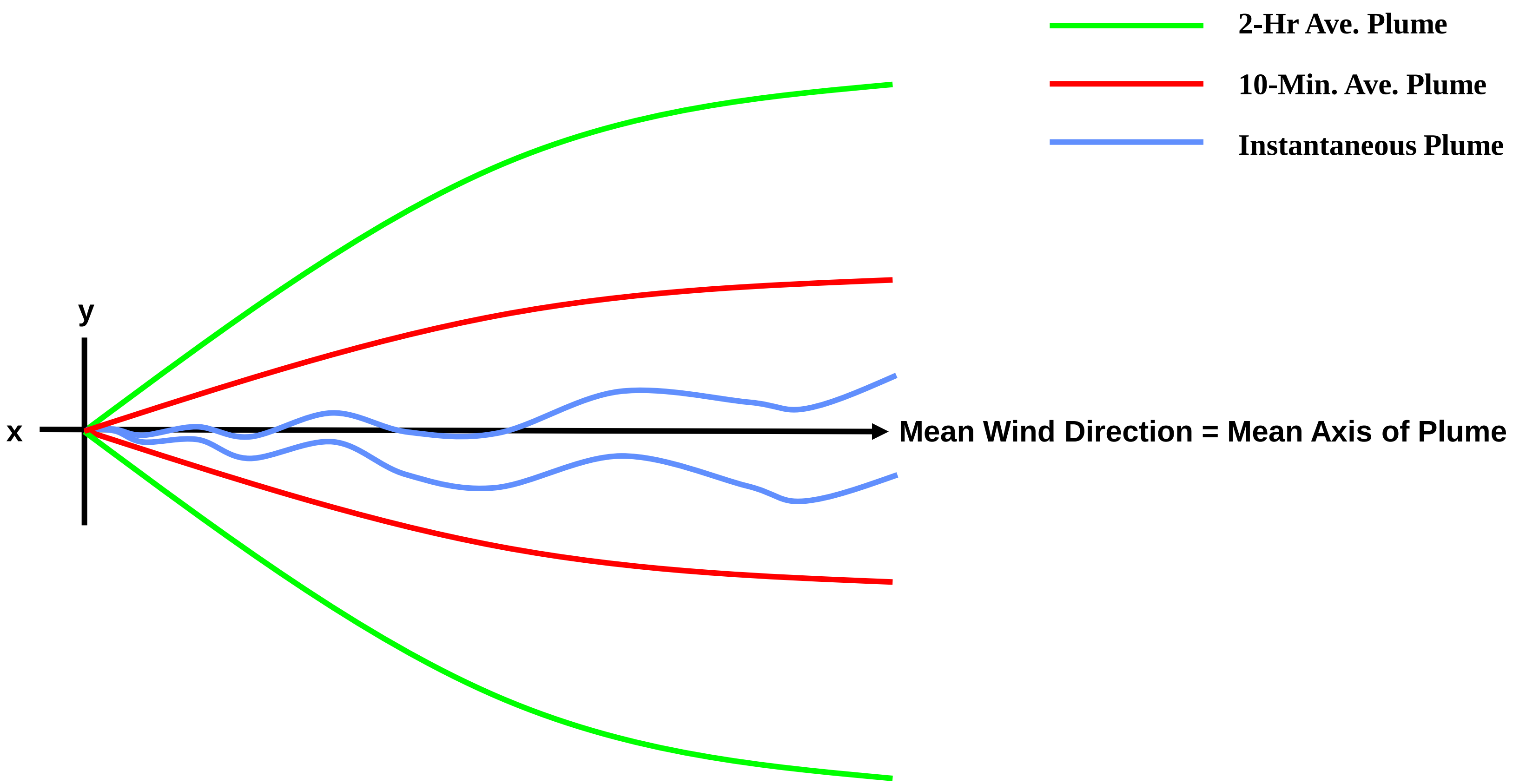
- **Account for material that would have been lost through boundaries**
  - **Non-reflected component: H-z [vertical distance from centerline]**
  - **1st reflection: H + z [off ground] (h - H) + (h - z) [off cap]**
  - **2nd reflection: (h - H) + h + z [off ground] (H + h) + (h - z) [off cap]**

$$C = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z u}\exp\left(\frac{-y^2}{2\sigma_y^2}\right)\sum_{n=-\infty}^{\infty}\left\{\exp\left[-\frac{1}{2}\left(\frac{2nh-H-z}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{2nh+H-z}{\sigma_z}\right)^2\right]\right\}$$

- **Simplified equation when release is at ground level and observation point is on plume centerline (H = y = z = 0)**

$$C = \frac{\dot{Q}}{2\pi\sigma_y\sigma_z u}\sum_{n=-\infty}^{\infty}2\exp\left[-2\left(\frac{nh}{\sigma_z}\right)^2\right]$$

Effect of Dispersion Averaging Times



Original MACCS2 Plume Meander

- **Increases effective plume spread in y direction**
- **Effect of plume meander continues downwind indefinitely**

$$\sigma_{y,m} = \sigma_y \left(\frac{\Delta t}{\Delta t_{ref}} \right)^m$$

Δt = Release duration (s)

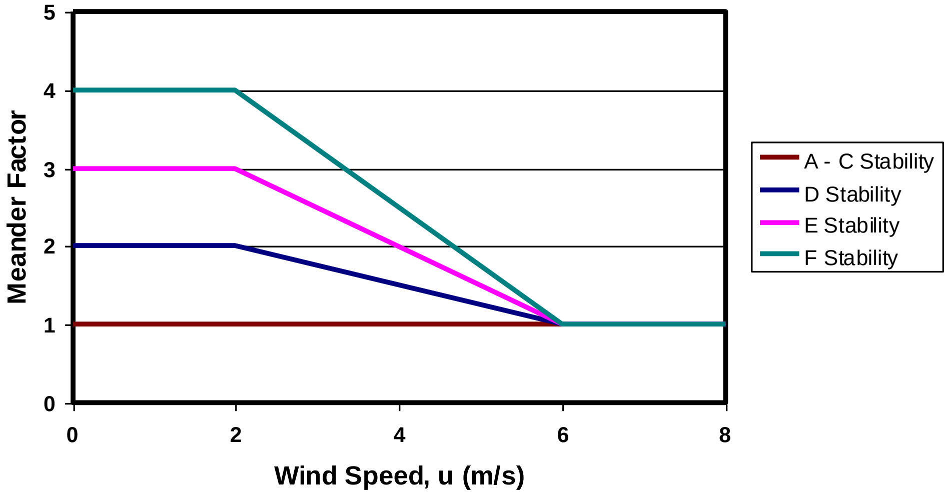
Δt_{ref} = 600, the experimental duration of the Prairie Grass tests (s)

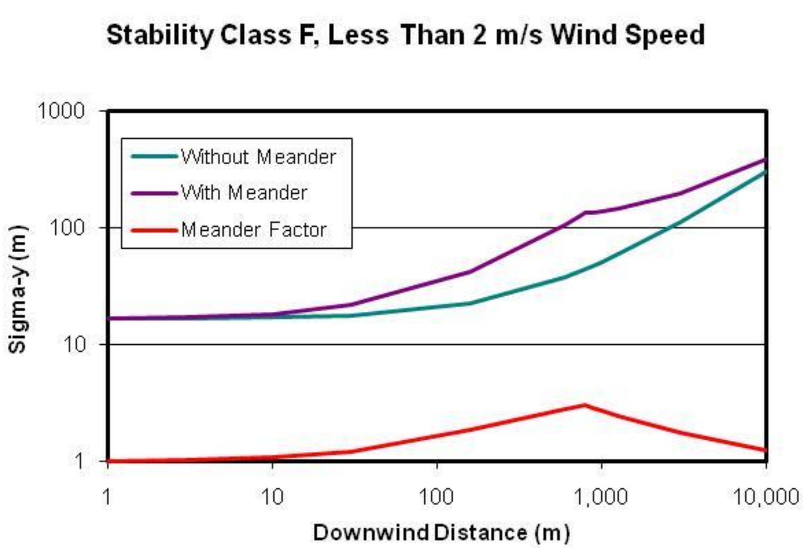
m = an empirical exponent

= 0.2 when Δt < 1 hr

= 0.25 when Δt > 1 hr

Regulatory Guide 1.145 Plume Meander Model





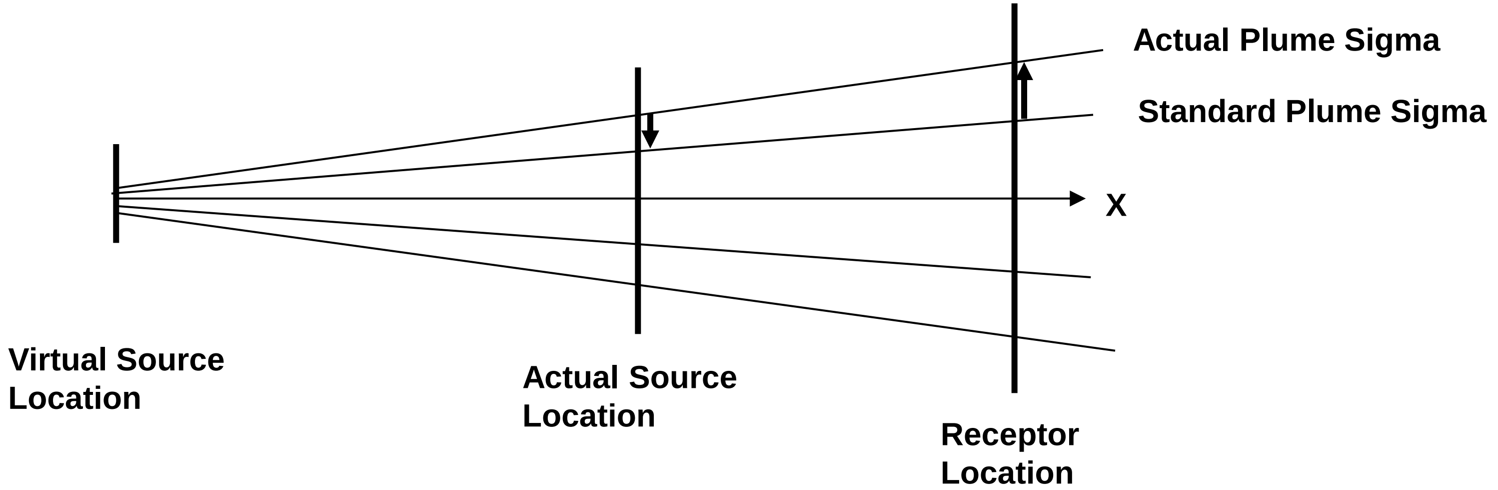
- Meander factor depends on stability class and wind speed
- Model is based on a 1-hr plume duration
- Effect of plume meander diminishes beyond 800 m from source
- Plot shows
  - Dispersion not accounting for plume meander
  - Dispersion accounting for plume meander (<2 m/s and F stability)
  - Effective meander factor

Adjustments to Virtual Source Locations

- **Virtual source location has to be modified to account for plume meander (σ_y) and surface roughness (σ_z)**

e.g., $\sigma_{y,m} = M \cdot \sigma_y$ (chart); σ_y (chart) $= \sigma_{y,m} / M$

Actual plume sigma is standard plume sigma times the meander factor



Plume Rise – Original Model

- **Plume contains thermal energy – buoyant**
- **Original Briggs' model is used to estimate plume rise**
  - **Near-field trajectory (used for stability classes A – D)**

$$\Delta H(x) = \frac{1.6(Fx^2)^{1/3}}{\bar{u}}$$

  - **Final rise for stability classes A – D**

$$\Delta H_f = \frac{300F}{\bar{u}^3}$$

  - **Final rise for stability classes E – F**

$$\Delta H_f = 2.6\left(\frac{F}{\bar{u}s}\right)^{1/3}$$

Where $F = 8.79 \cdot 10^{-6}\dot{E}$ **is the buoyancy flux (m⁴/s³)**

$\dot{E}$ **is the power content in the plume (W)**

$s = 5.04 \cdot 10^{-4}$ **for S-C E and** $s = 1.27 \cdot 10^{-3}$ **for S-C F**

$\bar{u}$ **is the wind speed averaged over** ΔH

Plume Rise – Improved Model

- **Earlier Briggs' model is used to estimate plume rise**
  - **Near-field trajectory (used for stability classes A – D)**

$$\Delta H(x) = \frac{1.6(Fx^2)^{1/3}}{\bar{u}}$$

  - **Final rise for stability classes A – D**

$$\Delta H_f = 38.7\frac{F^{0.60}}{\bar{u}} \quad \textbf{when} \quad F \geq 55$$

$$\Delta H_f = 21.4\frac{F^{0.75}}{\bar{u}} \quad \textbf{when} \quad F < 55$$

  - **Final rise for stability classes E – F**

$$\Delta H_f = 2.4\left(\frac{F}{\bar{u}s}\right)^{1/3}$$

Plume Trapping in Building Wake

- **Plume is trapped in building wake when**

$$u > \left(\frac{9.09F}{H_b}\right)^{1/3}$$

Where H_b **is the building height (m)**

F **is the buoyancy flux defined previously (m^4/s^3)**

u **is wind speed (m/s)**

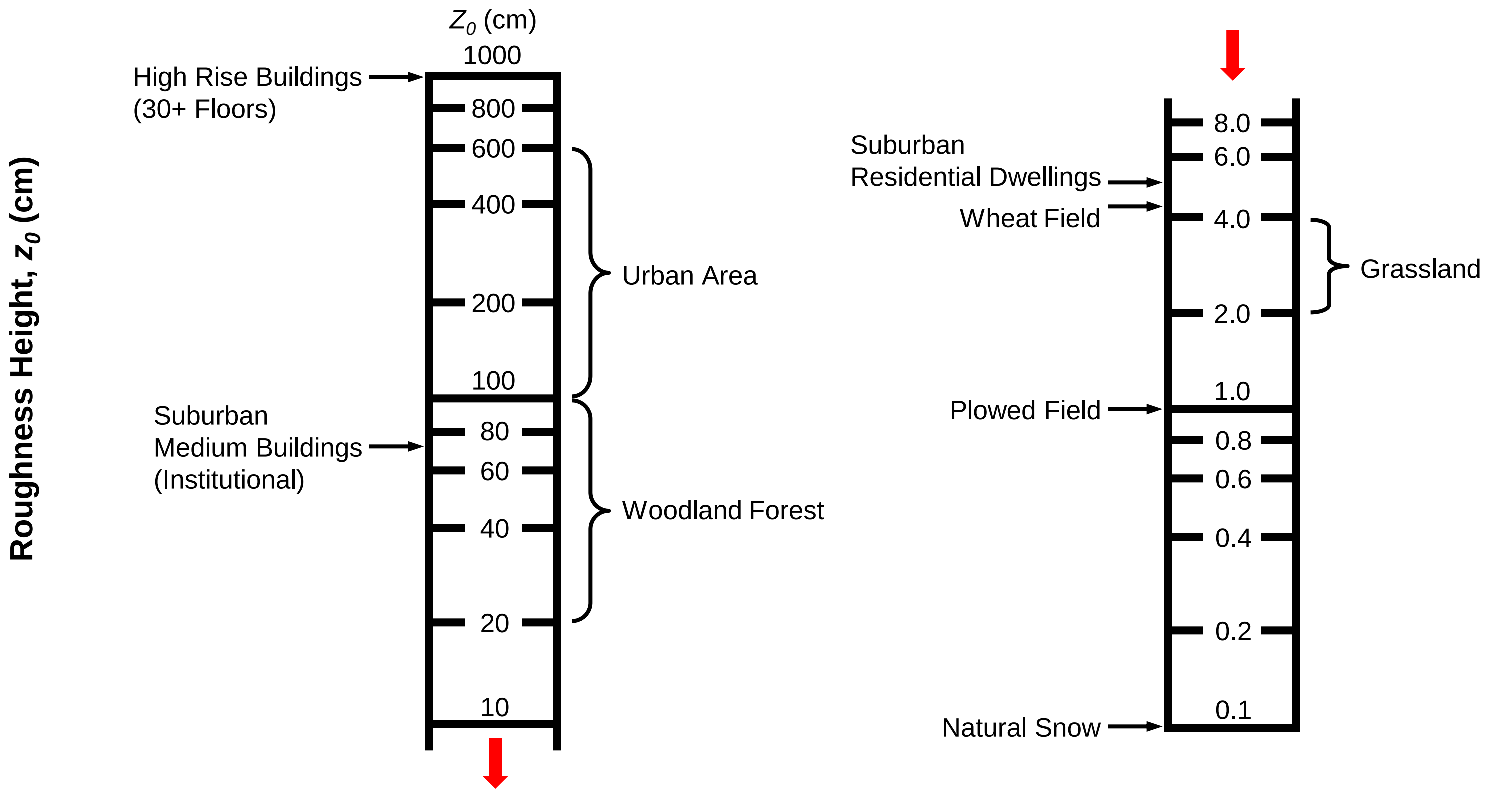
- **A trapped plume is**
  - **Released at the level of the initial release point**

Roughness Length, z_0

- **Function of size and spacing of roughness elements**
- **Dependent on the frontal area of the average element (facing the wind) divided by the ground width it occupies**
- **A lower roughness length implies less momentum exchange between the surface and the atmosphere**
- σ_z **was measured over flat terrain during Prairie Grass tests (**z_0 **= 3 cm)**

$$\sigma_z = \sigma_{z,\,PG}\left(\frac{z_0}{3}\right)^{0.2}$$

Roughness Lengths for Various Surfaces



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Workshop Example 1 – Pasquill-Gifford Chart

For a 30 minute release from this building (assume dimensions of 200 ft. high by 120 ft. wide) of 1 Ci of ^{137}Cs, what is the maximum ground concentration 1/2 mile downwind and at the mall (8 miles downwind). Assume worst case conditions.

Assumptions:

Worst Case - **Wind blowing directly towards mall**

Concentration at plume centerline (y = z = H = 0)

Low wind speed (u = 1 m/s; may not be worst case for short half lives)

Minimize atmospheric dispersion; stability = F

Heat low enough so that no plume rise

Other - **Converting dimensions of interest:**

1/2 mi ~ <u>800m</u>

8 mi ~ <u>13000m</u>

Building height = 200ft ~ <u>60m</u>

Building width = 120ft ~ <u>37m</u>

Roughness length (z_0) = 100cm (suburban/urban)

WORKSHOP EXAMPLE 1 (cont.)

Meander (5-26): $$\sigma_{y,m} = \sigma_y \left(\frac{30}{10} \right)^{0.2} = 125\sigma_y$$

Roughness (5-32): $$\sigma_{z,z_0} = \sigma_z \left(\frac{100}{3} \right)^{0.2} = 2.0\sigma_z$$

Building Wake (5-15): $$\sigma_{y_0} = .23(37) = 8.6m$$
$$\sigma_{z_0} = .47(60) = 28m$$

Mixing Height: **Morning = 550m (worst case meteorologically)**
(5- 21, 5-22) **Afternoon = 1500m (worst case because most people at mall)**

WORKSHOP EXAMPLE 1 (cont.)

from (5-9) and (5-10)

Receptor Distance (m)	σ_y (m)	σ_z (m)
	8.6/1.25 = 6.9 $\Rightarrow$ X_{y_0} = 180	28/2.0 = 14 $\Rightarrow$ X_{z_0} = 1100
800	39 (@ X = 800 + 180) * 1.25 = 49	21 (@ X = 800 + 1100) * 2 = 42
13000	390 (@ X = 13000 + 180) * 1.25 = 490	53 (@ X = 13000 + 1100) * 2 = 106

Series Terms (5-24):

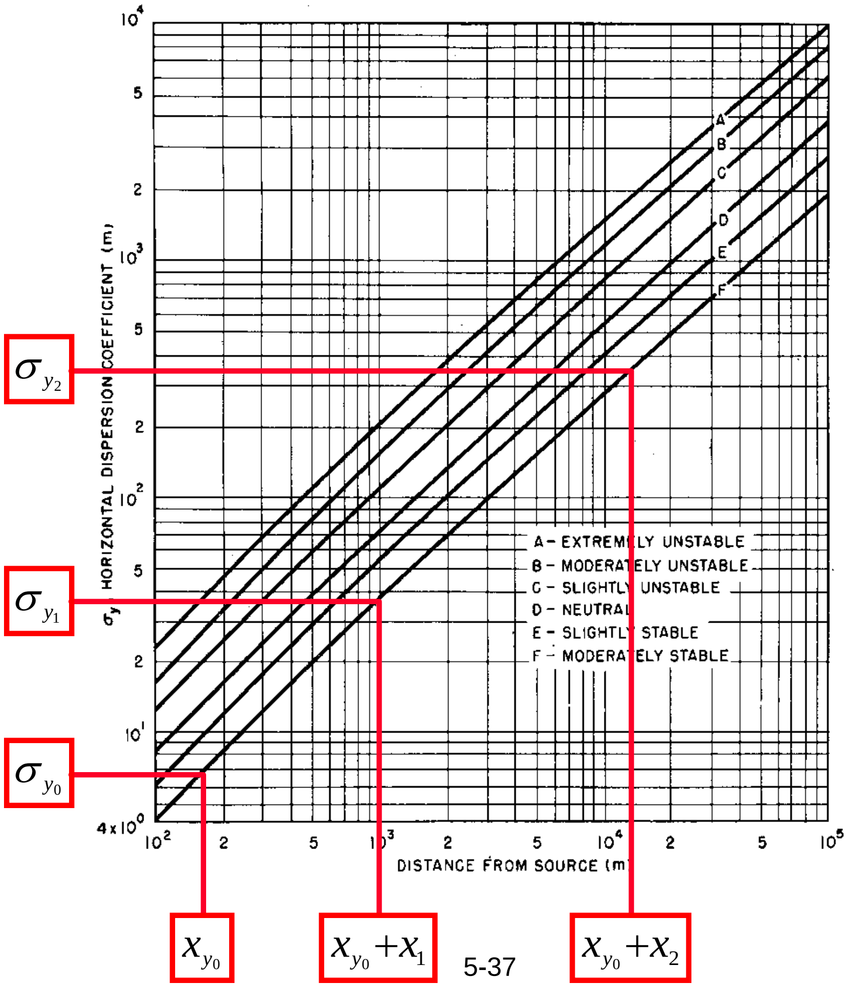
$$\sum_{n=-\infty}^{\infty} 2e^{\left[-2\left(\frac{n1500}{\sigma_z}\right)^2\right]}$$

Z=0
H=0

σ_z \ n	0	-1	+1
42	2	0	0
106	2	0	0

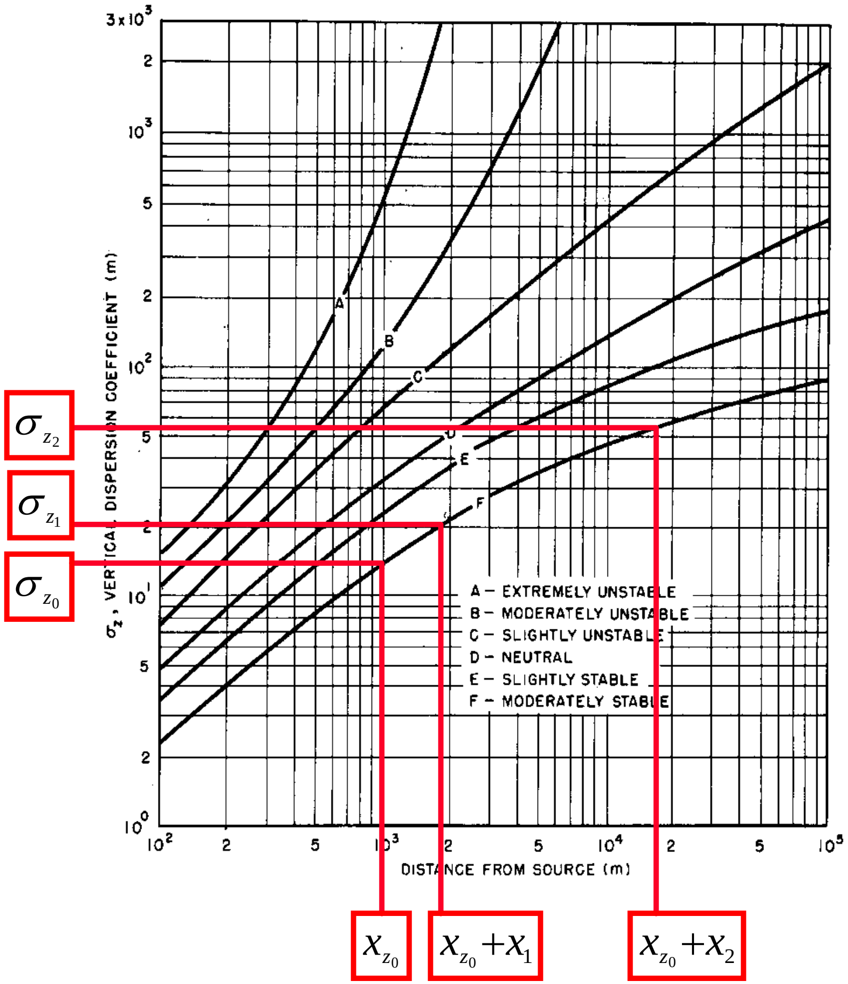
WORKSHOP EXAMPLE 1 (cont.)

Lateral Dispersion (5-9), σ_y, vs. Downwind Distance From Source for Pasquill's Stability Classes



WORKSHOP EXAMPLE 1 (cont.)

Vertical Dispersion (5-10), σ_z, vs. Downwind Distance From Source for Pasquill's Stability Classes



WORKSHOP EXAMPLE 1 (cont.)

(5-24)

1/2 mile | **8 miles**

$$\frac{C}{\dot{Q}} = \frac{1}{2\pi(49)(42)(1)}(2) = 16x10^{-4}\frac{\sec}{m^3}$$

$$= \frac{1}{2\pi(490)(106)(1)}(2) = 6.1x10^{-6}\frac{\sec}{m^3}$$

$$C = 16x10^{-4}\frac{\sec}{m^3} x \frac{1 \;\; curie}{1800\sec} = 8.9x10^{-8}\frac{curie}{m^3}$$

$$= 6.1x10^{-6}\frac{\sec}{m^3} \times \frac{1 \;\; curie}{1800\sec} = 3.4x10^{-9}\frac{curie}{m^3}$$

C = Inversely proportional to $\sigma_y \cdot \sigma_z$ (plume centerline, no reflections, no decay)

dist	$\sigma_y \cdot \sigma_z$	$C/C_{0.5\ mi}$
0.5 mi	(39) (21)	1
8 mi	(390) (53)	1/25
50 mi	(1700) (87)	1/180

Workshop Example 1 – Tadmor and Gur Parameters

For a 30 minute release from this building (assume dimensions of 200 ft. high by 120 ft. wide) of 1 Ci of ^{137}Cs, what is the maximum ground concentration 1/2 mile downwind and at the mall (8 miles downwind). Assume worst case conditions.

Assumptions:

Worst Case - **Wind blowing directly towards mall**

Concentration at plume centerline ($y = z = H = 0$)

Low wind speed (u = 1m/s; may not be worst case for short half lives)

Minimize atmospheric dispersion; stability = F

Heat low enough so that no plume rise

Other - **Converting dimensions of interest:**

1/2 mi ~ <u>800m</u>

8 mi ~ <u>13000m</u>

Building height = 200ft ~ <u>60m</u>

Building width = 120ft ~ <u>37m</u>

Roughness length (z_0) = 100cm (suburban/urban)

WORKSHOP EXAMPLE 1 – T&G (cont.)

Meander: $$\sigma_{y,m} = \sigma_y \left(\frac{30}{10}\right)^{0.2} = 125\sigma_y$$

Roughness: $$\sigma_{z,z_0} = \sigma_z \left(\frac{100}{3}\right)^{0.2} = 2.0\sigma_z$$

Building Wake: $$\sigma_{y_0} = .23(37) = 8.6m$$

$$\sigma_{z_0} = .47(60) = 28m$$

Mixing Height: **Morning = 550m (worst case meteorologically)**

Afternoon = 1500m (worst case because most people at mall)

WORKSHOP EXAMPLE 1 – T&G (cont.)

from (5-11)

Parameter	Distance Range (km)	Stability Class A	B	C	D	E	F
a	0.5 - 50	0.36580	0.2751	0.2089	0.1474	0.1046	0.0722
b	0.5 - 50	0.90310	0.9031	0.9031	0.9031	0.9031	0.9031
c	0.5 - 5	0.00025	0.0019	0.2000	0.3000	0.4000	0.2000
	5 - 50			0.5742	0.9605	2.1250	2.1820
d	0.5 - 5	2.12500	1.6021	0.8543	0.6532	0.6021	0.6020
	5 - 50			0.7160	0.5409	0.3979	0.3310

Receptor Distance (m)	σ_y(m)	σ_z(m)
Initial Virtual Source Distance	$8.6 = 1.25 \cdot 0.0722 \cdot x^{0.9031}$ $x = 155$	$28 = 2.0 \cdot 0.2000 \cdot x^{0.6020}$ $x = 1160$
800 m	$1.25 \cdot 0.0722 \cdot (155 + 800)^{0.9031}$ $= 44$	$2.0 \cdot 0.2000 \cdot (1160 + 800)^{0.6020}$ $= 38$
5000 m	$1.25 \cdot 0.0722 \cdot (155 + 5000)^{0.9031}$ $= 203$	$2.0 \cdot 0.2000 \cdot (1160 + 5000)^{0.6020}$ $= 76$

WORKSHOP EXAMPLE 1 – T&G (cont.)

Distance (m)	σ_y (m)	σ_z (m)
Virtual Source Distance @ 5000 m	$203 = 1.25 \cdot 0.0722 \cdot x^{0.9031}$ $x = 5155 - 5000 = 155$	$76 = 2.0 \cdot 2.1820 \cdot x^{0.3310}$ $x = 5712 - 5000 = 712$
13,000	$1.25 \cdot 0.0722 \cdot (155 + 13000)^{0.9031}$ $= 474$	$2.0 \cdot 2.1820 \cdot (712 + 13000)^{0.3310}$ $= 102$

Reflections:

$$\sum_{n=-\infty}^{\infty} 2e^{\left[-2\left(\frac{n\times 1500}{\sigma_z}\right)^2\right]}$$

Z=0
H=0

σ_z	n		
	0	-1	+1
38	2	0	0
124	2	0	0

WORKSHOP EXAMPLE 1 – T&G (cont.)

1/2 mile

$$C/\dot{Q} = \frac{2}{2\pi(44\ m)(38\ m)(1\ \frac{m}{s})} = 1.8\text{x}10^{-4}\ \text{s}/m^3$$

$$C = 1.8\text{x}10^{-4}\ \frac{s}{m^3} \times \frac{1\ Ci}{1800\ s} = 1.0\ \text{x}10^{-7}\ \frac{Ci}{m^3}$$

8 miles

$$C/\dot{Q} = \frac{2}{2\pi(474\ m)(102\ m)(1\ \frac{m}{s})} = 6.6\text{x}10^{-6}\ \text{s}/m^3$$

$$C = 6.6\text{x}10^{-6}\ \frac{s}{m^3} \times \frac{1\ Ci}{1800\ s} = 3.7\ \text{x}10^{-9}\ \frac{Ci}{m^3}$$

Workshop Exercise 1

- For a two hour ground level release in the morning of 10 curies of ^{132}I (half-life = 2.3 hours) containing one-half million Btu (147 KW-hr) heat content from a building which is 38.3 meters high and 56.5 meters wide located in a rural area of central Kentucky, what is the concentration of iodine that would be inhaled by a farmer standing in his plowed field 5.67 miles (9100 meters) downwind? Measurements on a met tower near the release indicate a typical day of 4 m/sec wind speed; the temperature at the 10-meter (height) sensor is 0.6 deg F (0.33 deg C) higher than that at the 30-meter sensor.

- Part 2: What concentration would the farmer see if the PBL were moderately stable?
- Part 3: Moderately stable with a wind speed of 1 m/sec?

Deposition Processes

- **Dry Deposition**
  - **Impaction**
  - **Diffusion (Brownian motion)**
  - **Gravitational settling**
- **Wet Deposition**
  - **Scavenging by precipitation (washout)**
  - **Scavenging by cloud droplets (rainout)**

Dry Deposition

- **Continuous and slow**

$$D = CV_d\Delta t$$

$D =$ dry deposition (ground concentration) (Bq/m^2)

$C =$ near-surface air concentration (Bq/m^3)

$V_d =$ deposition velocity (m/s)

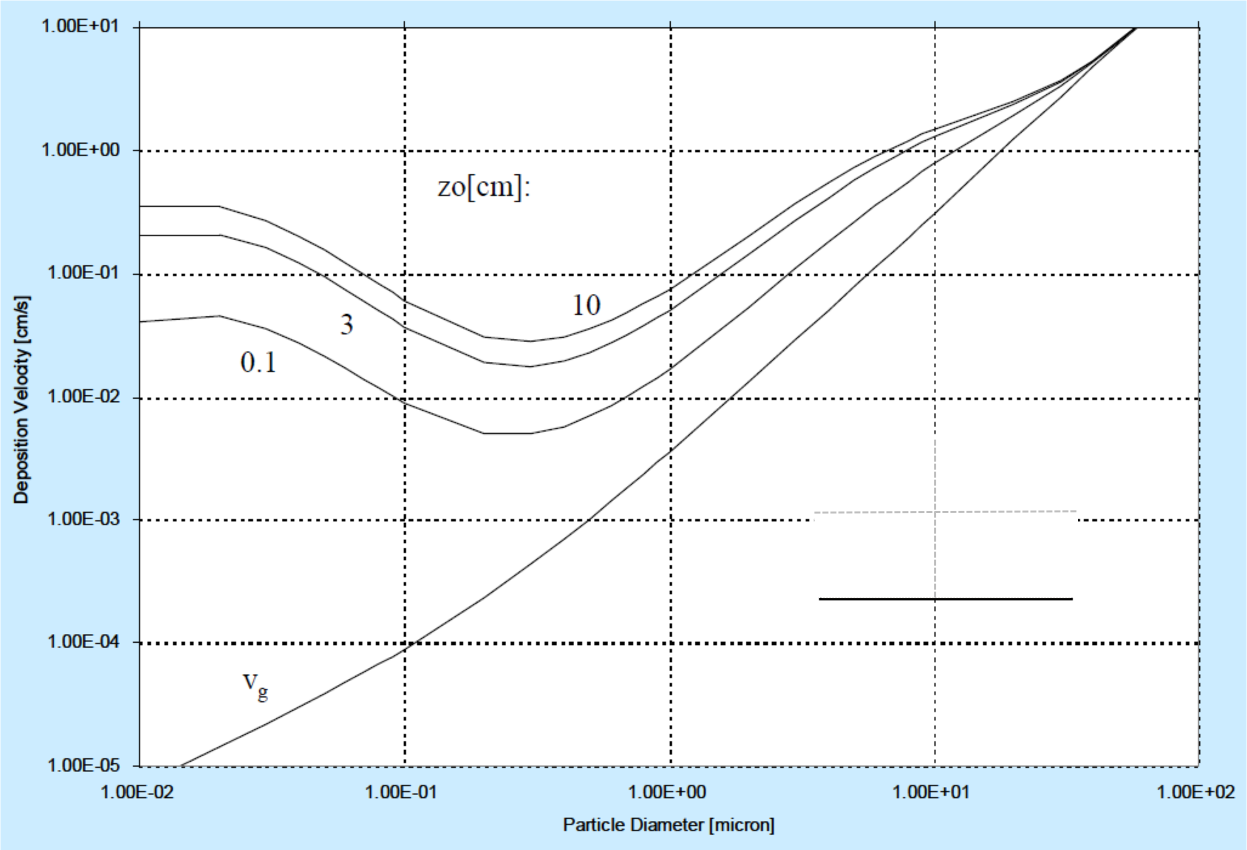
$\Delta t =$ plume residence time (s)

- **Approximate formula for deposition losses**

$$\frac{Q}{Q_0} = exp(-\frac{V_d\Delta t}{\bar{z}}) \qquad \bar{z} = \sqrt{\frac{\pi}{2}}(\frac{\sigma_z}{\bar{\bar{\Sigma}}})$$

Where Q is the material suspended in the plume (Bq) and Σ represents the summation term in the expression for σ_z (p. 5-24).

Average Deposition Velocities (cm/s)



Wet Deposition

- **Discontinuous (precipitation events)**
- **Rapid (relative to dry)**
  - **Λ = scavenging or washout rate (1/s)**
  - **Λ = function of precipitation type and rate, saturation conditions, contaminant characteristics**

$$\frac{dQ}{dt} = -\Lambda\ Q \quad ; \quad \frac{Q}{Q_0} = e^{-\Lambda \cdot \Delta t}$$

Δt = duration of precipitation (s)

$\Lambda = aI^b$

Λ = scavenging rate (1/s)

I = precipitation rate (mm/hr)

$a = 9.5\text{x}10^{-5}$

b = 0.8

Workshop Exercise 2 (Deposition)

- For the release of ^{137}Cs analyzed in the workshop example, what is the deposition (Ci/m^2) one-half mile downwind and at the mall?
- Assumptions (same as workshop example):
  - No rain
  - V_d = 1 cm/sec
- How much of the plume would have deposited prior to the mall if it had been raining steadily throughout the plume's path at a rate of 1 inch/hour?

Dose Pathways to People

- **Calculating doses begins with estimating two basic quantities**
  - **Time integrated air concentration, χ**
  - **Ground concentration, D**
- **Internal**
  - **Direct inhalation**

    Dose = χ x (Breathing Rate) x SF_{Inh} x DCF_{Inh}
  - **Ingestion**

    Dose = D x (Area Occupied by Crop) x (Transfer Factor) x (Fraction Consumed) x SF_{Ing} x DCF_{Ing}
  - **Resuspension inhalation**

    Dose = D x (Resuspension Factor) x (Breathing Rate) x SF_{Inh} x DCF_{Inh}

Dose Pathways to People (cont'd)

- **External**
  - **Cloudshine (Immersion)**

    Dose = χ x SF_{CS} x DCF_{CS}
  - **Cloudshine (Finite Cloud)**

    Dose = χ x SF_{CS} x Finite Cloud Correction Factor x DCF_{CS}
  - **Groundshine**

    Dose = D x SF_{GS} x DCF_{GS}

Internal Pathways

- **Inhalation**
  - **Breathing rate (20-30 m^3/day, 23 m^3/day used by NRC)**
  - **DCF = inhalation dose conversion factor (function of radionuclide) (e.g., ^{137}Cs $DCF_{inh} = 3.2E^{-2}$ rem/μCi EDE)**
- **Ingestion**
  - **Water**
    - **Drinking**
    - **Bathing**
  - **Crops**
    - **Deposition onto plants (leafy vegetables)**
    - **Deposition of irrigation water onto plants**
    - **Root uptake (other vegetables)**
  - **Animal products (dairy and meat)**
    - **Feed**
    - **Water**
    - **Dirt**
    - **Accumulation factor**

Workshop Exercise 3 - Internal Exposure (Inhalation)

- **Continuing the workshop example, what is the effective inhalation dose to an individual located on the mall who is present at the time the plume is passing? Account for dry deposition as in Exercise 2a.**

Resuspension Inhalation

- **Contaminated soil resuspends in atmosphere from wind depending on**
  - **Particle size**
  - **Surface roughness**
  - **Vegetative cover**
  - **Wind speed**
- **Mechanical (vehicles, walking)**
- **Resuspension diminishes over time from**
  - **Weathering (removal by overland runoff, leaching, covering)**
  - **Radioactive decay**
- **Air concentration is usually calculated from an empirical equation**

$$C = kD \qquad k = C_1 \cdot 2^{-t/H_1} + C_2 \cdot 2^{-t/H_2} + C_3 \cdot 2^{-t/H_3}$$

Emergency Phase

i	C_i (m^{-1})	H_i (yr)
1	10^{-4}	0.05

Long-Term Phase

i	C_i (m^{-1})	H_i (yr)
1	10^{-5}	0.5
2	10^{-7}	5
3	10^{-9}	50

Workshop Exercise 4 - Resuspension

- **For the workshop example, what would be the average concentration of ^{137}Cs in air at the mall one year after the plume has passed? Hint: ground concentration was calculated previously to be 8.57×10^{-9} Ci/m^2. Half life for ^{137}Cs is 30 yr.**

Finite Cloud Dose Correction Factors

Diffusion Parameter $\sqrt{\sigma_y \sigma_z}$ (m)	Dimensionless Distance to Cloud Centerline $\sqrt{y^2+z^2}/\sqrt{\sigma_y \sigma_z}$ (Unit of Effective Plume Size)					
	0	1	2	3	4	5
3	0.020	0.018	0.011	0.007	0.005	0.004
10	0.074	0.060	0.036	0.020	0.015	0.011
20	0.150	0.120	0.065	0.035	0.024	0.016
30	0.220	0.170	0.088	0.046	0.029	0.017
50	0.350	0.250	0.130	0.054	0.028	0.013
100	0.560	0.380	0.150	0.045	0.016	0.004
200	0.760	0.511	0.150	0.024	0.004	0.001
400	0.899	0.600	0.140	0.014	0.001	0.001
1000	0.951	0.600	0.130	0.011	0.001	0.001

Note: Data from Reactor Safety Study Table VI 8-1 with correction of a typographic error of data. For 0.7 MeV gamma photons.

6. Health Effects and Economic Consequences

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Outline

- Objectives
- Background
- Dose response
- Dosimetry
- Health effects and risk
- Economic consequences
- References
- Summary

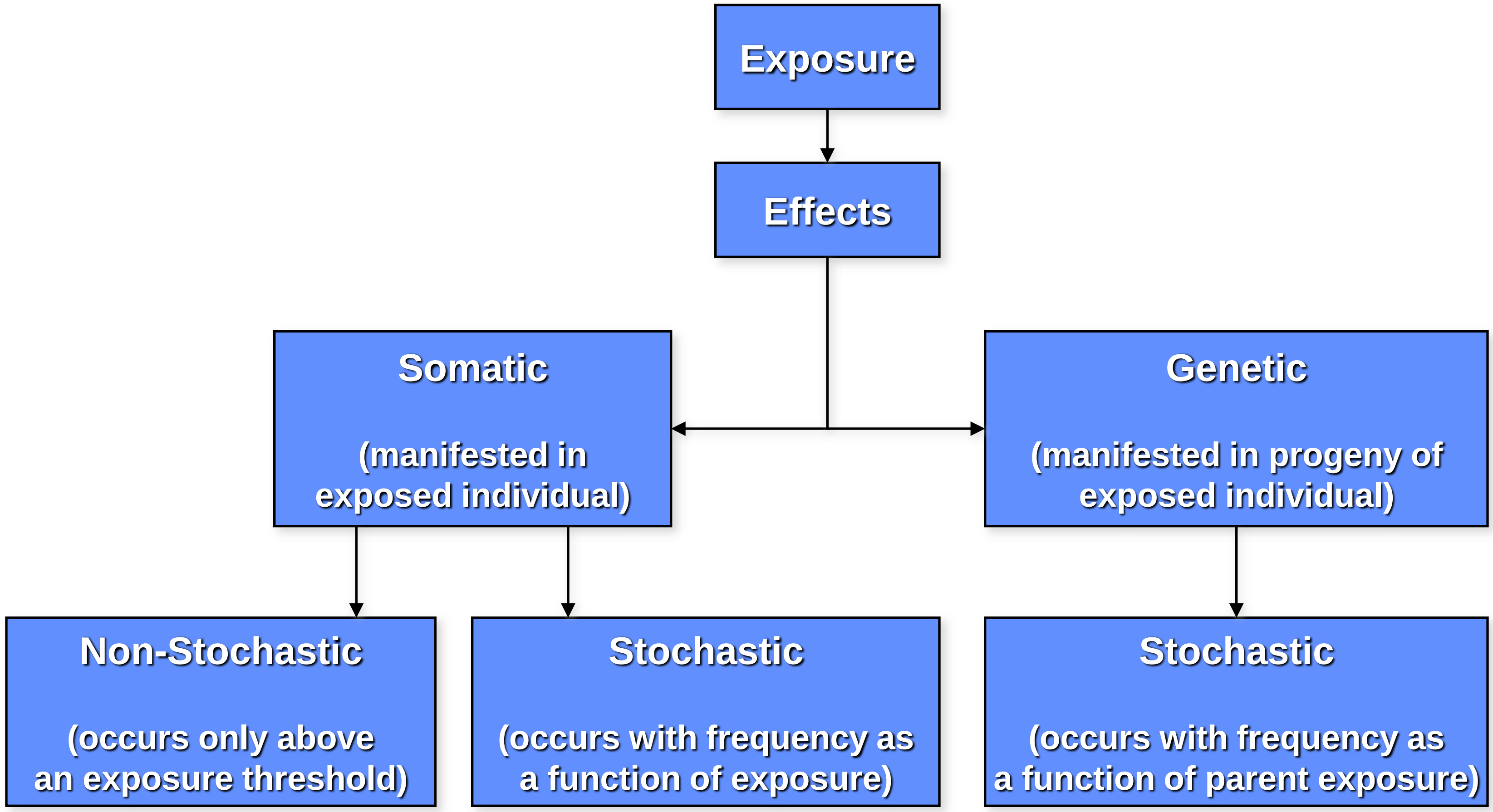
Objectives

- Learn the basis for relating exposure to health effects
- Understand categorization of health effects
- Be able to calculate health effects for a given dose
- Learn about past and present research done in the health effects area
- List the costs that are calculated by MACCS
- Describe the general formulas relating to the various types of costs
- Discuss other real costs not calculated

Effects of Radiation on Cells

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

Radioactive Exposure can Induce Somatic and Genetic Health Effects



Dose-Response Curves

Relationship for a population between dose and response

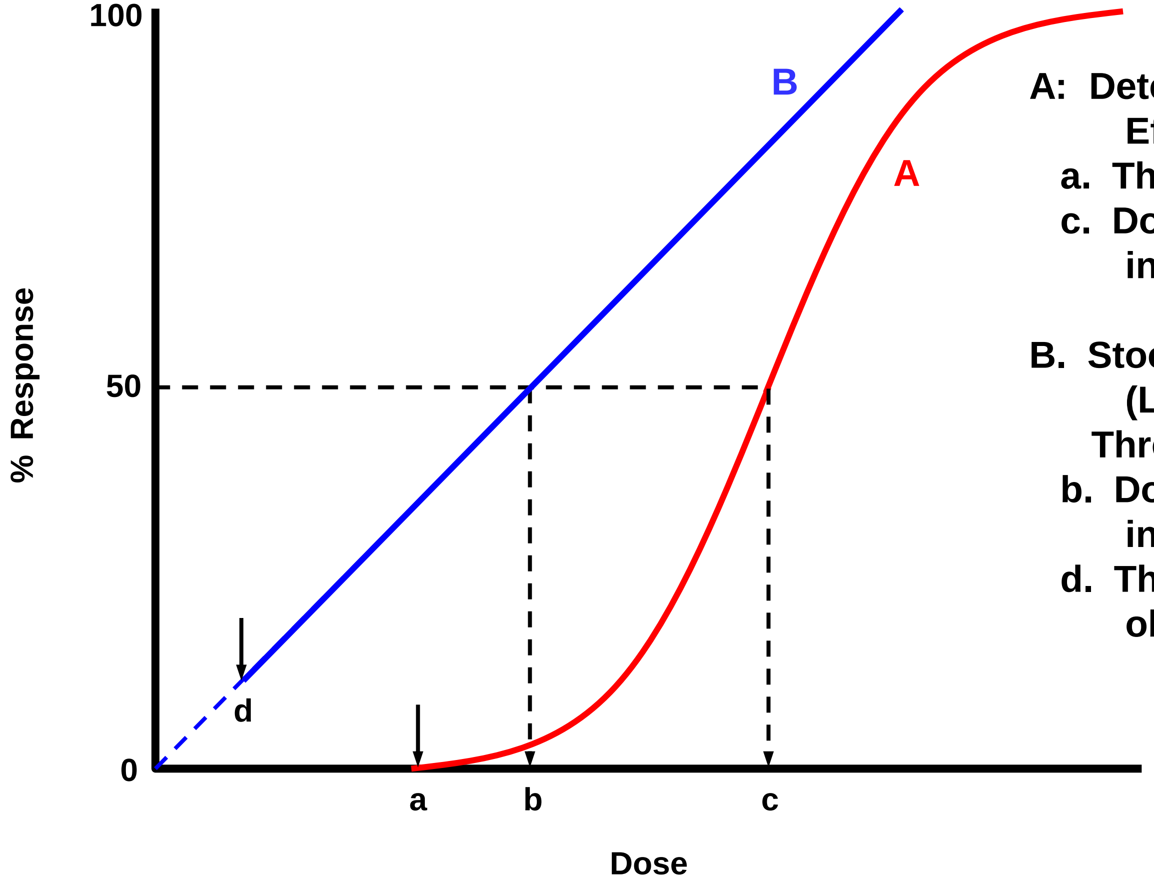
Response varies with end point of interest:

- **Type of acute injury or syndrome**
- **Site of solid tumor**
- **Leukemia**

Response depends on other factors

- **Quality factor of radiation (radiation weighting factor)**
- **Dose rate**
- **Sex**
- **Age at exposure**
- **Other**

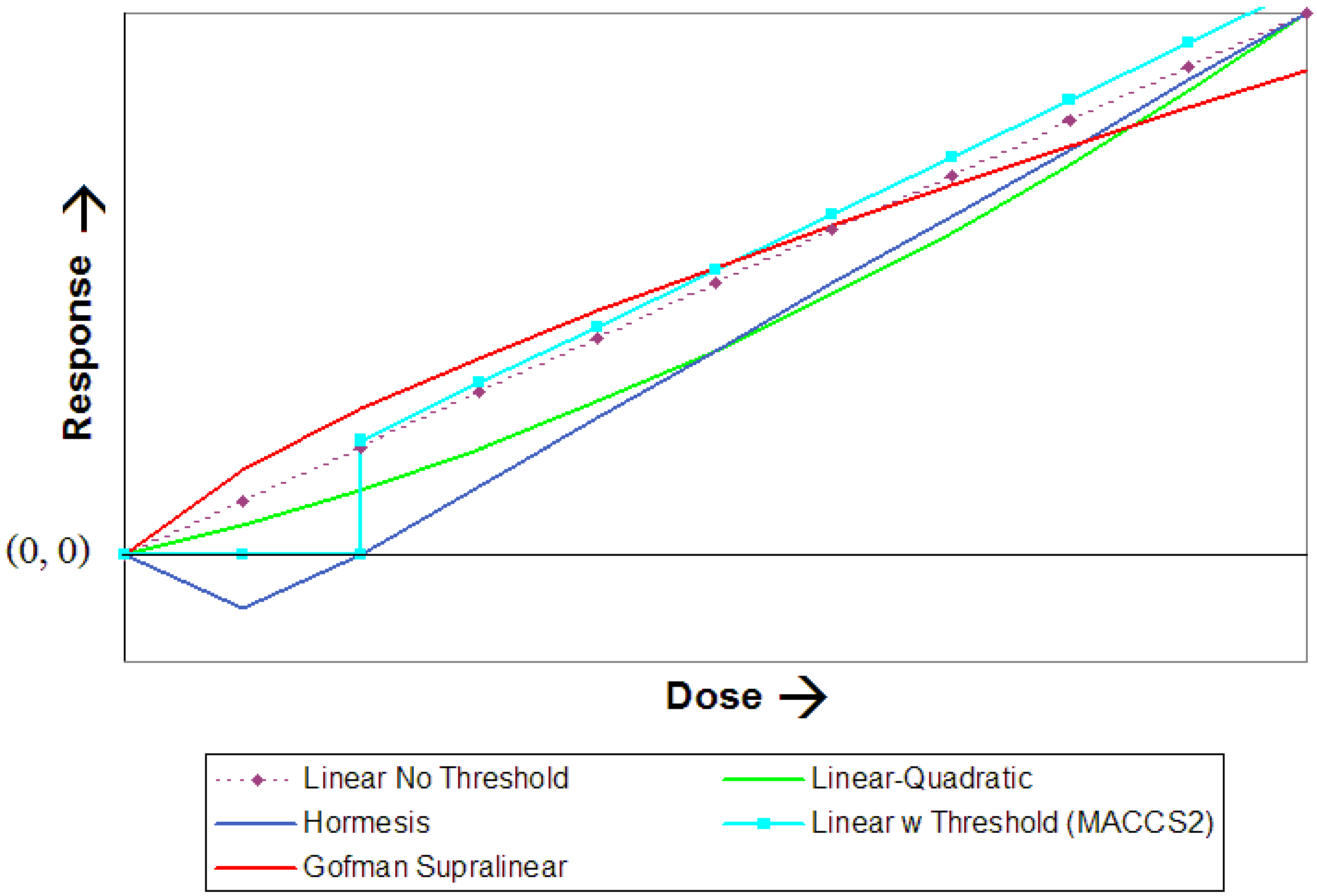
Dose-Response Curves



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

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

Other Possible Dose-Response Curves for Stochastic Health Effects



Dose-Response (DR) Curves In WinMACCS

- **DR 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" windows**

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 CHRONC**
- **Acute Exposure Characteristics:**
  - **Dose ≥ 10 rad or 0.1 Gray (10^3 erg/gram)**
  - **Exposure duration up to a few days (EARLY ≤ 1 week)**
  - **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 depend on dose.**

Acute Doses and Effects

Table of Acute Doses and Frequency of Acute Health Effects Assuming Minimal Medical Support

Prodromal Effects (rad illnesses)		**Acute Fatalities**	
Whole Body Absorbed Dose (rad)	Percent Affected	Whole Body Absorbed Dose (rad)	Percent Affected
50	2	140	5
100	15	200	15
150	50	300	50
200	85	400	85
250	98	460	95

FRMAC Radiological Response Manual, Vol. 2. (2003) SAND2003-1072P

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 chance to distort the 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 <u>if</u> 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 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 in the quantities equivalent and effective dose. • 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 now 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. • The fluence to effective dose conversion coefficients were derived from the obtained organ dose conversion coefficients, the radiation weighting factor W_R and the tissue weighting factor W_T, following the procedure described in ICRP Publication 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

- 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, and Skin = 50 rem
- Commission Direction:
  - Develop regulatory basis for revision to 10 CFR 20 to align with the most recent methodology and terminology for dose assessment (i.e., change tissue weighting factors to ICRP 103, adopt current metabolic models, etc.)
  - Disapproved staff recommendation to develop regulatory basis to reduce occupational Total Effective Dose Equivalent (TEDE)
  - Continue discussions regarding possible revision to dose limit for the lens of the eye. Staff recommended considering single values for 5 rem (50 mSv) or 2 rem (20 mSv) per year versus the current 15 rem (150 mSv) per year
    - ICRP recommends 2 rem (20 mSv) average over 5 years, with 5 rem (50 mSv) maximum per year.
  - Continue discussions regarding reducing embryo/fetus dose limit from 500 mrem to 100 mrem, and consider applying over entire gestation period or only after declaration.
    - ICRP recommends 100 mrem (1 mSv) applied after declaration.

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

- **Absorbed dose, D; proportional to the absorbed energy; expressed in rad or gray:**
  100 rad = 1 J/kg = 10^4 erg/gram = 1 gray
- **Dose Equivalent to tissue "T"; H_T (rem or Sv)**

  Dose equivalent takes into account the effectiveness of different types of radiation in causing stochastic health effects (latent cancers and heritable effects).

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

- **Quality factor, Q. Per ICRP 26 and 10 CFR 20:**

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":**

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

W_R is analogous to "Q" in ICRP-26 and 10 CFR 20.

- **Equivalent dose to a tissue needed to determine stochastic health effects**
- **Radiation weighting factor, $W_{R,}$ from ICRP 60:**

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.

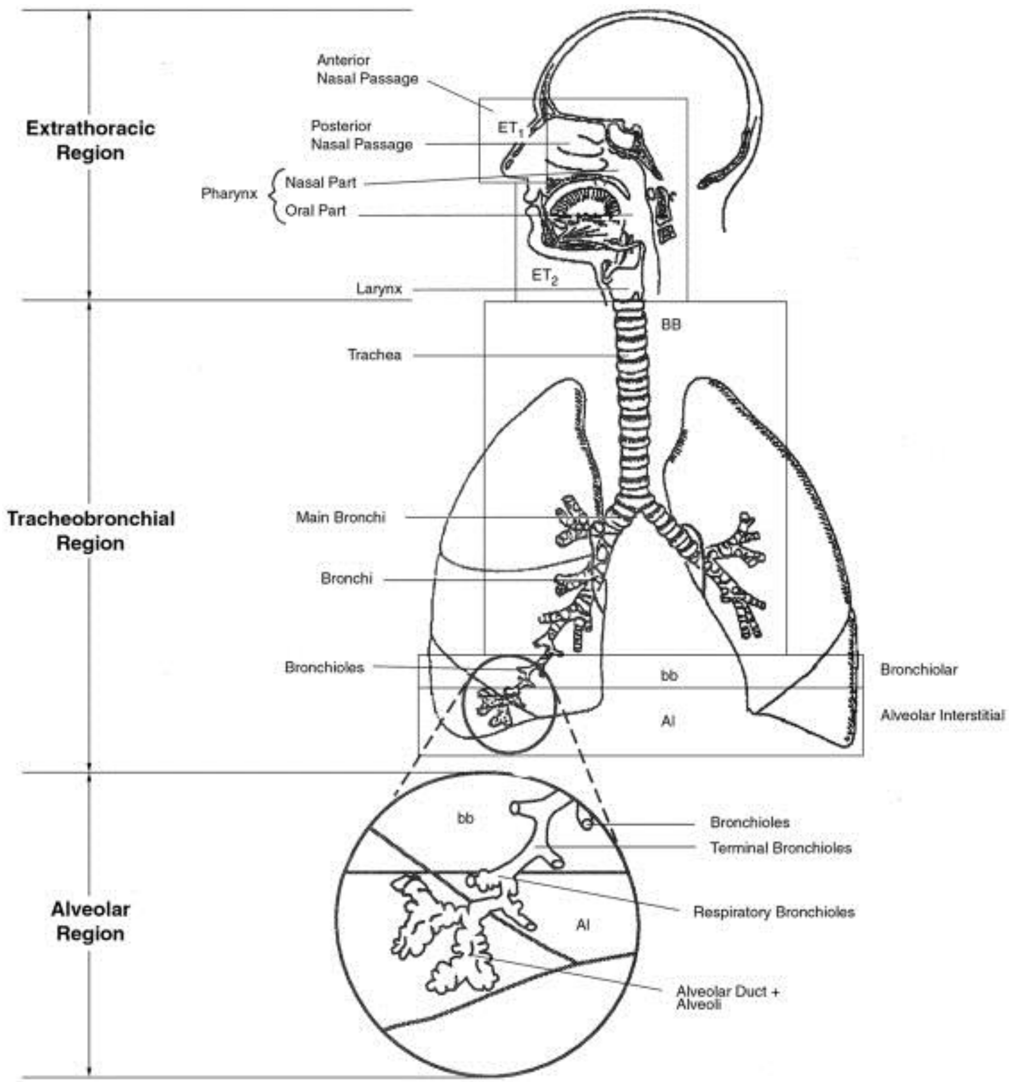
***SECY-08-0197**

Radiation Weighting Factor Comparison*

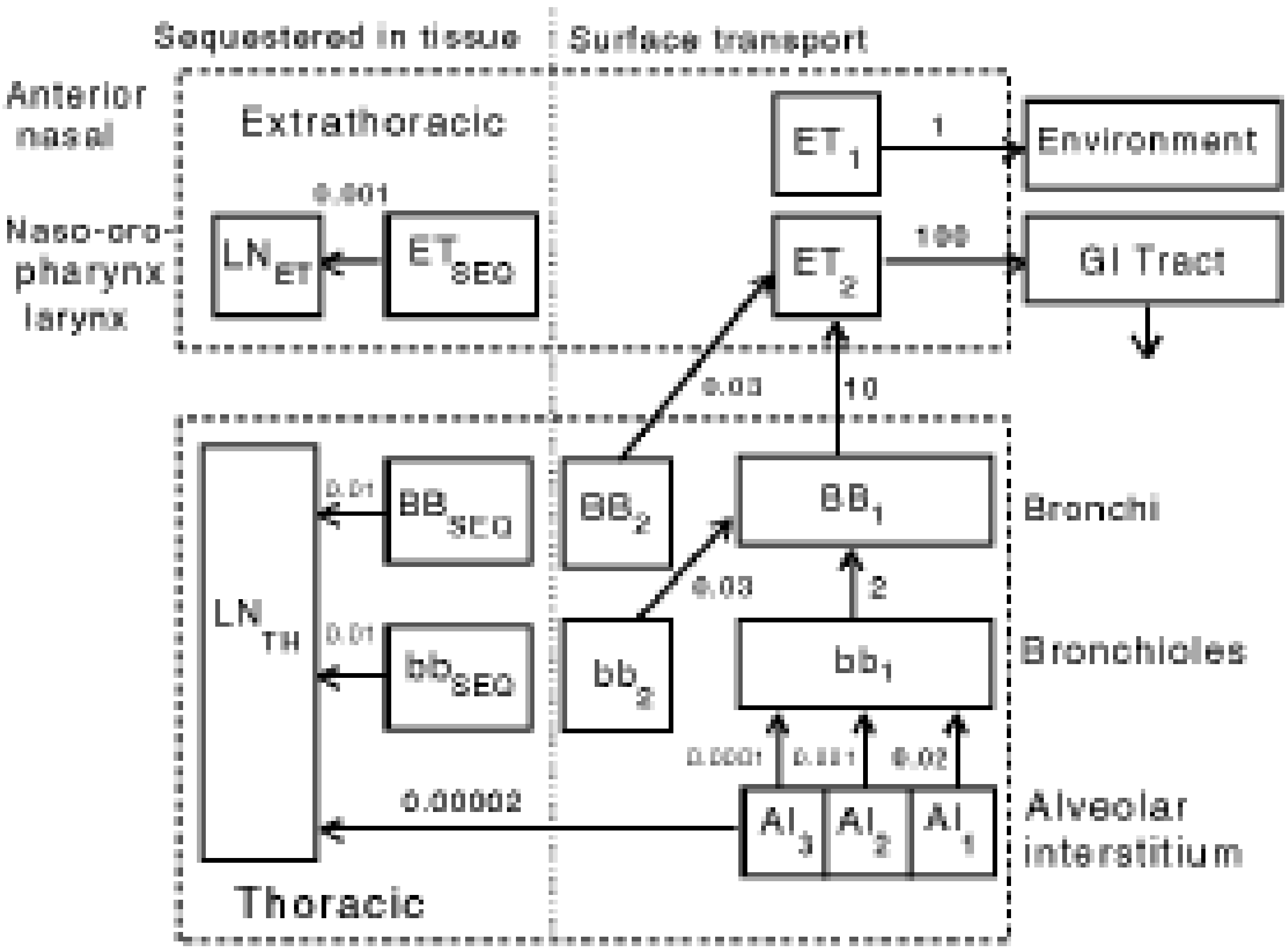
Issue	ICRP 26	ICRP 60	ICRP 103	Part 20
Radiation Weighting Factors, w_R				
Photons, all energies	1	1	1	1
Electrons and muons, all energies	1	1	1	1
Neutrons, all (unknown) energies	10	Step function	continuous function	10
< 10 keV		5	2.5	2 to 2.5
10 - 100 keV		10	2.5 to 10	2.5 to 7.5
100 - 2 MeV		20	10 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 Respiratory Tract Model (1994)



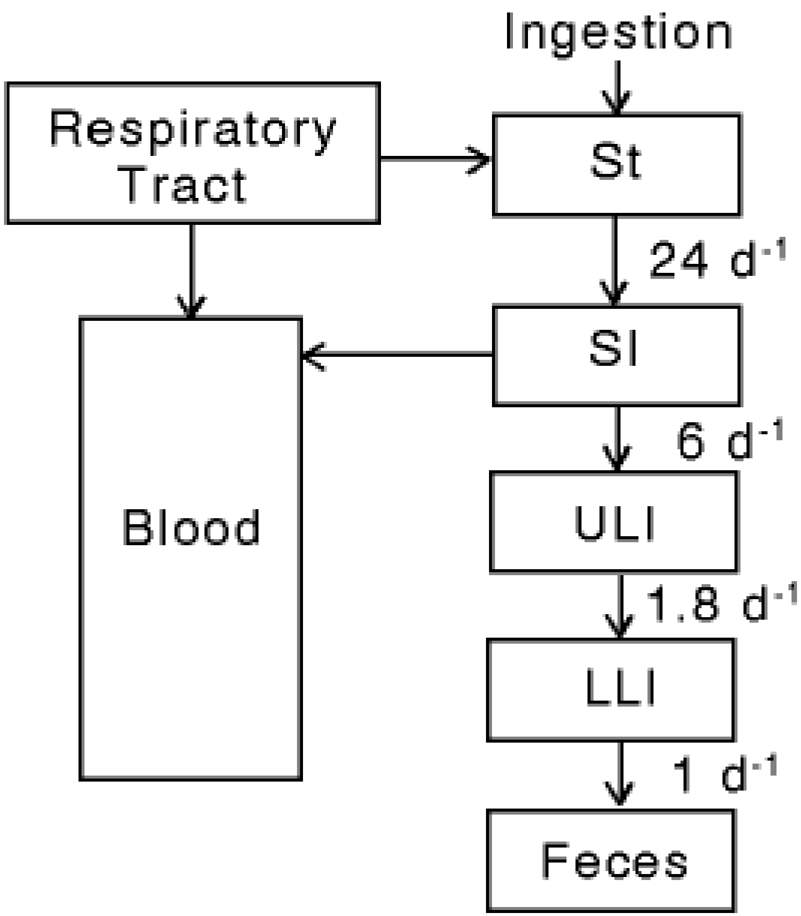
ICRP Respiratory Tract Model (1994)



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

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

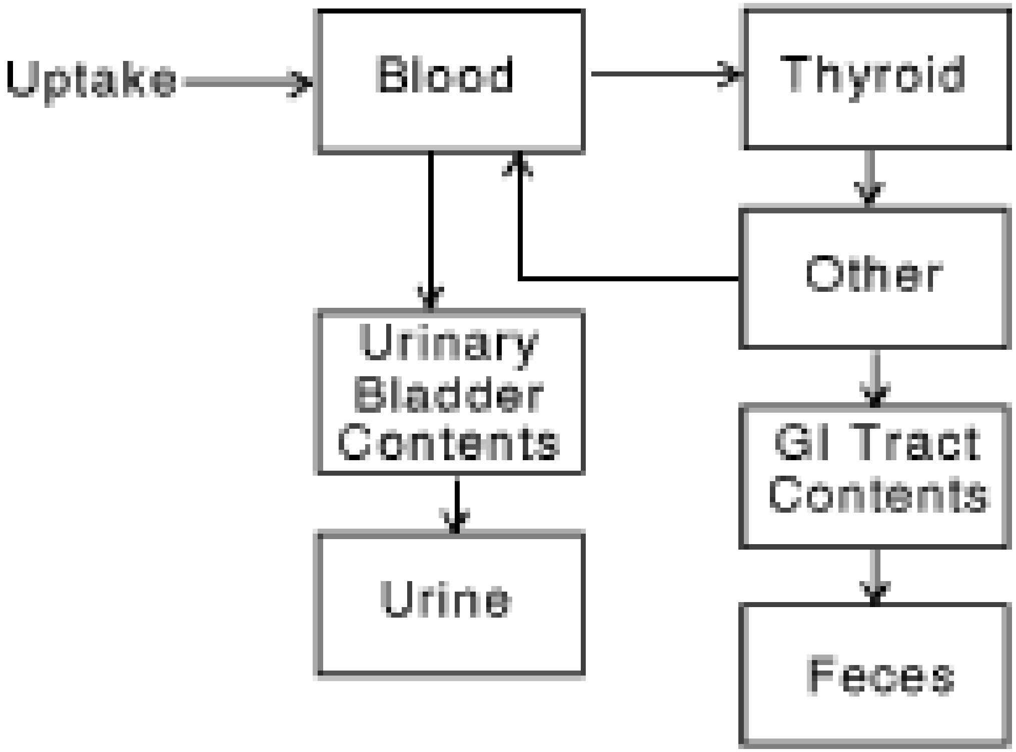
ICRP Gastrointestinal Tract Model (1979)



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

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

ICRP Biokinetic Iodine Model (1989)



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

Doses from Inhalation

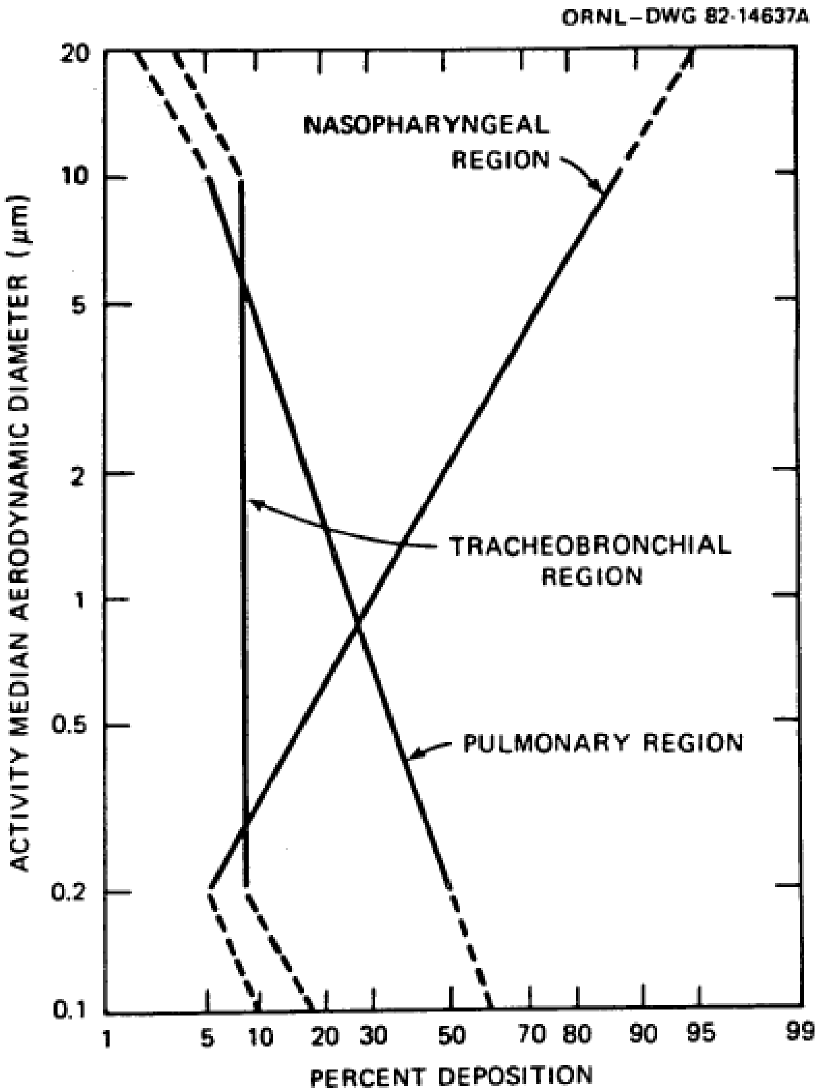
- **Based on Lung Clearance Model**
  - **How fast is the isotope removed from the respiratory passage**

Clearance Class	Pulmonary Region Clearance Half-Time (days)
Y or S	> 100
W or M	10-100
D or F	< 10

- **Activity Mean Aerodynamic Diameter (AMAD) (μm) –** The diameter of a unit density sphere with the same terminal settling velocity in air as that of an aerosol particle whose activity is the median for the entire aerosol.

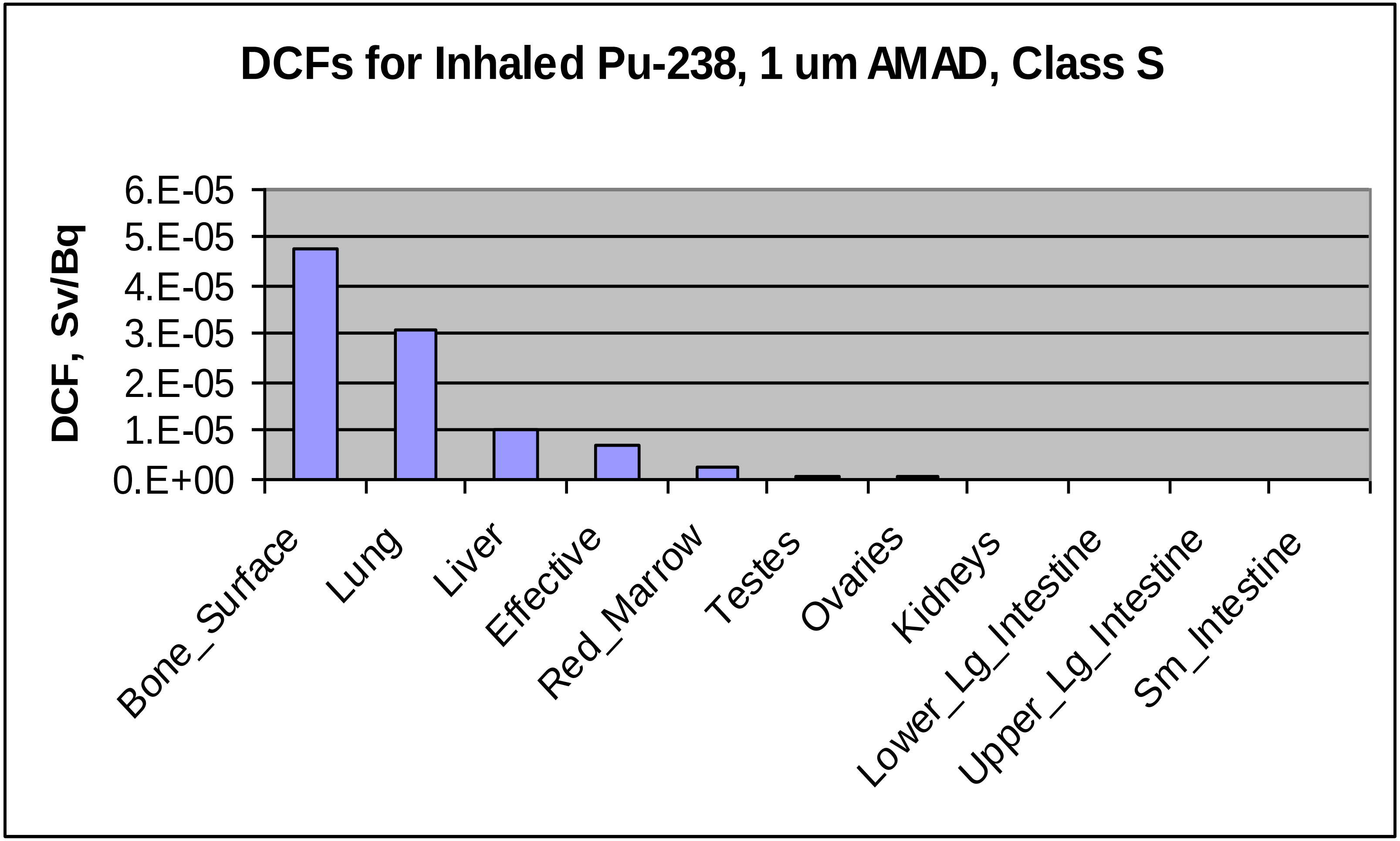
Doses from Inhalation

- **Respiratory deposition is a function of Activity Mean Aerodynamic Diameter (AMAD) [ICRP 30]**



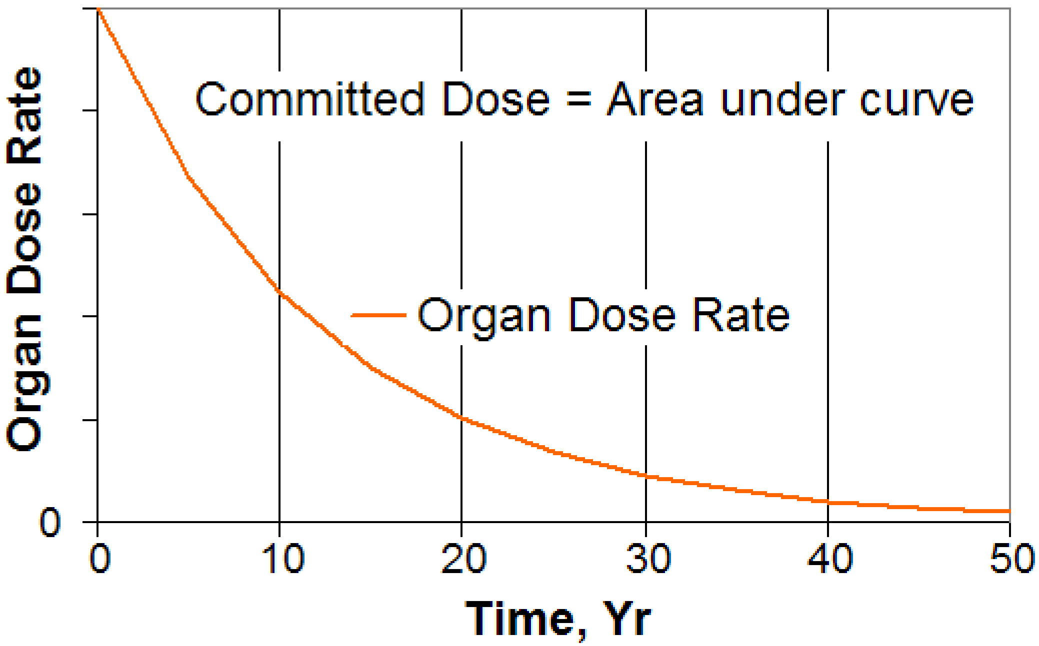
Non-Uniform Irradiation

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



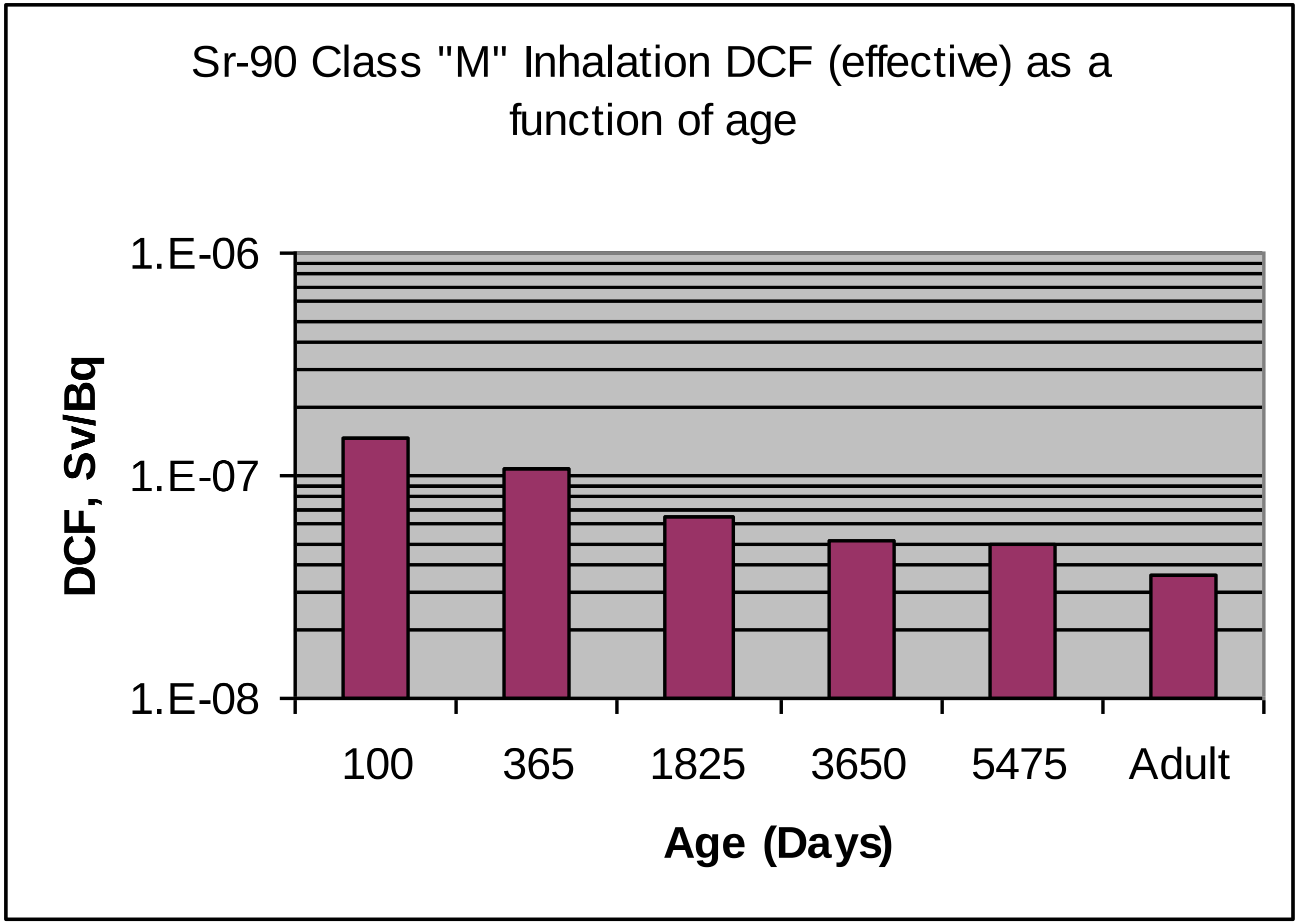
Doses from Inhalation and Ingestion

- **Committed dose**
  - **Dose equivalent received in a period of time following an intake of radioactive material.**



Doses from Inhalation and Ingestion

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



Dose Conversion Factor (NUREG-3332)

based on ICRP 30

Table 7.19. Committed dose equivalent per unit intake via inhalation (Sv/Bq)

Nuclide		Clearance class	f_1	Gonads	Breast	R. Marrow	Lungs	Thyroid	Endosteal	Remainder	Effective
H	3		1.0E 00	1.70E-11	1.70E-11	1.70E-11	1.70E-11	1.70E-11	1.70E-11	1.73E-11	1.70E-11
BE	10	W	5.0E-03	5.94E-10	5.94E-10	1.77E-08	4.22E-08	5.94E-10	5.26E-09	2.44E-09	9.75E-09
		Y	5.0E-03	2.56E-10	2.54E-10	7.65E-09	7.78E-07	2.56E-10	3.27E-08	3.35E-09	9.58E-08
C	14[a]		0.0	6.36E-12	6.35E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12	6.36E-12
C	14[b]		0.0	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10	5.64E-10
C	14[c]		0.0	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13	7.83E-13
NA	22	D	1.0E 00	1.77E-09	1.65E-09	2.73E-09	2.47E-09	1.60E-09	2.71E-09	2.00E-09	2.07E-09
NA	24	D	1.0E 00	1.78E-10	1.61E-10	2.13E-10	1.25E-09	1.53E-10	2.59E-10	2.35E-10	3.27E-10
P	32	D	8.0E-01	4.83E-10	4.83E-10	5.57E-09	2.50E-09	4.83E-10	5.81E-09	7.94E-10	1.64E-09
		W	8.0E-01	3.77E-10	3.37E-10	4.17E-09	2.56E-08	3.37E-10	4.05E-09	1.13E-09	4.19E-09
CA	41	W	3.0E-01	2.43E-12	2.78E-12	1.52E-09	4.53E-10	2.57E-12	3.65E-09	1.99E-11	3.64E-10
SC	46	Y	1.0E-04	1.70E-09	2.15E-09	2.21E-09	4.52E-08	2.02E-09	1.68E-09	4.79E-09	9.01E-09
CR	51	D	1.0E-01	2.71E-11	1.94E-11	2.58E-11	3.81E-11	1.82E-11	2.74E-11	3.55E-11	2.95E-11
		W	1.0E-01	2.21E-11	1.50E-11	1.37E-11	3.77E-10	1.10E-11	1.50E-11	4.93E-11	7.08E-11
		Y	1.0E-01	2.07E-11	1.58E-11	1.67E-11	5.34E-10	1.09E-11	1.30E-11	5.26E-11	9.03E-11
MN	54	D	1.0E-01	9.85E-10	9.13E-10	1.56E-09	1.18E-09	6.52E-10	2.56E-09	2.00E-09	1.42E-09
		W	1.0E-01	7.09E-10	6.59E-10	1.10E-09	6.66E-09	7.40E-10	1.25E-09	1.73E-09	1.81E-09
MN	56	D	1.0E-01	2.19E-11	1.47E-11	2.36E-11	4.40E-10	1.20E-11	2.05E-11	1.26E-10	1.02E-10
		W	1.0E-01	6.46E-12	7.79E-12	1.92E-11	5.37E-10	6.13E-12	8.23E-12	6.50E-11	8.91E-11

f_1 = fractional absorption of swallowed activity from respiratory to GI tract

Doses from Inhalation and Ingestion

Acute Organ Dose Coefficient Sources

1. *ICRP database* (ICRP 1998): Q=20 for high LET, not recommended for acute health calculations, workers and several age groups, and based on ICRP-68, ICRP-72
2. *DOSFAC2:* Limited to workers, 60 isotopes, ICRP-30 based, used by MACCS2, and uses high LET Q=10 for acute coefficients
3. MACCS dose factors based on Federal Guidance Report 13: adults only, uses high LET Q=10 for acute coefficients
4. Federal Guidance Report 13: several ages, unweighted absorbed dose rates, calculated using ORNL's DCAL software package

Dose Factor Files in MACCS

Files Generated by FGRDCF utility

- External, FGR-12:
  - ground surface (Sv-m^2/Bq-sec)
  - air submersion (Sv-m^3/Bq-sec)
- Internal, FGR-11, weighting based on ICRP-26/30, only 50-yr dose commitment coefficients. (Sv/Bq)
- Adult only
- No support for acute health effects
- 825 radionuclides
- Department of Energy users

Dose Factor Files in MACCS

Files based on DOSFAC2 utility

- External factors from DOE/EH-0070 (older than FGR12)
- Internal factors from FGR-11, tissue weighting based on ICRP-26 and ICRP-60
- Only isotopes important to reactor accidents (60)
- Adult only
- Choice of particle size values
- Acute, annual, and 50-yr DCFs
- NRC users
- Considered obsolete

Dose Factor Files in MACCS

FGR13DCF files

- 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, current (1990s) metabolic models
- 825 isotopes
- Adult, but data are available to calculate internal factors for other age groups (newborn, 1, 5, 10, 15 yrs & adult male)
- 1 μm particle size, but data are available for other sizes
- Acute, annual, and 50-yr DCFs

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) – Published. *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

Radiation Epidemiology: New Research

INWORKS Study

- Retrospective cohort study design
- 308,000 occupationally exposed workers in US, France and the United Kingdom
- 8.2 million person years of follow-up
- Mostly low-dose exposure histories
- Results generally consistent with Life Span Study assuming a dose and dose rate reduction factor of 1

Risk of Cancer from Occupational Exposure to Ionising Radiation: Retrospective Cohort Study of Workers in France, the United Kingdom, and the United States (INWORKS). David B. Richardson et al. British Medical Journal, 2015; 351:h5359

Radiation Epidemiology: New Research

- NCRP 1 million Worker Study (Boice, 2013)
- Sources of Data
  - Landauer microfilm dosimetry reports
  - NRC Radiation Exposure Information and Reporting System (REIRS)

Characteristic	Million Worker Study	Atomic Bomb Survivor Study
Number Studied	~ 1,000,000	86,611 with doses estimates
Exposure Year/s	~1940 - ~1985	1945
Number of Death to Date	~ 400,000	50,620
Number > 100 mSv	> 27,000	18,444
Estimated Deaths due to Radiation	To Be Determined	~ 600

Ozasa et al, *Rad Res* 177; 2012

Cancer and Non-Cancer Health Effects

- Development of lethal and non-lethal cancers
- Somatic 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
  - Childhood cancer
  - 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*)

Life Span Study Cohort of A-Bomb Survivors: Non-Cancer* Risk (Preston, 2003)

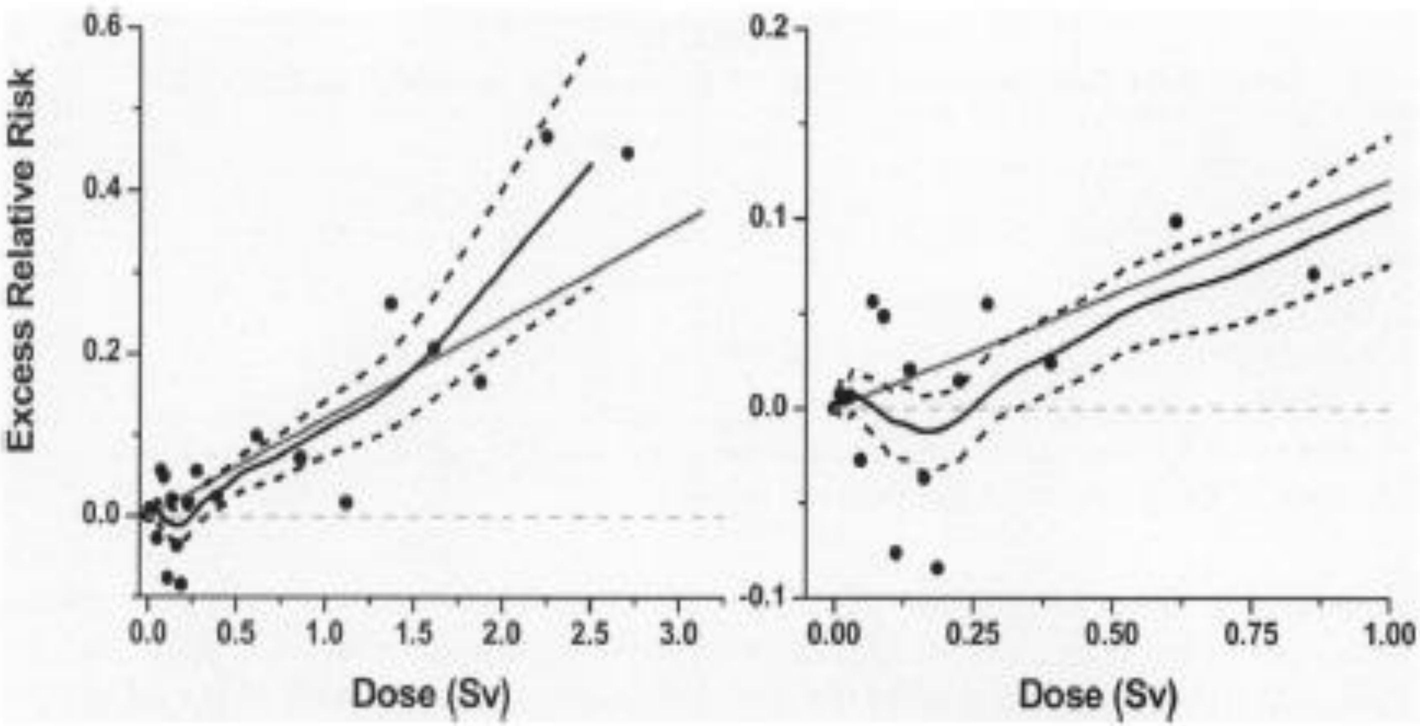
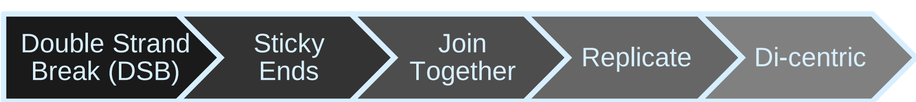


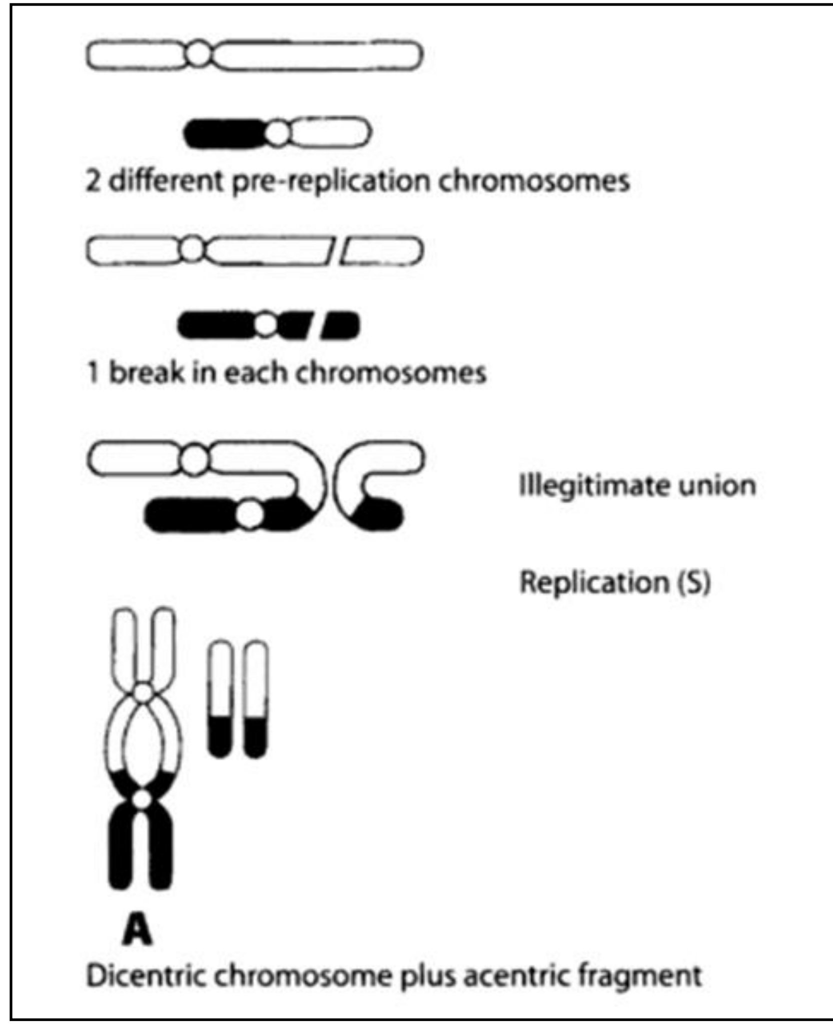
FIG. 10. Noncancer dose–response function for the period 1968–1997. The solid straight line indicates the fitted linear ERR model without any effect modification by age at exposure, sex or attained age. The points are dose category-specific ERR estimates, the solid curve is a smoothed estimate derived from the points, and the dashed lines indicate upper and lower one-standard-error bounds on the smoothed estimate. The right panel shows the low-dose portion of the dose–response function in more detail.

***Non-cancer refers to other diseases that occur from radiation exposure (e.g., stroke, heart disease, etc.)**

Health Effects

- **Early Acute Effects:** ***hematopoietic, gastro-intestinal, pulmonary, early transient incapacitation***
- **Genetic Effects**
  - **Chromosome abnormalities: rings, di-centrics, and translocations**
  - **Heritable: mutation doubling dose ~ 1Gy (100 rad) per BEIR VII, trisomies, spontaneous abortion, malformations**





Levitt, 2008

Health Effects

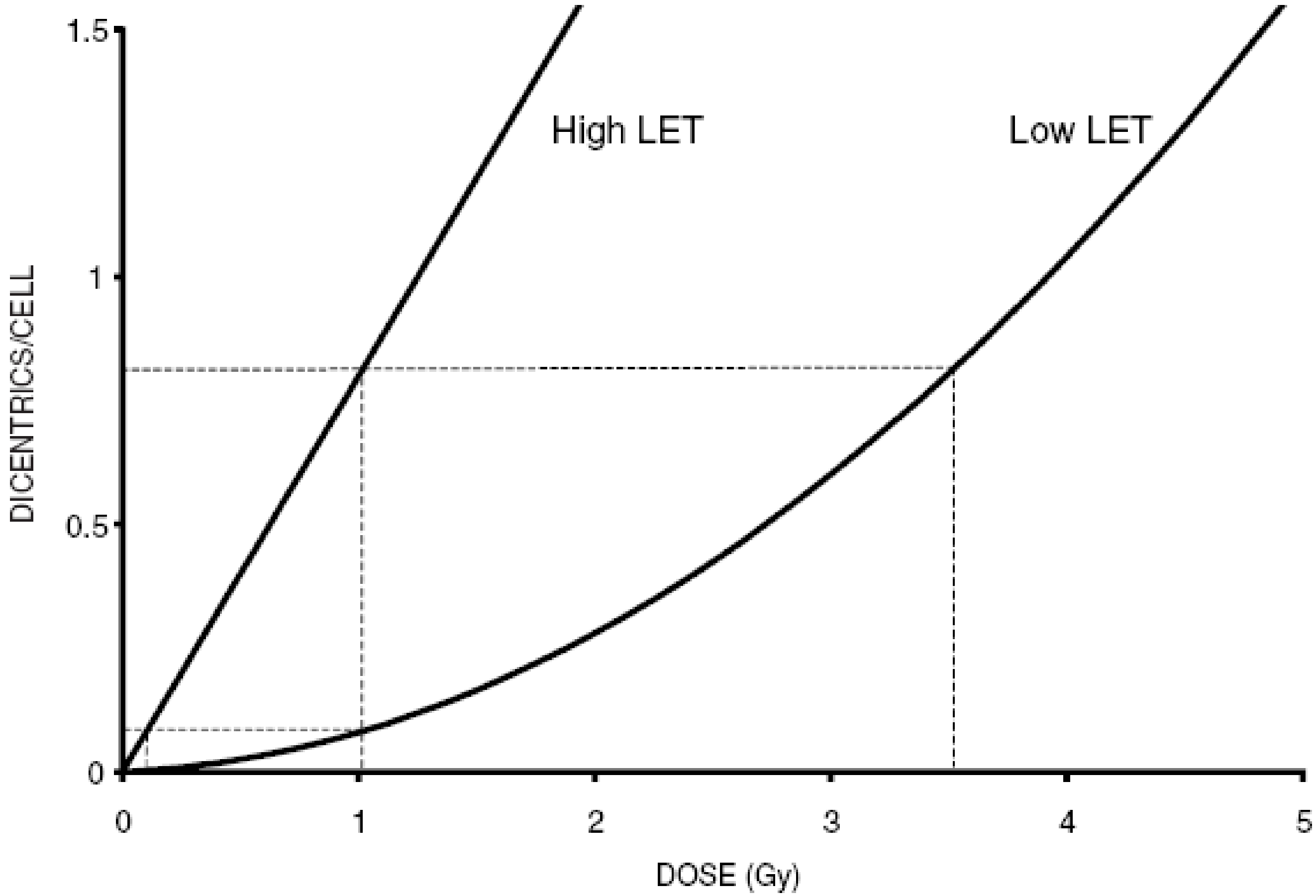
Two dicentric chromosomes and one centric ring with their associated fragments.

IAEA Report 405.

Health Effects

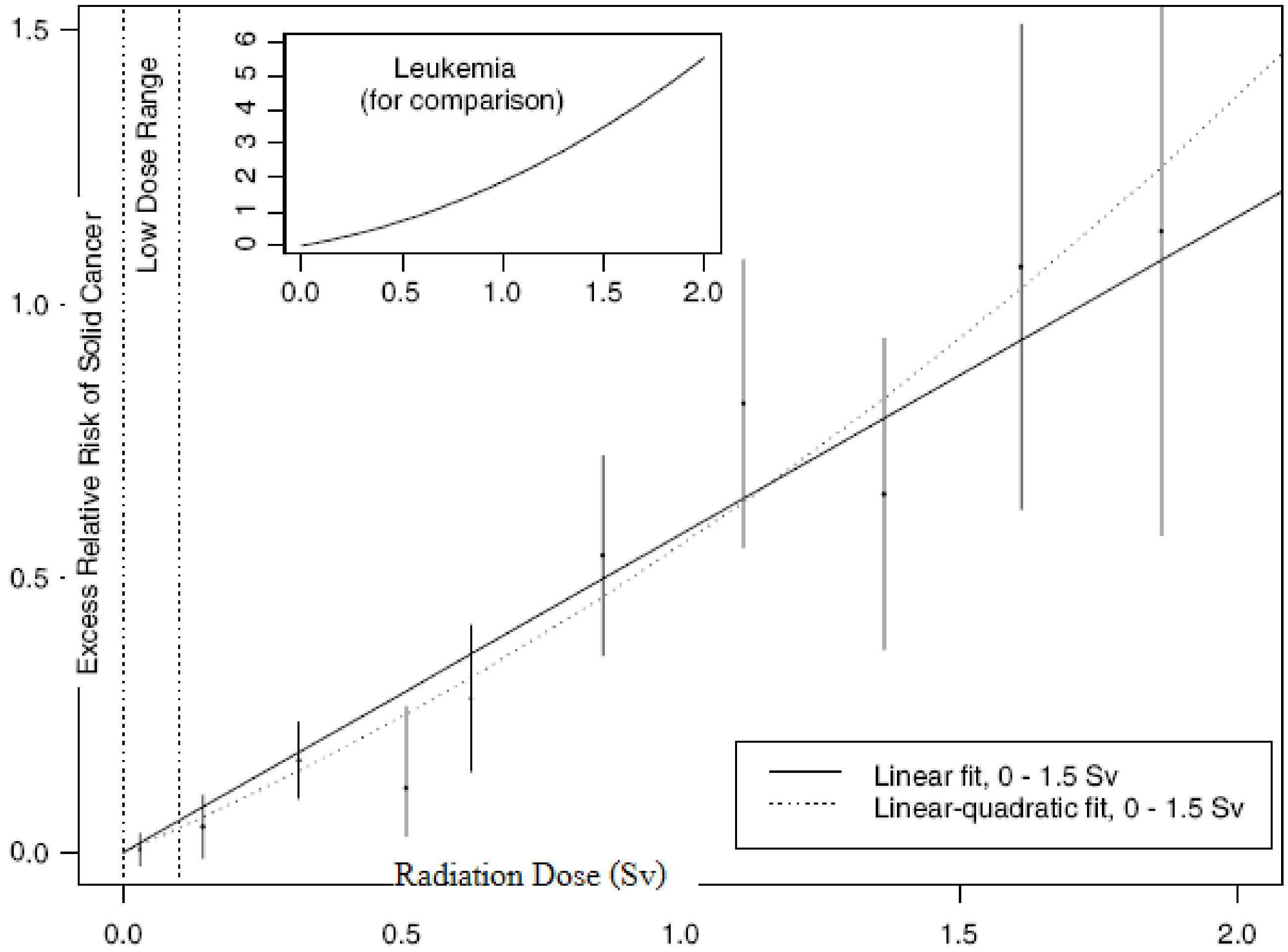
Low LET Dose-Response Curve (Linear-Quadratic)
<u>Examples</u>
•High Energy Protons
•Fast Neutrons

High LET Dose-Response Curve (Linear)
<u>Examples</u>
•Fission Neutrons
•Alpha Particles



Typical linear and linear quadratic dose response curves showing how dicentric formation changes with dose. IAEA Report 405 (2001).

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***

- For an easier read, see the Lawrence Berkeley National Laboratory article at http://newscenter.lbl.gov/news-releases/2011/12/20/low-dose-radiation/

- ICRP Publication 99: Life Span Study indicates that if there is a threshold, then it appears to be below 6 rem, if a threshold exists at all.

Carcinogenic Effects

- BEIR VII uncertainty estimate: +100% to -50%
- Older BEIR V cancer death estimates following a 0.1 Gy acute dose to each of 100,000 persons: 800. Also provides organ-specific risk estimates
- 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
  - This implies that the risk per unit dose observed at high acute doses should be divided by 2 before applying to low dose
  - "Low Dose" < 0.2 Gy and "Low Dose Rate" < 0.1 mGy/min
- "Calculation of the number of cancer deaths based on collective dose from trivial individual exposures should be avoided" (ICRP 103)

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. Appropriate for doses less than about 0.4 Gy. Values based on 0.1 Gy.

Exercise 5

- **Open WinMACCS Projects/SOARCA/SurryR7/SurryISLOCA**
- **Go to "Latent Cancer Parameters" under "Early" and:**
  - **Update the values in the Cancer Incidence Risk (CIRISK) and Cancer Fatality Risk (CFRISK) columns with BEIR VII values (previous slide) for <u>Colon, Liver, Lung, Breast, Thyroid, and Leukemia</u>**
  - **Update the DDREFA values from the BEIR V value of DDREFA = 2 to the BEIR VII value of DDREFA = 1.5. The value for Breast remains DDREFA = 1.**
- **Under Early>Output Control>Health Effect Cases, verify that "CAN INJ/TOTAL" and "CAN FAT/TOTAL" are requested for 0 to 80 km (Hint: refer to ATMOS for distances corresponding to integer values).**
- **Under General>Properties>Weather tab, switch to Uniform Bin Sampling.**
- **Go to the "Weather/Samples per Bin" under "ATMOS" and set NSMPLS = 2.**
- **Run the problem.**
- **What is the maximum value of "peak dose on spatial grid" for cohort 6 beyond 0.5 km?**
  - **Answer: 17.9 Sv. Since above ~0.4 Sv, the BEIR VII risk for Leukemia shouldn't have been treated as linear.**
- **What are the overall numbers of cancer injuries and cancer fatalities within 50 miles?**
  - **Answer: BEIR V numbers are 2,280 injuries and 999 fatalities; BEIR VII numbers are 3,230 injuries and 1,280 fatalities.**

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:** $\mathbf{Risk = \alpha Dose + \beta Dose^2}$
  - ***BEIR III***
  - ***BEIR VII for leukemia***
  - **Relative importance of 2 terms varies for different tissues**
  - **Balance of 1 track (one cell break) and 2 track (chromosomal aberration consequence of interactions between breaks in 2 separate chromatids)**
  - **Dose at which 2 terms are equal: 100-1000+ rads BEIR III**
  - **Original equation in MACCS; retained but not 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 most 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 Seivert (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, stroke). Noted in BEIR VII, discussed in UNSCEAR 2006 report.**

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

Acute dose coefficients in "FGR13DCF.inp" and "DOSDATA20Organs.inp" are the risk-weighted sum of dose coefficients for day 0-1, 1-7, …, 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

$$D_t = \text{absorbed dose (Gray) delivered to the target organ "T" over time "t"}$$

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

$$x_T = \text{normalized dose to organ "T" for a particular effect}$$

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

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

MACCS Early Health Effects Model

Early Health Effect and Dose Threshold (Gy)	LD_{50} or D_{50} (Gy) Time Period (days)							
	0-1	**2-7**	**8-10**	**11-14**	**15-21**	**22-30**	**31-200**	**201-365**
Hematopoietic Syndrome – 1.5	3.8	-	-	7.6	-	15	-	-
Pulmonary Syndrome - 5	10	-	-	160	-	-	370	920
Gastro-intestinal Syndrome - 8	15	35	-	-	-	-	-	-
Prodromal vomiting - 0.5	2	5	-	-	-	-	-	-
Diarrhea - 1	3	6	-	-	-	-	-	-
Pneumonitis - 5	10	-	-	160	-	-	370	920
Skin erythrema - 3	6	-	20	-	-	-	-	-
Transepidermal Injury - 10	20	80	-	-	-	-	-	-
Thyroiditis - 40	-	-	-	-	240	-	-	-
Hypothyroidism - 2	-	-	-	-	60	-	-	-

MACCS Early Health Effects Model

$$H = \text{cumulative hazard} = 0.693\, x^{\beta} \quad \text{where } \beta \text{ is called the "shape parameter"}$$

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

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

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

- **Most early health effects have threshold dose for brief (< 1 day) intense exposures: $H = 0$ if $D < D_{th}$**
- **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**

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

$$H_{D}\ was\ 0.693$$

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

MACCS Cost-Based Economic Model

- The original MACCS economic model estimates offsite costs based on the following cost categories
  - Evacuation/relocation costs on a per diem basis
  - Long-term relocation – one-time expenses
  - Decontamination costs
  - Loss of use
    - 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 costs
  - Litigation costs
  - Stigma costs (lost tourism and trade)
  - Affect on commercial 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

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

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_{sp} = Farm land 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

Long-Term Cost from Loss of Use

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

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
- In the MACCS implementation of REAcct, also includes
  - Decontamination costs
  - Evacuation/relocation costs
  - Long-term relocation cost (one time)
  - Depreciation
  - 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
- 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 losses
  - Indirect losses
  - Induced losses
- Disposal of crops not included

MACCS GDP-Based Economic Model Continued

- GDP-based model estimates direct losses at the county level
  - Underlying database contains the GDP generated by each county at the industry level
  - MACCS provides the fraction of each county affected by
    - Area
    - Population
  - Some industrial sectors are apportioned to a grid element by area fraction; others are apportioned by population fraction
  - GDP-based model adds up the contributions by industrial sector for each county in the affected area
- 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)

Economic Sectors

- Direct and Indirect GDP are reported by economic sector

		By Area	By Population
Industry # 3	Agriculture, forestry, fishing, and hunting	X	
Industry # 6	Mining	X	
Industry #10	Utilities	X	
Industry #11	Construction		X
Industry #12	Manufacturing		X
Industry #34	Wholesale trade		X
Industry #35	Retail trade		X
Industry #36	Transportation and warehousing	X	
Industry #45	Information		X
Industry #51	Finance and insurance		X
Industry #56	Real estate and rental leasing		X
Industry #60	Professional, scientific, and technical services		X

Economic Sectors Continued

		By Area	By Population
Industry #64	Management of companies and enterprises	X	
Industry #65	Administrative and waste management services	X	
Industry #69	Educational services		X
Industry #70	Health care and social assistance		X
Industry #75	Arts, entertainment, and recreation		X
Industry #78	Accommodation and food services		X
Industry #81	Other services, except government		X
Industry #83	Federal Civilian		X
Industry #85	State and Local Government		X

MACCS GDP-Based Economic Model Continued

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

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

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

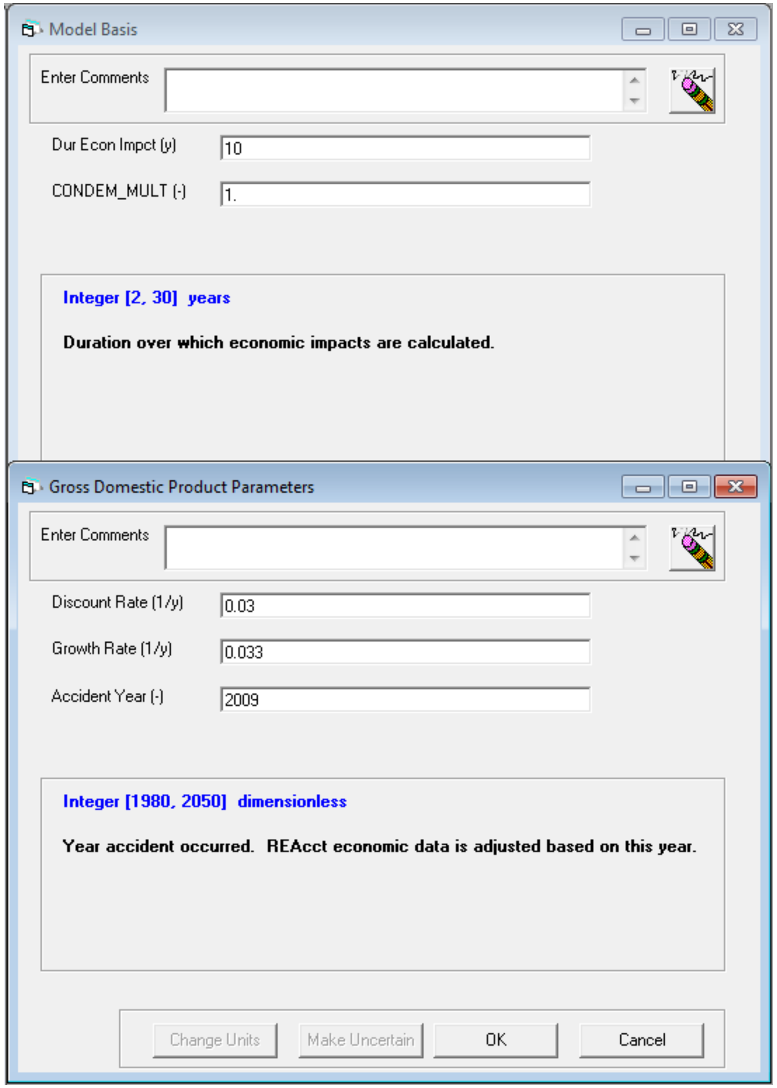
- GDP-based model uses the following formula to estimate total GDP losses (outside the affected region)

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

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

- Five new parameters were added for the GDP-based economic model
  - Duration of economic impacts (number of years over which losses are calculated)
  - 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
  - Social discount rate (discount rate used for social investments)
  - GDP growth rate (change in the GDP per year)
  - Accident year (year for which dollar values are reported)



Comparison of Decision Process for Decontamination

- Cost-based model – decontaminate when inequality is satisfied

  Cost to Decon. + Cost of Perm. Reloc. + Loss of Return + Depreciation <

  Prop. Value + Cost of Perm. Reloc.

- GDP-based model – decontaminate when inequality is satisfied

  Cost to Decon. + Cost of Perm. Reloc. + GDP Loss During Interdict. + Depreciation <

  (Prop. Value + Cost of Perm. Reloc.) * (condemn. mult.)

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 and rulemaking
  - Require a cost/benefit analysis
- PRAs like NRC's 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)**
- **Cost categories modeled by MACCS**
- **Two economic models, cost- and GDP-based**
- **Difficulties of modeling economic consequences**

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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 MACCS2 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.

7. Protective Measures

Objectives

- **Distinguish between the three phases of the accident for the application of protective measures**
- **List the various zones that can be modeled and their spatial relationship**
- **List the mitigative measures available in each phase and their general objectives**
- **Describe how different portions of the public can be treated via different emergency scenarios (cohorts)**

Outline

- Introduction to Protective Measures
- MACCS2 Modeling
- Emergency-Phase Actions
- Intermediate-Phase Actions
- Long-Term-Phase Actions

Introduction to Protective Measures

- **Mitigative actions are protective measures designed to balance**
  - **Radiation exposures and public health effects**
  - **Economic costs from an accident**
- **Mitigative measures in MACCS2 are divided into three phases (as defined by the EPA) with different protective actions possible in each phase**
  - **Emergency phase – up to one week from the beginning of an accident**
  - **Emergency-phase protective actions are called emergency-response (ER) actions**
    - **Evacuation**
    - **Sheltering**
    - **Temporary relocation**

Introduction to Protective Measures (cont.)

- **MACCS2 Mitigative Actions**
  - **Intermediate phase - begins immediately after the emergency phase and extends up to 1 year**
    - **Continuation of temporary relocation when projected dose exceeds the user specified limit**
  - **Long-term phase - follows the intermediate phase**
    - **Mitigative actions attempt to reduce long-term health effects**
      - **Crop disposal**
      - **Decontamination***
      - **Temporary interdiction***
      - **Condemnation***
      - **Restricted crop production**

*** Control long-term exposure from groundshine and resuspension inhalation**

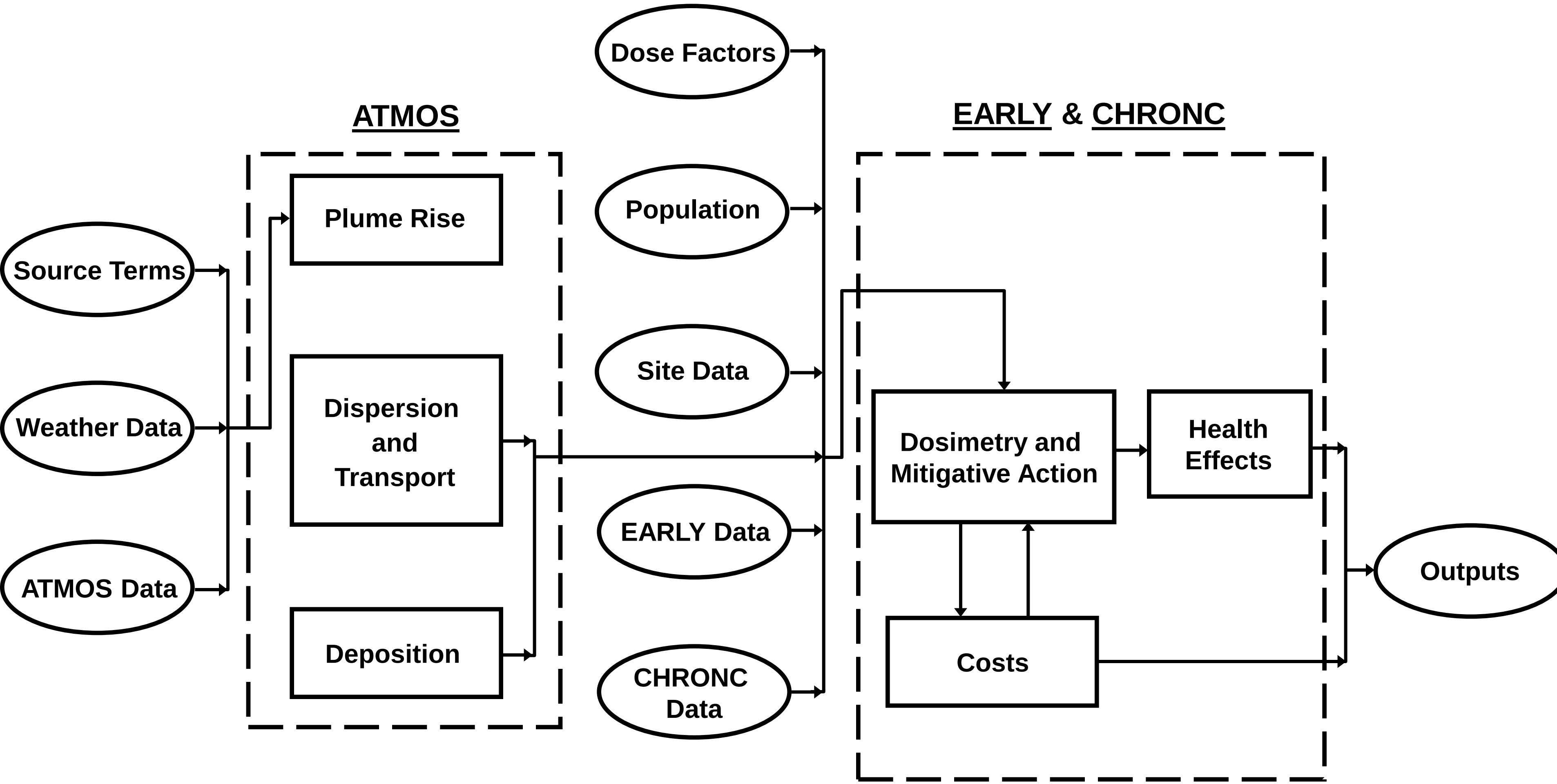
MACCS2 Modeling of Phases

- **ATMOS does not model a phase directly but provides necessary information to EARLY and CHRONC:**
  - **Atmospheric transport**
  - **Dispersion**
  - **Deposition**
  - **Radioactive decay prior to human exposure**
- **The Emergency Phase is modeled by EARLY.**
  - **Duration is specified by user**
  - **Extends up to one week after the arrival of the first plume at a spatial location**

MACCS2 Modeling of Phases (cont.)

- **CHRONC models intermediate and long-term phases.**
- **EARLY can model up to twenty emergency response cohorts (scenarios).**
  - **EARLY results are combined by population fractions, time fractions, or using individual populations for each cohort.**
  - **The intermediate and long-term results from CHRONC are added to the combined EARLY results.**
- **These combined, weighted results are termed the "overall combined" results.**
- **The discussion in the balance of this section is for a single emergency response cohort.**

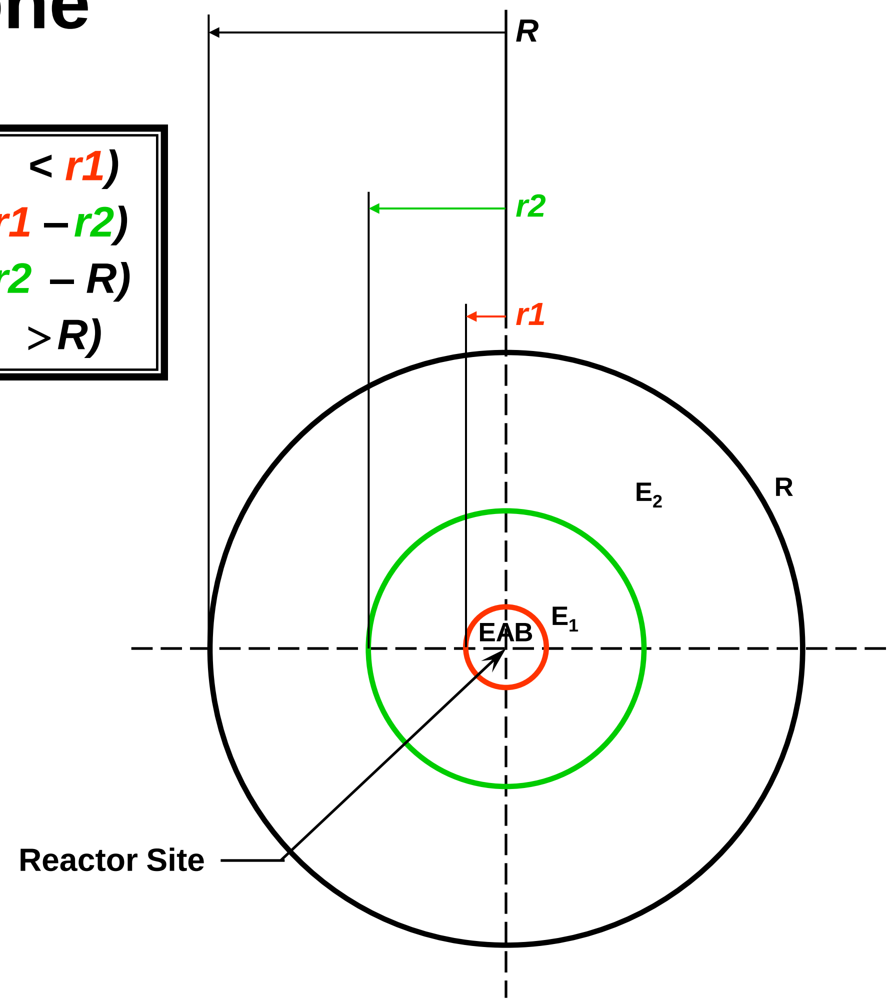
MACCS2 Modeling Diagram



Emergency Planning Zone

Exclusion Area Boundary	*(< r1)*
↗ E_1: Emergency Planning Zone (EPZ)	*(r1 – r2)*
↗ E_3: Shadow Evacuation Zone	*(r2 – R)*
↗ R: Relocation Zone	*(> R)*

- **The exclusion area boundary is bounded by *r1*.**
- **Evacuation and sheltering generally occur within the EPZ.**
- **Shadow or ad hoc evacuation may occur beyond the EPZ.**
- **Relocation applies to all spatial elements beyond the evacuation or sheltering zones.**



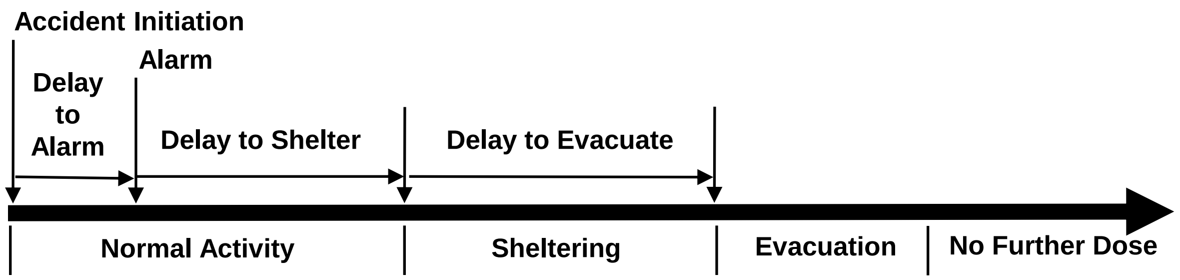
Shielding Factors

- **Specified for each of three groups**
  - **Evacuees**
  - **People taking shelter**
  - **People continuing normal activity**
- **Shielding factors are multipliers in dosimetry calculations for each pathway and activity**
  - **Cloudshine**
  - **Groundshine**
  - **Inhalation**
  - **Skin**
- **Typical relationship**

  1.0 ≥ SFs for evacuees ≥ SFs for normal activity ≥ SFs for sheltering ≥ 0.0

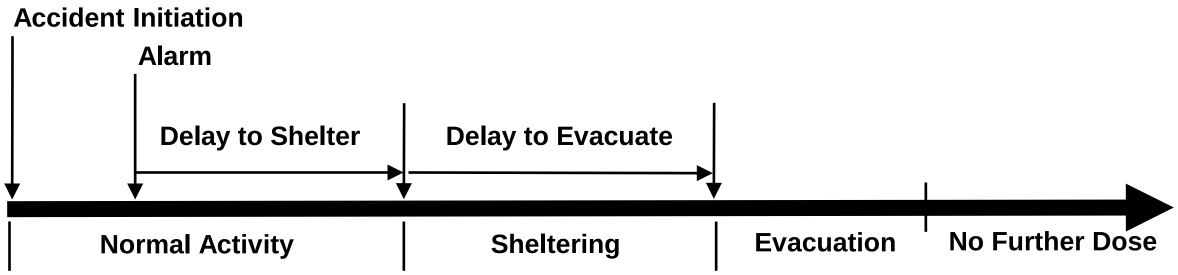
Sheltering and Evacuation

- **First period: Delay time prior to sheltering (user-specified for each zone)**
  - **Normal activity (and normal activity shielding factors) assumed**
  - **Delay time is from off-site alarm time**
- **Second period: Delay time prior to evacuation (user-specified for each zone)**
  - **Shielding factors for sheltering are used**
  - **Delay time is from beginning of sheltering**



Sheltering and Evacuation (cont.)

- **Third period: Evacuation**
  - **Speeds are user specified and can vary with**
    - **Three subphases**
    - **Weather**
    - **Grid element**
  - **Evacuation is to (user-specified) distance from reactor site**
  - **Evacuating shielding factors apply**
  - **Exposure to plume depends on location relative to front and back of plume**
- **Fourth period: After evacuation**
  - **Following evacuation, evacuees avoid further exposure in EARLY**



Sheltering and Evacuation (cont.)

- **Fifth period: After end of Emergency Phase**
  - **Evacuees move back to original spatial element if habitability criterion satisfied.**
  - **Population unaffected by plume effectively are not evacuated.**
  - **Any additional exposures are from long-term exposure pathways.**

Relocation

- **Relocation**
  - **Temporary relocation following plume arrival**
  - **Outside of emergency planning zone (EPZ)**
- **Two sets of criteria**
  - **Hot spot**
    - **Higher dose limit (e.g., 0.05 Sv over 1 week)**
    - **Shorter delay to relocate (e.g., 12 hr)**
  - **Normal**
    - **Lower dose limit (e.g., 0.01 Sv over 1 week)**
    - **Longer delay to relocate (e.g., 24 hr)**
  - **Critical organ is user specified (usually Effective)**

Relocation (cont.)

- Total dose projection
  - Normal activities
  - Entire emergency phase
  - Pathways
    - Cloudshine
    - Groundshine
    - Direct and resuspension inhalation
- Individuals relocated if projected dose commitment to specified organ exceeds specified limit
- Relocated individuals
  - Receive no further exposure during emergency phase
  - May return during or after intermediate phase

Intermediate Phase

- The Intermediate Phase begins at the end of the Emergency Phase
- Extends for a user-specified interval of time
- Optional (interval can be set to zero)
- Relocation is the only mitigative action during intermediate phase
- Relocation criterion parameters
  - Dose limit
  - Critical organ

Intermediate Phase (cont.)

- **Total dose commitment is projected for**
  - **Normal activities**
  - **Entire intermediate phase period**
  - **Pathways**
    - **Groundshine**
    - **Resuspension inhalation**
- **Intermediate-phase relocation**
  - **Projected dose commitment exceeds the dose limit**
  - **Population may return during long-term phase**

Long-Term Phase

- Initiation
  - End of intermediate phase
  - At the end of the emergency phase if there is no intermediate phase
- Mitigative actions depend of the following:
  - Projected doses
  - Cost-effectiveness of the action
- Decontamination worker doses are calculated for
  - Farmland
  - Non-farm properties

Long-Term Phase (cont.)

- **Possible mitigative actions are defined by the dose pathways:**
  - **Habitation doses from groundshine and resuspension inhalation**
    - **Decontamination of land and property**
    - **Interdiction during and possibly extending after decontamination**
    - **Condemnation with removal and resettling of people**
  - **Ingestion of food crops or milk**
    - **Removal of farm land from production during interdiction**
    - **Temporary or permanent removal of farmland from production when too contaminated to grow crops**
    - **Disposal of contaminated milk and/or non-milk crops**

Decontamination and Temporary Interdiction

- **Habitability criterion**
  - **Based on dose projection over a user-specified time period**
  - **Land is habitable when projection is less than dose limit**
  - **Population is present for rest of long-term phase when habitability criterion is met**
  - **Mitigative actions are considered in order when the habitability criterion is not met**
    - **Decontamination (three levels of increasing effectiveness)**
    - **Period of interdiction following the maximum decontamination**
      - **Atomic decay**
      - **Weathering**
    - **Condemnation of land**

Decontamination and Temporary Interdiction (cont.)

- **Fixed time steps of 1, 5, and 30 years are used to estimate habitability by interpolation.**
- **Land is condemned if costs exceed land value.**
- **Most values are user specified**
  - **Decontamination effectiveness**
  - **Worker exposure factors**
  - **Decontamination costs**
  - **Decontamination time periods**
  - **Depreciation and expected return rates**
- **The doses after return are calculated to the end of the long-term phase.**

Long-Term Ingestion Doses

- **Three mitigative actions are modeled for farmland.**
  - **Removal of farmland from production when uninhabitable**
  - **Removal of farmland from production when too contaminated to grow crops (not farmable)**
  - **Disposal of milk and/or crops during growing season**
- **The user specifies the maximum allowable food doses.**
  - **Short-term milk dose**
  - **Short-term food dose (other than dairy)**
  - **Long-term dose from all food**

Long-Term Ingestion Doses (cont.)

- **Farmland is condemned if**
  - **Land cannot be restored to habitability**
  - **Costs of decontamination and interdiction exceed farm value**
- **If accident occurs during growing season, user-specified limits affect**
  - **Milk disposal**
  - **Crop disposal**

Example Data Sources For Emergency Response Evacuation Model

- **Declaration of site-area and general emergencies**
  - **Dependent on accident sequence**
  - **Dependent on utility's classification criteria for emergencies as found in Emergency Plan (EP)**
  - **Measured from time of accident initiation (SCRAM)**
- **Emergency response follows declaration of emergency**
  - **Delay times and evacuation speeds not independent**
  - **Site specific applications based on evacuation time estimates (ETEs) provided by utilities**

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8. Uncertainties, V&V, and Development

Outline

- Definition of Uncertainty Categories
- General Relationship Between Code Verification and Model Validation
- Verification and Validation
- MACCS2 Developments

Uncertainty Categories

“Point values for phenomena for which large uncertainties are known to exist lack credibility without information relating to the uncertainty band for the model predictions.”

(NUREG/CR-6244: Probabilistic Accident Consequence Uncertainty Analysis)

- Three uncertainty categories dominate consequence assessment:
  - Aleatory (Stochastic) - natural parameter variability (e.g., meteorological data)
  - Epistemic (State-of-Knowledge)
    - Parameter - lack of complete information about system
    - Model - lack of complete information about phenomena
    - Completeness – unquantifiable uncertainty based on omitted, knowingly or unknowingly, aspects of the model

Uncertainty Category Definitions

- Aleatory Uncertainty, aka Stochastic Uncertainty
  - Uncertainty based on the randomness of the nature of the events or phenomena and cannot be reduced by increasing the analyst's knowledge of the systems being modeled. Therefore, it is also known as random uncertainty or stochastic uncertainty. In principle, aleatory uncertainty cannot be reduced by the accumulation of more data or additional information.
- Epistemic Uncertainty, aka State-of-Knowledge Uncertainty
  - Uncertainty related to the lack of knowledge or confidence about the system or model and is also known as state-of-knowledge uncertainty. Epistemic uncertainty is reflected in ranges of values for parameters, a range of viable models, the level of model detail, multiple expert interpretations, and statistical confidence. In principle, epistemic uncertainty can be reduced by the accumulation of additional information.
  - Categories of Epistemic Uncertainty
    - Parameter
    - Model
    - Completeness

Uncertainty And Sensitivity Analysis

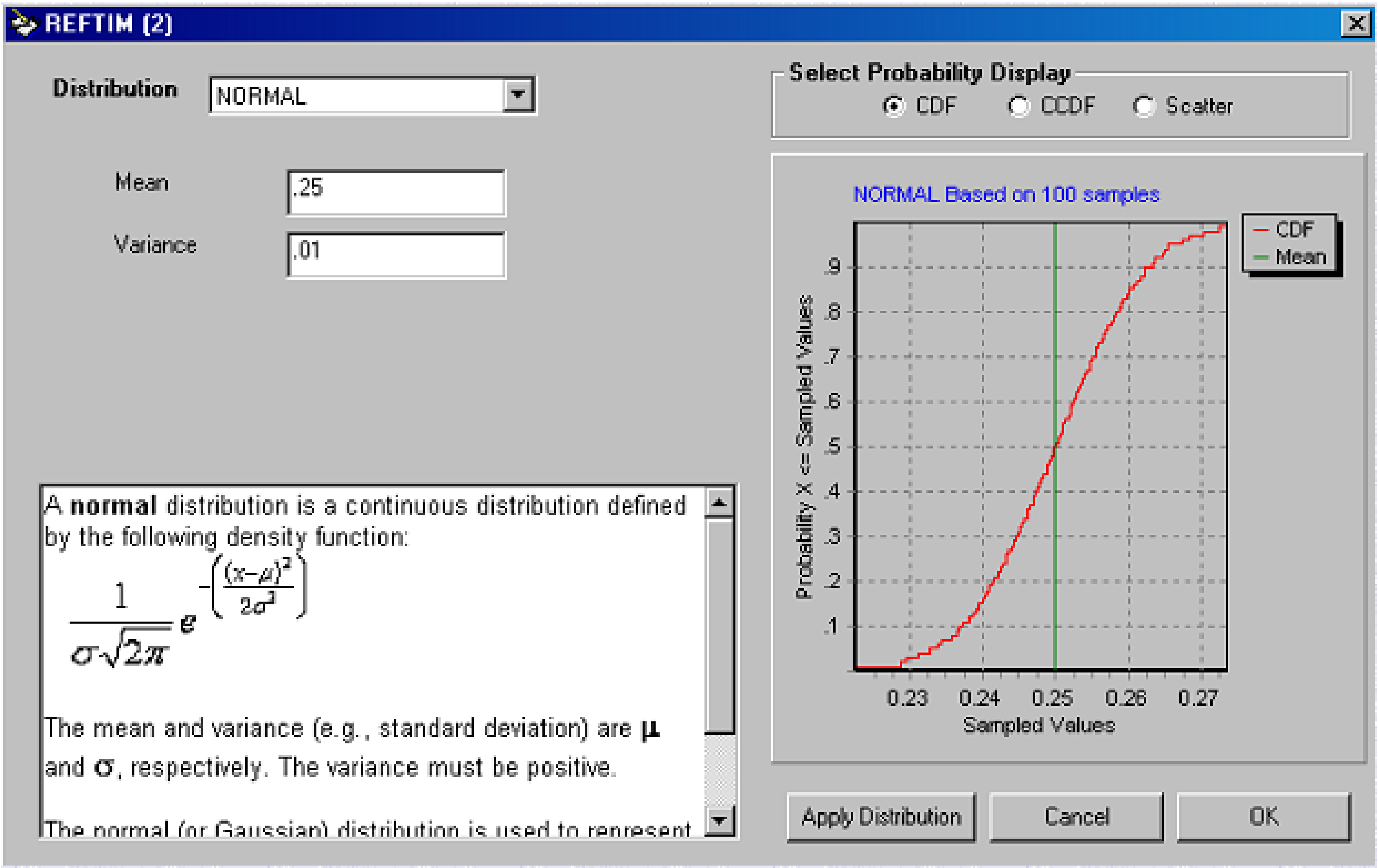
1. **Stochastic uncertainty (e.g., weather)**
   - Reflected by modeling the phenomenon in terms of a probabilistic model
   - Irreducible
2. **Model uncertainty (e.g., Gaussian plume model)**
   - The phenomenon being modeled is itself not completely understood (e.g., behavior of gravity-driven passive systems in new reactors, or crack growth resulting from previously unknown mechanisms)
   - For some phenomena, some data or other information may exist, but it needs to be interpreted to infer behavior under conditions different from those in which the data were collected (e.g., RCP seal LOCA information)
   - The nature of the failure modes is not completely understood or is unknown (e.g., digital instrumentation and controls)
   - Quantified by comparing with data, but not easily quantified in many cases

Uncertainty and Sensitivity (cont.)

3. Parameter Uncertainty (e.g., dry deposition velocities)

- Sensitivity analysis - identify parameters with greatest impact on results
  - Identify parameters
  - Identify probability distribution or range based on
    - data (site specific)
    - expert opinion (literature)
    - judgment
  - Evaluate response to parameter
  - Choose parameters which have greatest ratio of maximum/minimum or largest correlation coefficient (r)
- Uncertainty Analysis
  - Construct probability distributions of input parameters
    - uniform, normal, log-normal
  - Perform sampling to create realizations
    - Monte Carlo, Latin Hypercube (stratified random sampling)
  - Exercise model for each sample
  - Statistically summarize model results (e.g., mean, 5%, 50%, 95%, or complete CCDF)

WinMaccs Parameter Uncertainty

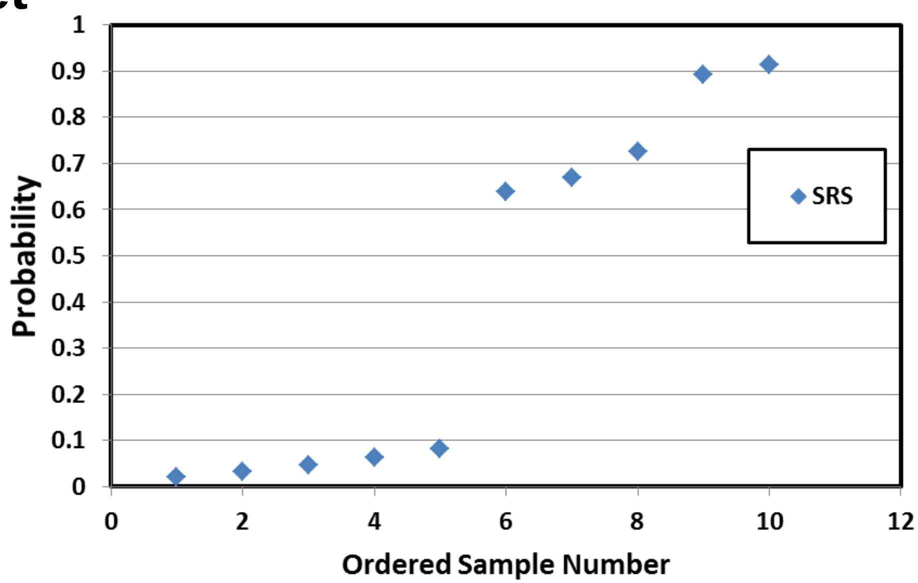


Monte Carlo Process

- **Process of inserting randomly sampled set of input parameters into a simulation and creating a set of results (realizations)**
- **Independent of the type of sampling method**
- **Monte Carlos allows any number of uncertain inputs to be sampled simultaneously**
- **WinMACCS supports two sampling options**
  - **Simple random sampling (SMS)**
  - **Latin hypercube sampling (LHS)**

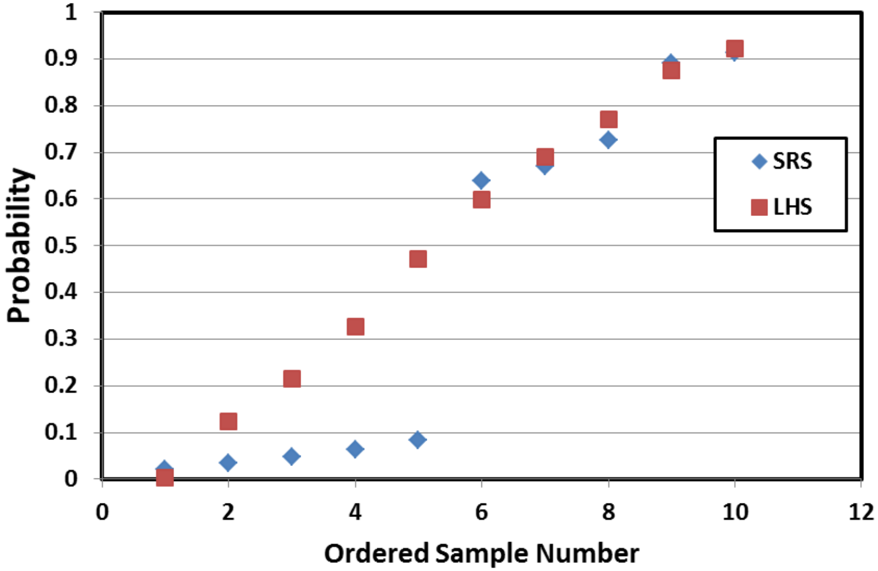
Simple Random Sampling

- **SMS selects a set of values randomly over the entire range of probabilities (0 to 1)**
  - **Advantages include**
    - **Most commonly used sampling method**
    - **Easy to expand sample set**
    - **Can use bootstrapping to evaluate statistical accuracy of sample set**
  - **Disadvantages include**
    - **Clustering**
    - **Gaps**
    - **Large sample set to get adequate statistics**



Latin Hypercube Sampling

- LHS selects a set of values randomly over each 1/N of the range of probabilities (0 to 1), where N is the number of samples
  - Advantages include
    - More efficient than SRS
    - Avoids clustering and sampling gaps
  - Disadvantages include
    - Can't use bootstrapping
    - More difficult to expand sample set



Integrated Uncertainty Accounts for All Three Levels of PRA

$$rC_m = \sum_{j=1}^{nPDS} \sum_{k=1}^{nAPB} \sum_{l=1}^{nSTG} fPDS_j \, pAPB_{jk} \, pSTG_{kl} \, cSTG_{lm}$$

where

rC_m = annual risk of consequence measure m (e.g. early fatalities)

$fPDS_j$ = frequency (per year) of plant damage state j

$pAPB_{jk}$ = conditional probability that PDS_j results in accident progression bin APB_k

$pSTG_{kl}$ = conditional probability that APB_k is assigned to STG_l

$cSTG_{lm}$ = statistical result (over weather variability) for consequence metric m conditional on the occurrence of STG_l

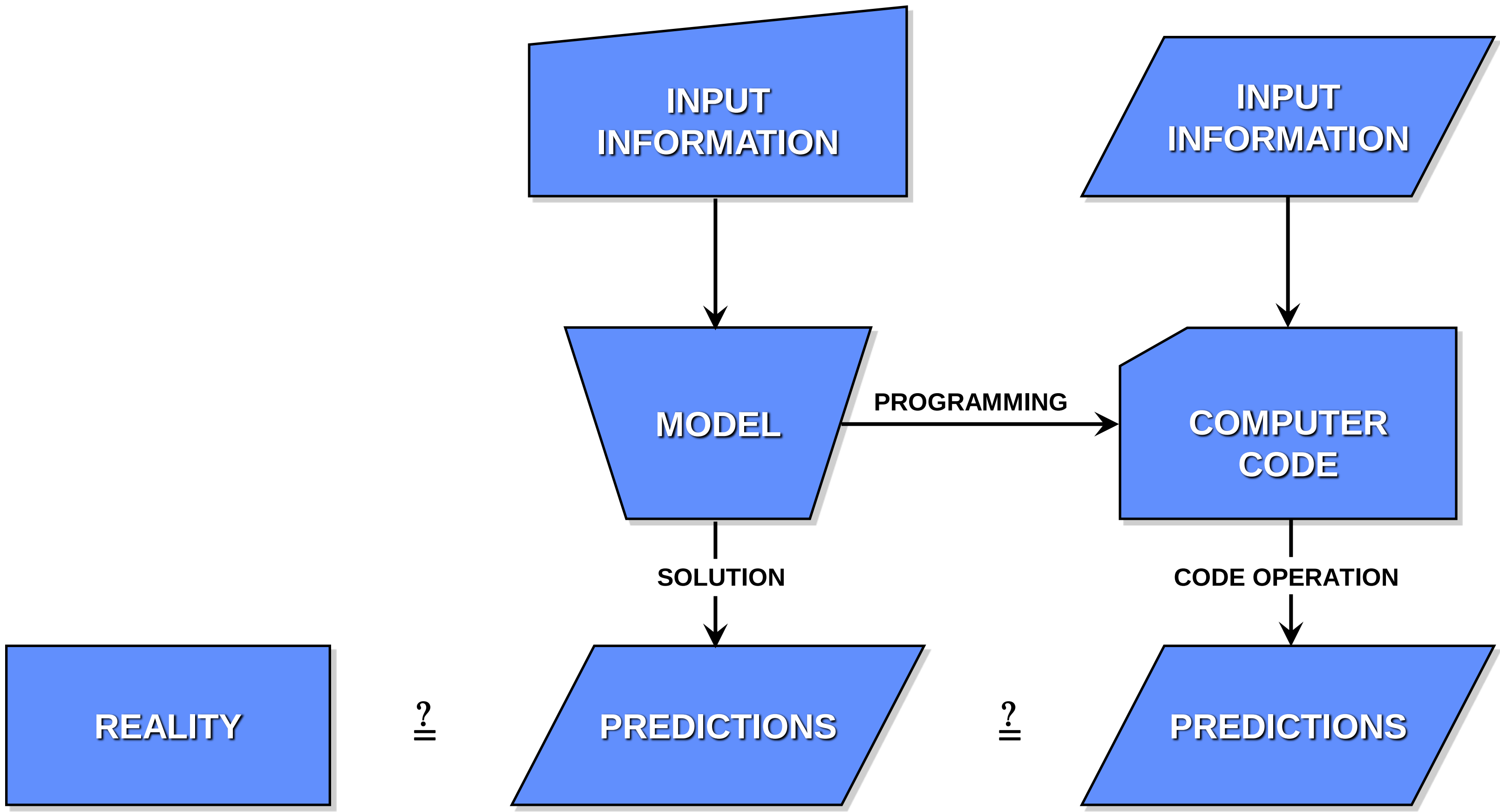
Verification vs. Validation

- Verification
  - ***The process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model.***

- Validation
  - ***The process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.***

AIAA G-077-1998, *"Guide for the Verification and Validation of Computational Fluid Dynamics Simulations"*

Verification And Validation Relationship



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Verification and Validation

- Verification - code working as desired?
  - MACCS verified:
    - Line by line check of code by INL
    - Widespread use
    - Ongoing testing according to QA plan
    - NRC Office Instruction on Software Quality Assurance
- Validation - code predictions compare with reality?
  - Gaussian plume model validated (factor of 30-40%)
  - Comparison with 2-D and 3-D codes (NUREG/CR-6853)
- Calibration - not validation
  - Adjust model parameters to mimic data
  - May be useful only for same site and situation

MACCS Developments

- Major development efforts
  - WinMACCS
    - User-friendly interface
    - Simplify analysis and minimize user errors
    - Reduce effort to perform uncertainty analysis
  - SECPOP
  - MELMACCS
- Code Verification
  - Ad hoc by large user community
  - University of New Mexico
  - Ongoing testing of new model developments

Recent MACCS Model Developments – I

- General
  - Increased dimensions, e.g., 200 plume segments
  - Increased angular resolution: 16, 32, 48, or 64 sectors
- Gaussian plume
  - Time-based dispersion option at long ranges
  - Improved plume buoyancy model
  - Meander model based on Reg. Guide 1.145
- Meteorology
  - Diurnal mixing-height model
  - Time resolution: 15-, 30-, or 60-minute periods

Recent MACCS Model Developments – II

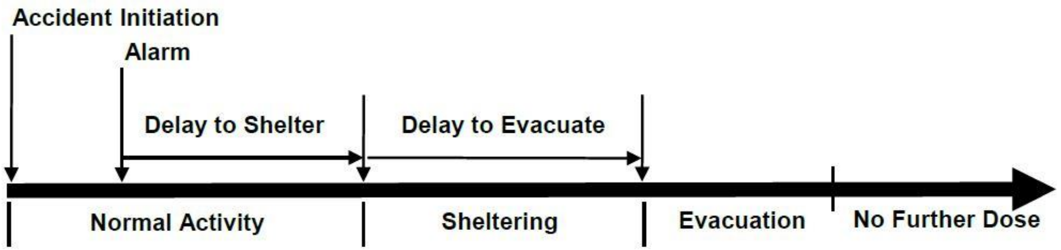
- Emergency response
  - Up to 20 emergency-phase cohorts
  - Map layer for network evacuation screens
  - More general specification of emergency-phase cohorts
  - Evacuation speed reduction during adverse weather
  - Evacuation speed multiplier by grid element
- Heath effects
  - KI ingestion model
  - No-food option
  - New comprehensive DCF file based on FGR-13
  - Several dose-response options, including dose threshold
  - Support for uncertain DCFs

Ongoing and Future Model Developments – I

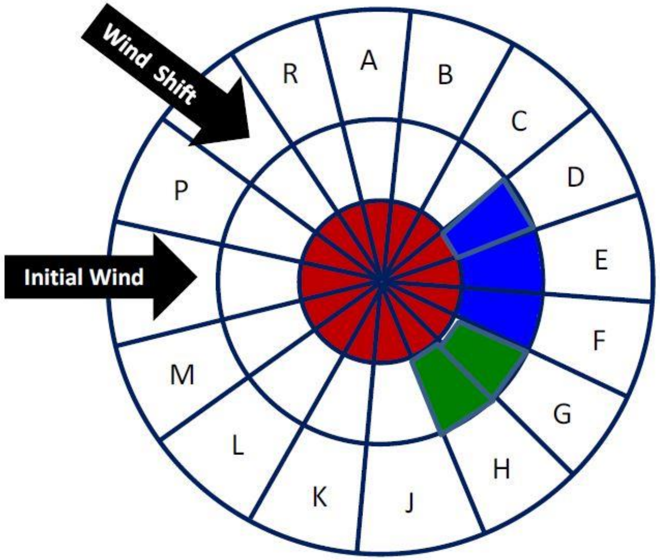
- Alternative economic model option
  - Based on Gross Domestic Product (GDP) losses
  - Uses standard input-output model
  - Based on the REAcct model developed for DHS
- New version of Java-based SECPOP
  - 2010 census data; 2007 economic and land use data
  - Supports 64 compass sectors and alternative economic model
- New ATD development
  - Gaussian puff approach
  - Interface with standard gridded weather data

Ongoing and Future Model Developments – II

- Timing of population movement



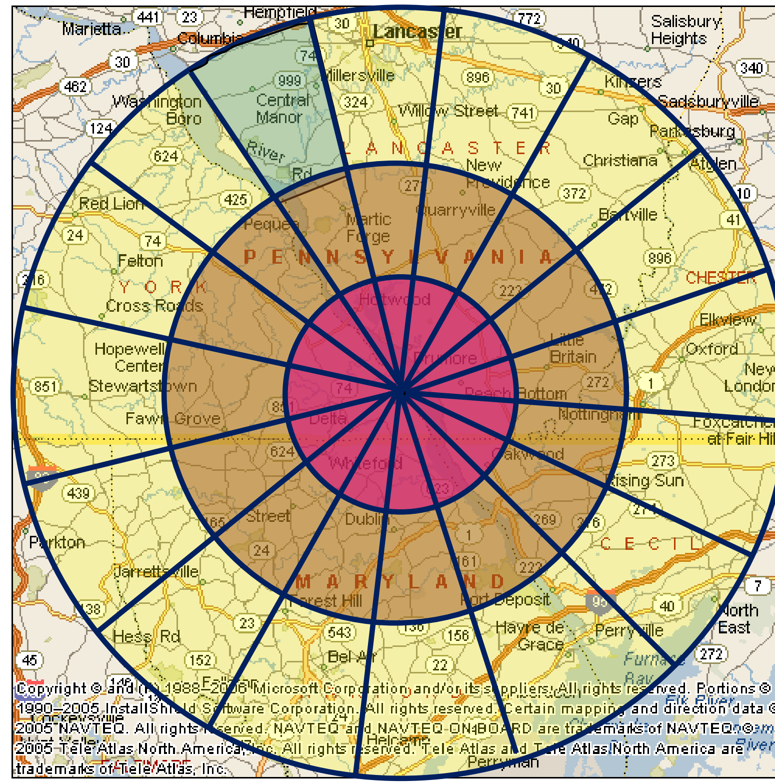
- Keyhole evacuation model



Ongoing and Future Model Developments – III

- Added flexibility in defining cohorts and mapping regions, e.g.,
  - Emergency Planning Zone
  - Shadow evacuation
  - No evacuation
  - Special facility

SOARCA Cohorts	Peach Bottom	Surry
Cohort 1	0 to 10 Public	
Cohort 2	10 to 20 Shadow	
Cohort 3	0 to 10 Schools and 0 to 10 Shadow	0 to 10 Schools
Cohort 4	0 to 10 Special Facilities	
Cohort 5	0 to 10 Tail	
Cohort 6	Non-Evacuating Public	



Ongoing and Future Model Developments – IV

- Improved copy and paste options
- Optional units
- Resizable maps for evacuation routing
- Resizable parameter input screens
- Additional reporting options
- Ability to calculate consequences from multiple reactor units and/or spent fuel pools

Ongoing and Future Model Developments – V

- New features in WinMACCS/MACCS 3.10 include:
  - A multi-source model was implemented to calculate offsite consequences for simultaneous releases from different sources (e.g., multiple units and/or spent fuel pools)
  - User-specified dose-projection periods were enabled for the emergency and intermediate phases
  - A new output type was added to detail the number of people evacuated and relocated during the three phases of the accident
  - An option was introduced to allow the user to specify the return time for evacuees from grid elements not affected by any plume segment in the early phase
  - Modified to allow up to 50 days (instead of 5 days) of weather data for a weather trial. This allows extended releases to be calculated with actual weather data rather than potentially switching to boundary weather data within the distance range established by LIMSPA. This change creates minor differences in results as compared with previous versions.

9. Course Summary & Test Preparation

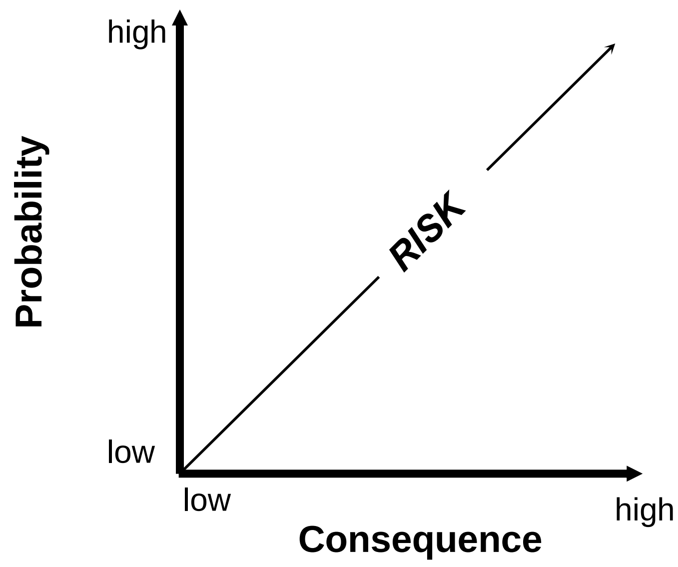
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Three Levels of Probabilistic Safety Analysis/Assessment

- ***Level 1 -*** **The assessment of plant failures leading to core damage and the determination of core damage frequency (CDF).**
- ***Level 2 -*** **The assessment of fission product release/transport and containment response that, together with the results of Level 1 analysis, leads to the determination of release frequencies, including LERF.**
- ➔ ***Level 3 -*** **The assessment of off-site consequences that, together with the results of Level 2 analysis, leads to estimates of risk to the public.**

Measure of Safety

- **Consequence = the undesired outcomes or losses resulting from an accident**
- **Probability = the likelihood of an event occurring**
- **Risk = Consequence × Probability (or Frequency)**



Level-3 PRA (Consequences)

- **Health or Economic Consequences**

RELEASE FROM PLANT

↓

TRANSPORT TO PUBLIC

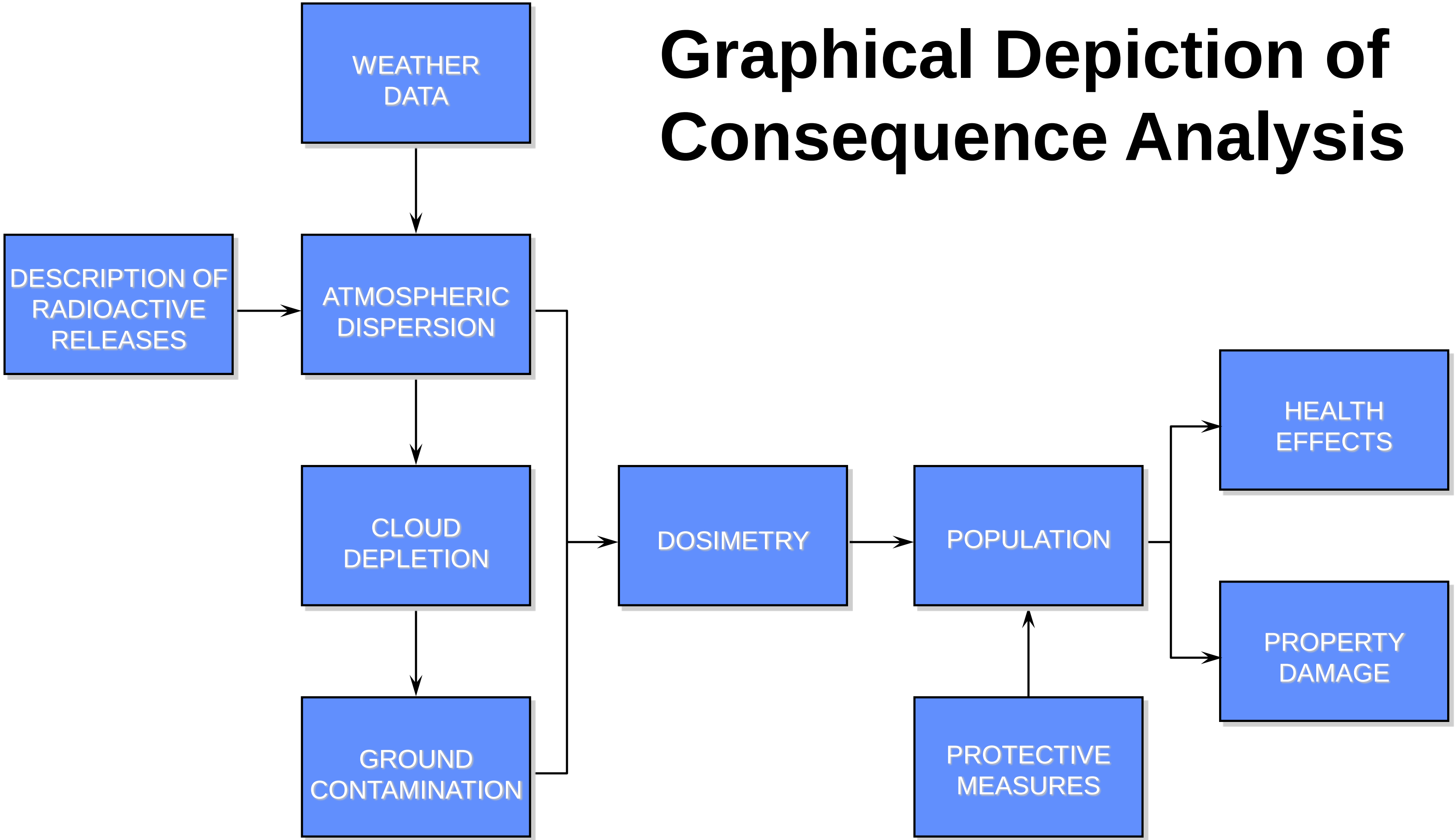
↓

EFFECT OF TRANSPORTED RELEASE ON PUBLIC HEALTH OR ECONOMIC IMPACT

Characteristics of Level-3 Consequence Analysis

- **Generally limited to atmospheric releases**
- **Conditional on the release occurring**
- **The major calculation steps are incorporated into computer codes:**
  - ✓ **MACCS & MACCS2 (US)**
  - ✓ **COSYMA (European Commission)**
- **Interest being rejuvenated following 9/11, by renaissance of nuclear power, and following Fukushima**

Graphical Depiction of Consequence Analysis



Consequence Code Evolution

CRAC

(1975)

WASH-1400

→

CRAC2

(1982)

Early PRAs

Rebaselined RSS

Sandia Siting Study

→

MACCS

(1990)

NUREG-1150

↓

MACCS2

(1997-1998)

Security Studies

PAR Study

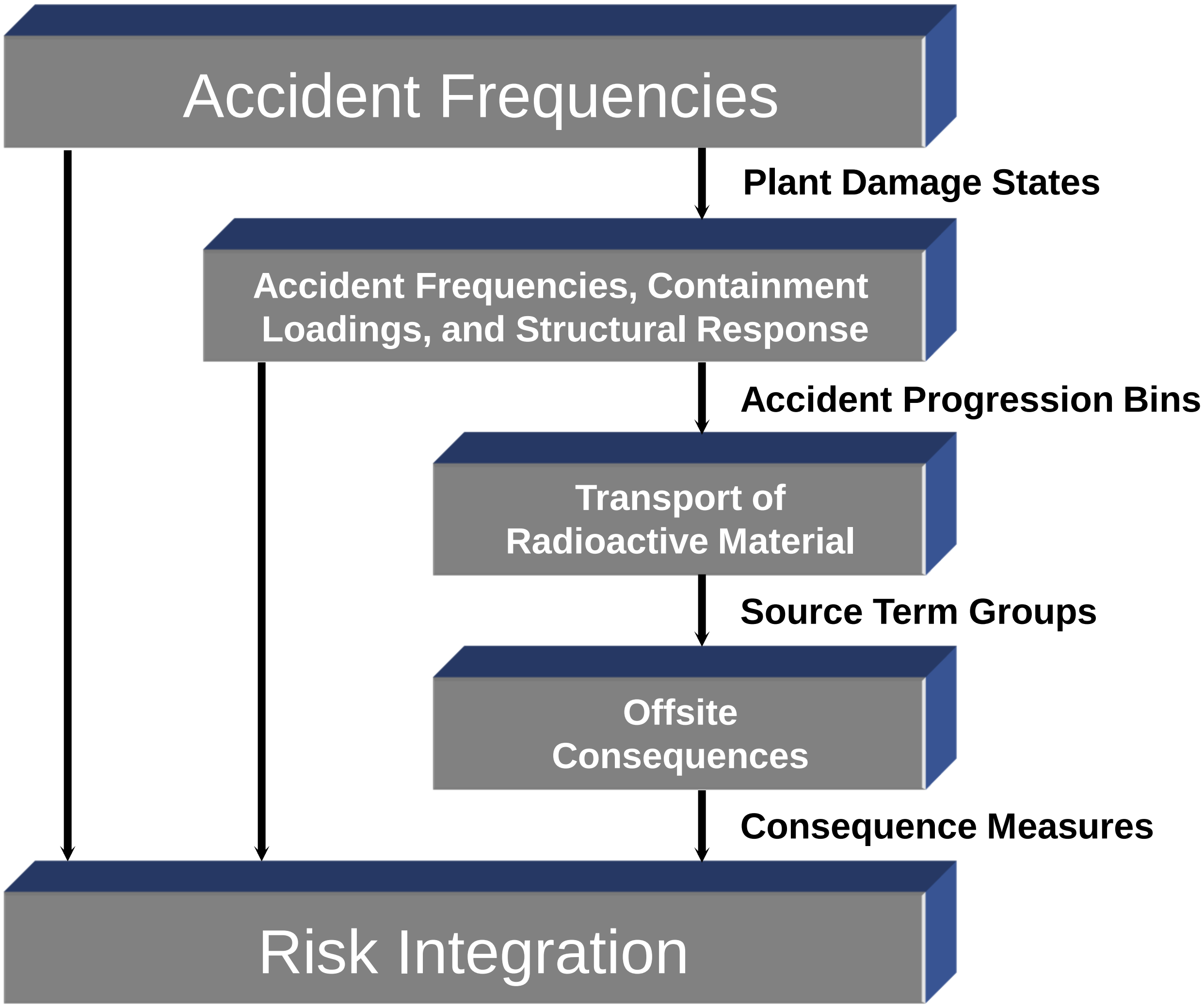
SOARCA

Post Fukushima

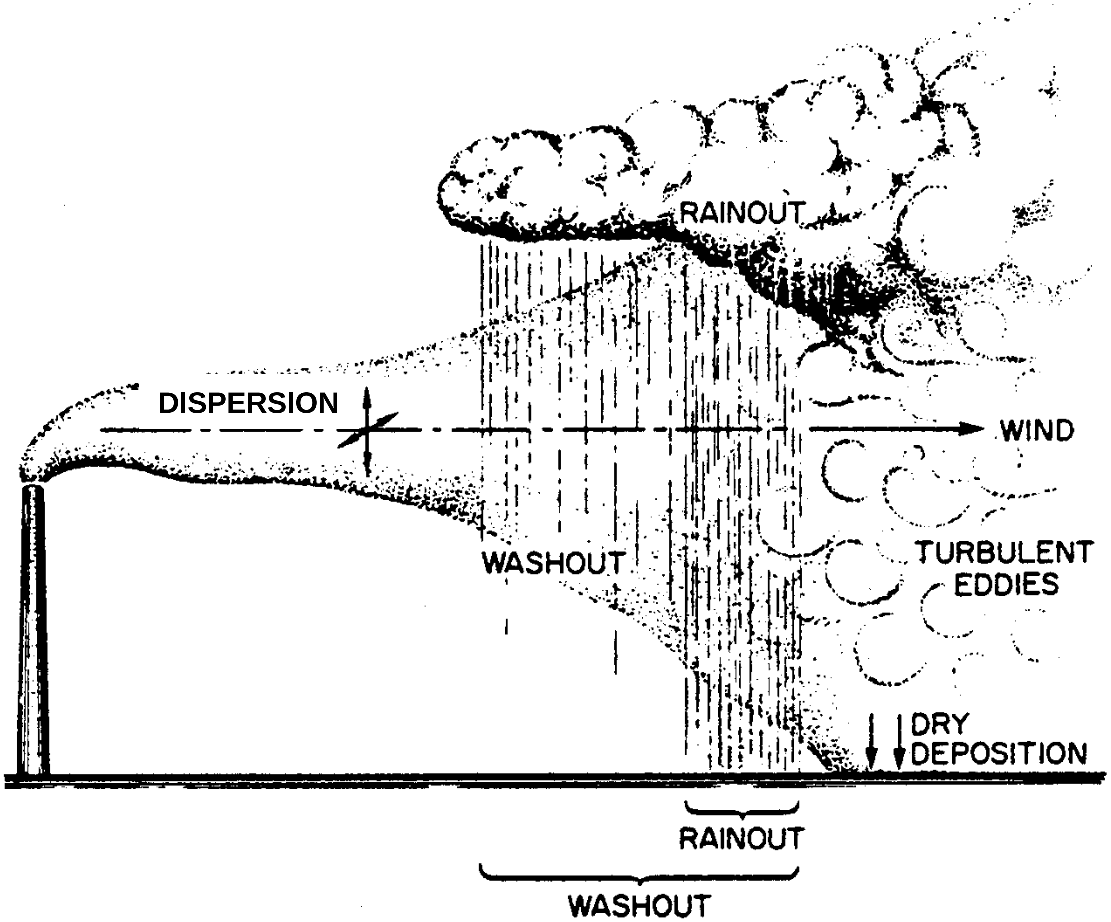
Level-2 PRA Results

- **Results**
  - **Timing of significant events (e.g., core melt, vessel breach, containment failure) for various accident sequences**
  - **Conditional probabilities of containment failure and source terms**
  - **Release of fission products into environment**
    - **amounts of various radionuclides**
    - **variation of release with time**
    - **energy in released cloud**
    - **release elevation**
  - **Release characteristics are binned into a set of Source Term Groups**

NUREG-1150 Risk Analysis Process



Atmospheric Dispersion Consists of Dispersion, Transport, and Depletion Processes



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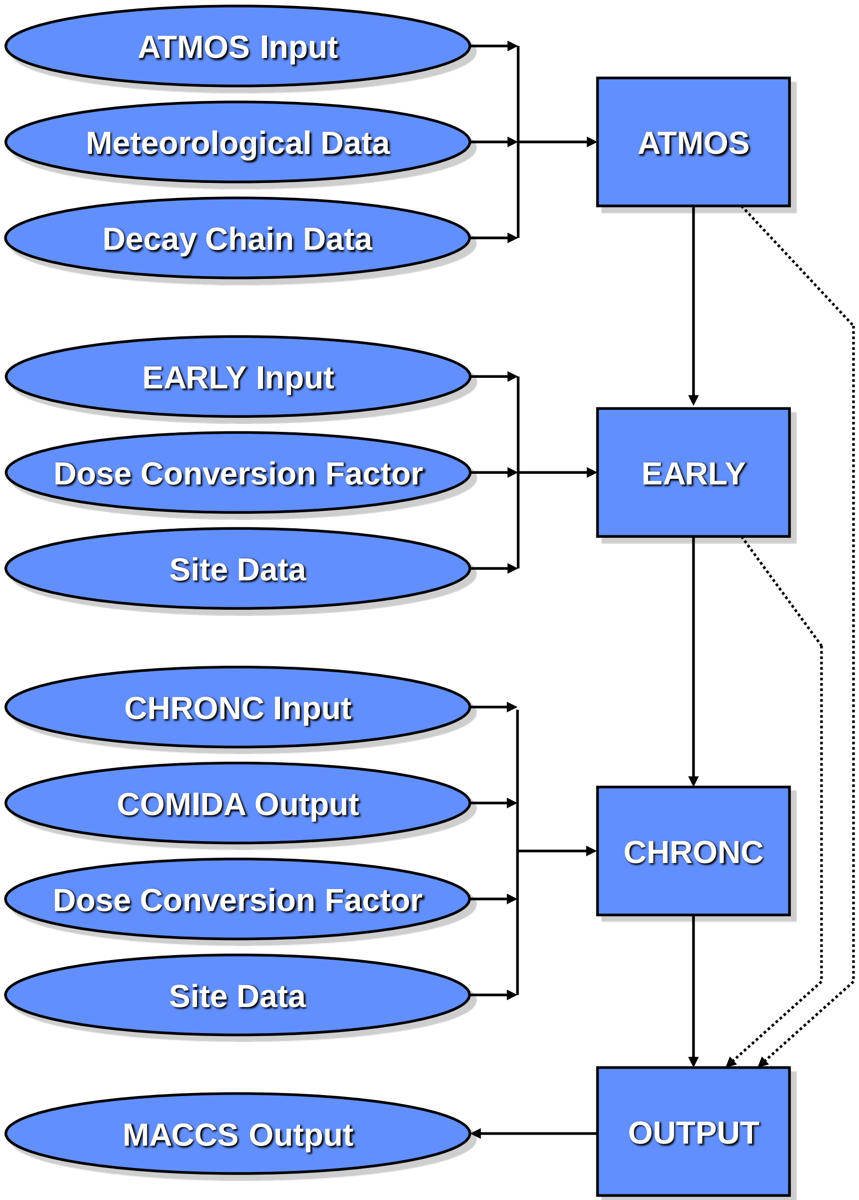
MACCS Data Flow

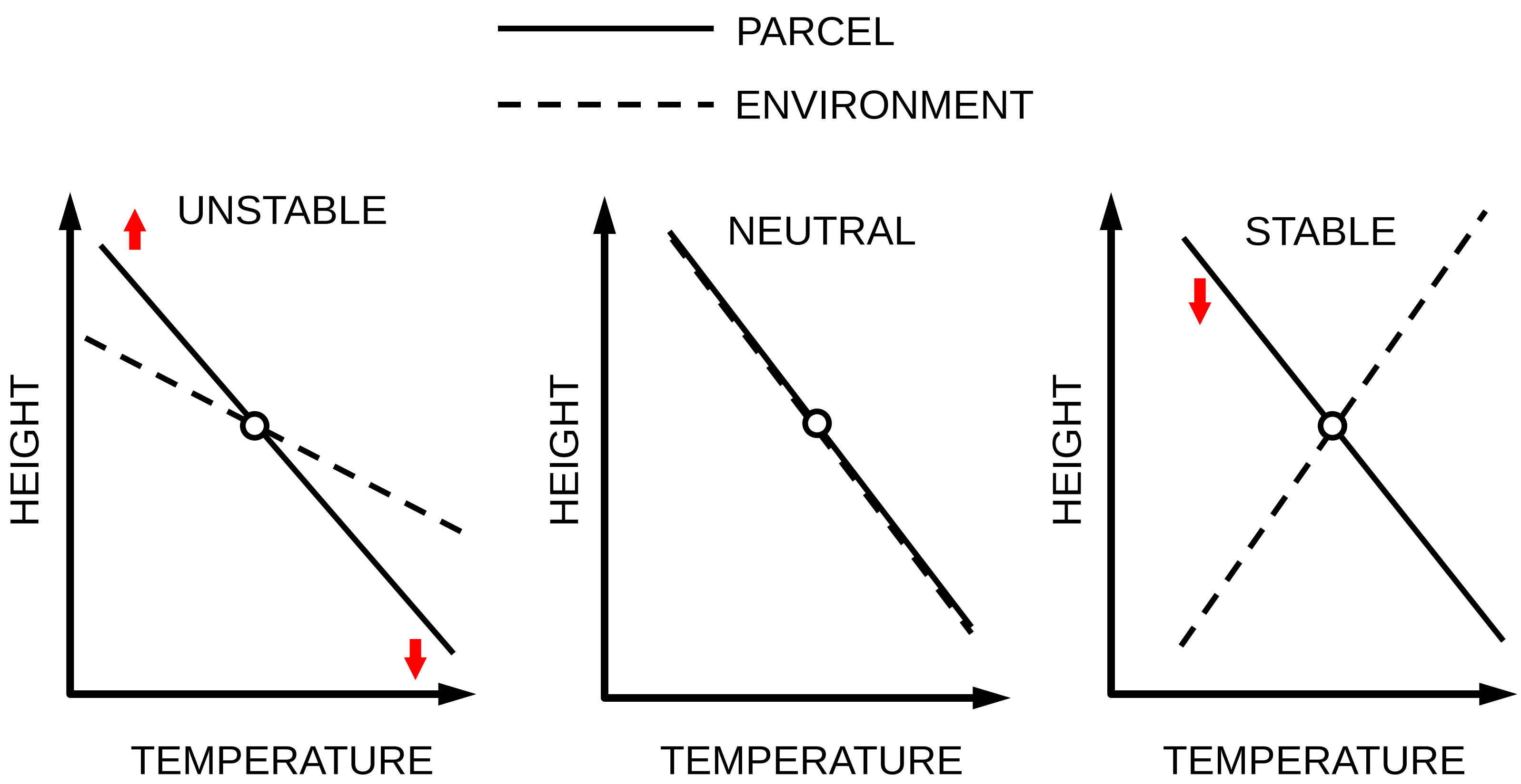
- User activates modules only as needed to determine results of interest
- Activated modules determine input files that are required
- Some required input files can be used as transmitted with MACCS (without user modification)



MACCS Overview

- **MACCS estimates doses, health effects, and economic costs associated with airborne radioactive releases**
  - **External and internal dose pathways**
  - **Acute and lifetime committed doses**
  - **Health effects include early and latent injuries/fatalities**
  - **Accounting for economic costs due to mitigating actions**
- **Radioactive dispersion based on Gaussian plume model with capabilities for sampling annual meteorological data**
- **Preprocessors provided for development of required**
  - **Dose conversion factors**
  - **Food chain data**
  - **Site data**

Illustrations of PBL Stability Conditions



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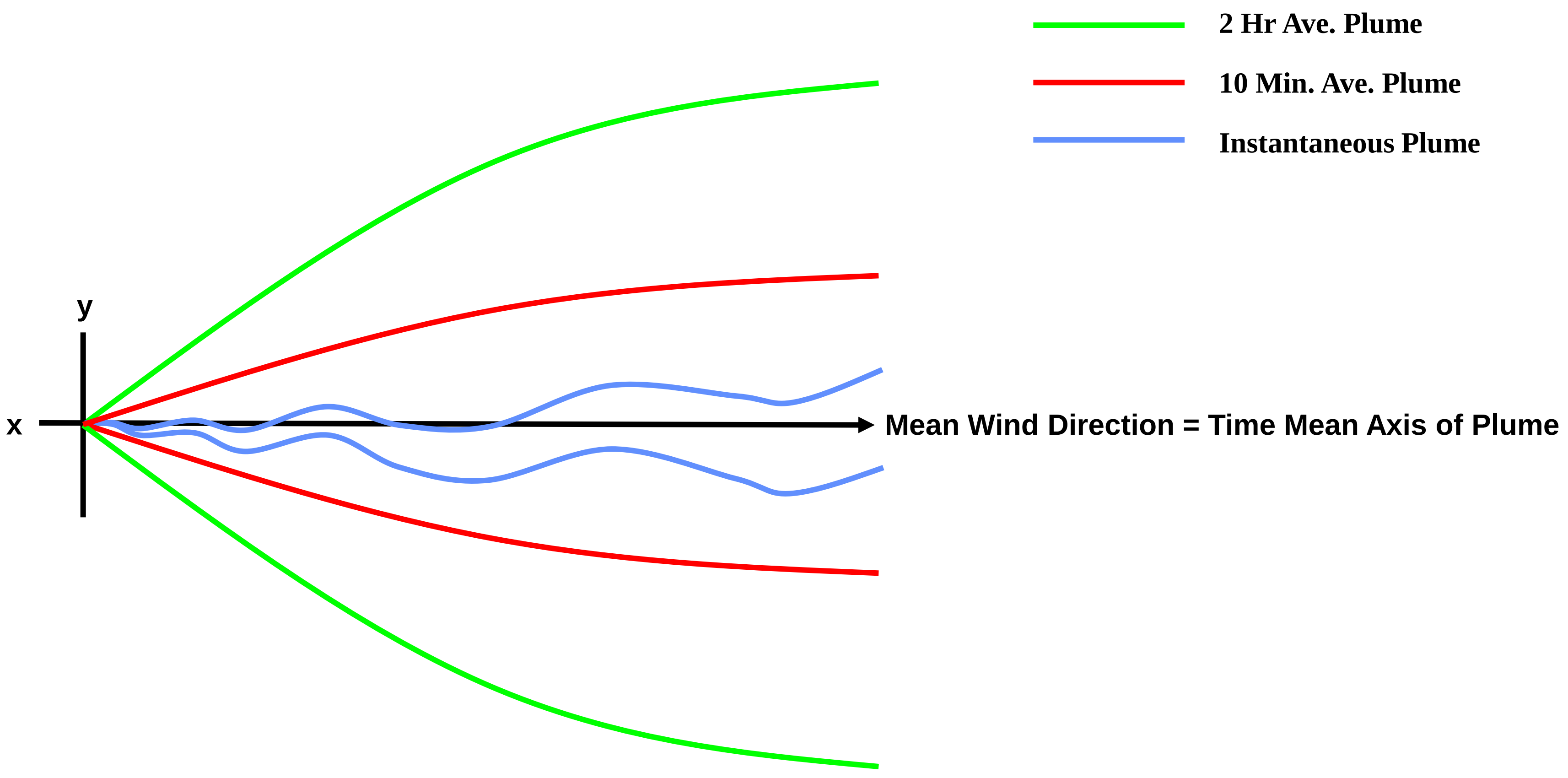
Effect of Dispersion Averaging Times

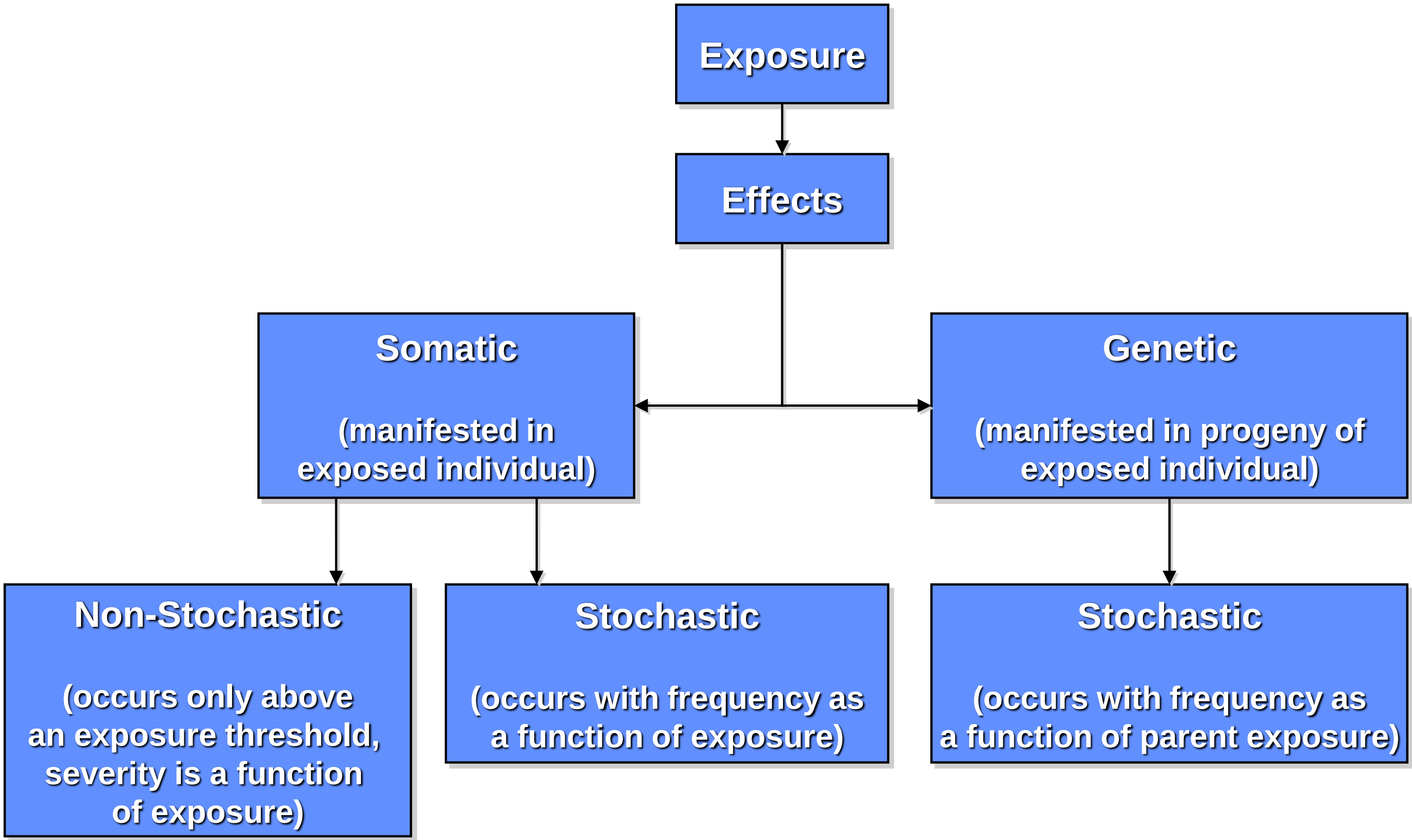


Surface Roughness

- **A smaller roughness length implies less exchange between the surface and the atmosphere**
- σ_z **scaled to Prairie Grass measurements (**z_0 **= 3 cm)**

$$\sigma_{z,z_0} = \sigma_{z,3}\left(\frac{z_0}{3}\right)^{0.2}$$

Radioactive Exposure can Induce Somatic and Genetic Health Effects



Radiation Exposure Types

- **Acute exposure - a single accidental exposure to a high dose of radiation during a short period of time.**
  - **Dose ≥ 10 rad**
  - **Exposure duration ≤ days**
  - **May produce effects within a short time after exposure**
  - **Affects all organs and systems of the body**
  - **Can cause a pattern of clearly identifiable symptoms (syndromes)**
- **Chronic exposure - long-term, low-level exposure**
  - **Human body can tolerate more than an acute dose**
  - **Effects of exposure may not be apparent for years**
  - **Effects are more difficult to determine**

Relationship Between Dose and Effects

- **Acute exposure**
  - **Stochastic effects**
    - **Probability of occurrence varies with dose**
    - **Classified as "latent" effects**
  - **Non-stochastic effects**
    - **Thresholds vary for different effects**
    - **Classified as "early" somatic effects**
- **Chronic exposure**
  - **Stochastic effects**
    - **Probability of occurrence is extrapolated from dose-effect curve for high doses**
    - **Epidemiological data cannot confirm or refute the calculated magnitude of risk at occupational levels**
  - **Non-stochastic effects**
    - **A few deterministic effects can occur with long-term exposure <u>if</u> dose exceeds the threshold for the effect**
    - **Dose limits are set so these thresholds are not expected to be reached in a normal working lifetime**

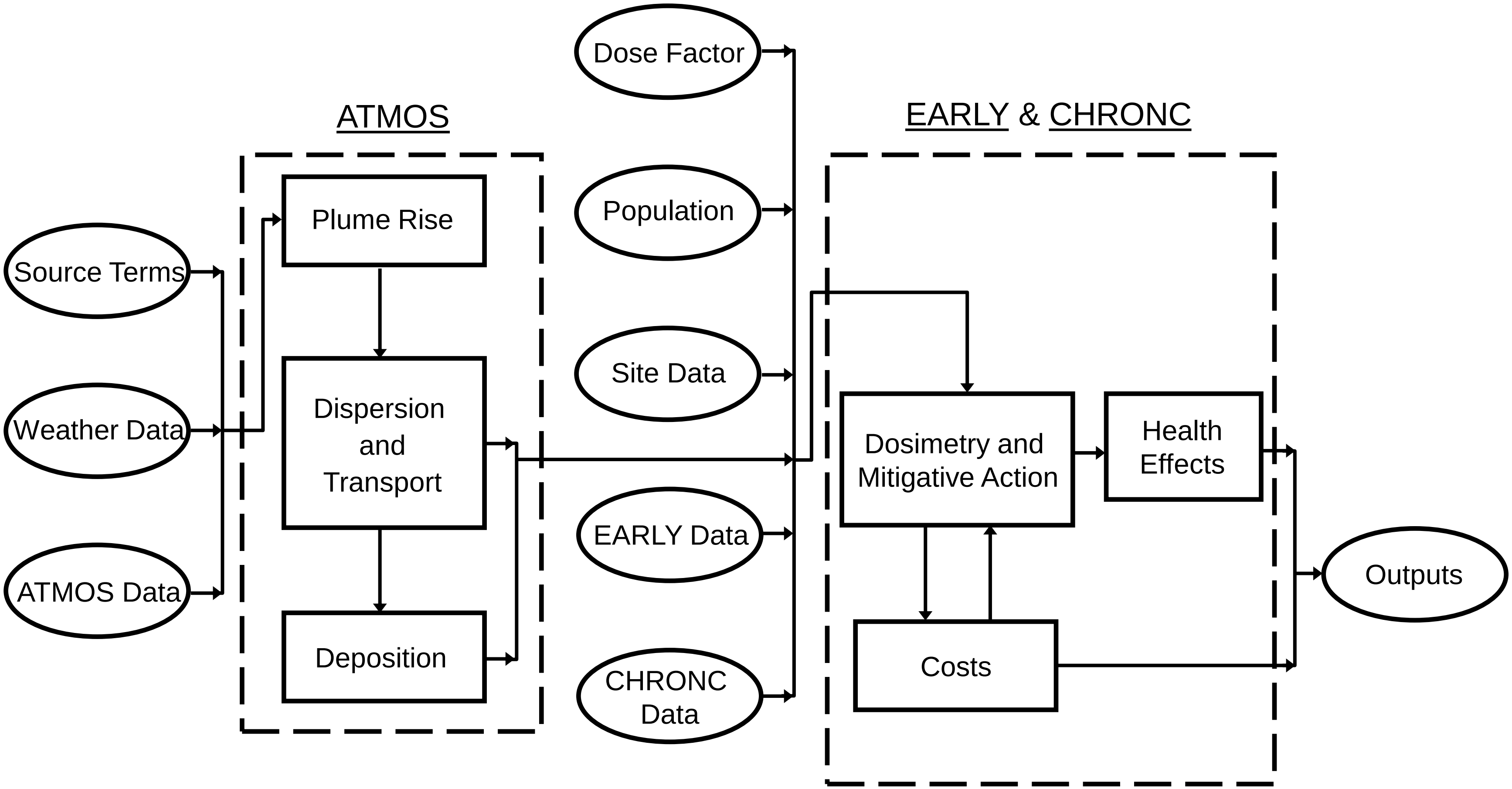
Summary of Cost Categories

- Short-term relocation/evacuation food and lodging costs
- Property decontamination costs
- Loss of use of property during temporary interdiction
- Loss due to milk and crop disposal
- Loss due to permanent interdiction (condemnation) of property

Summary of Protective Measures

- **Mitigative actions are protective measures designed to reduce**
  - **Radiation exposures**
  - **Public health effects**
- **Mitigative measures in MACCS are divided into three phases (as defined by the EPA) with different protection actions possible in each phase**
  - **Emergency phase - time period immediately preceding and following the accident**
  - **Intermediate phase - begins immediately after the emergency phase and extends up to 1 year**
  - **Long-term phase - follows the intermediate phase**

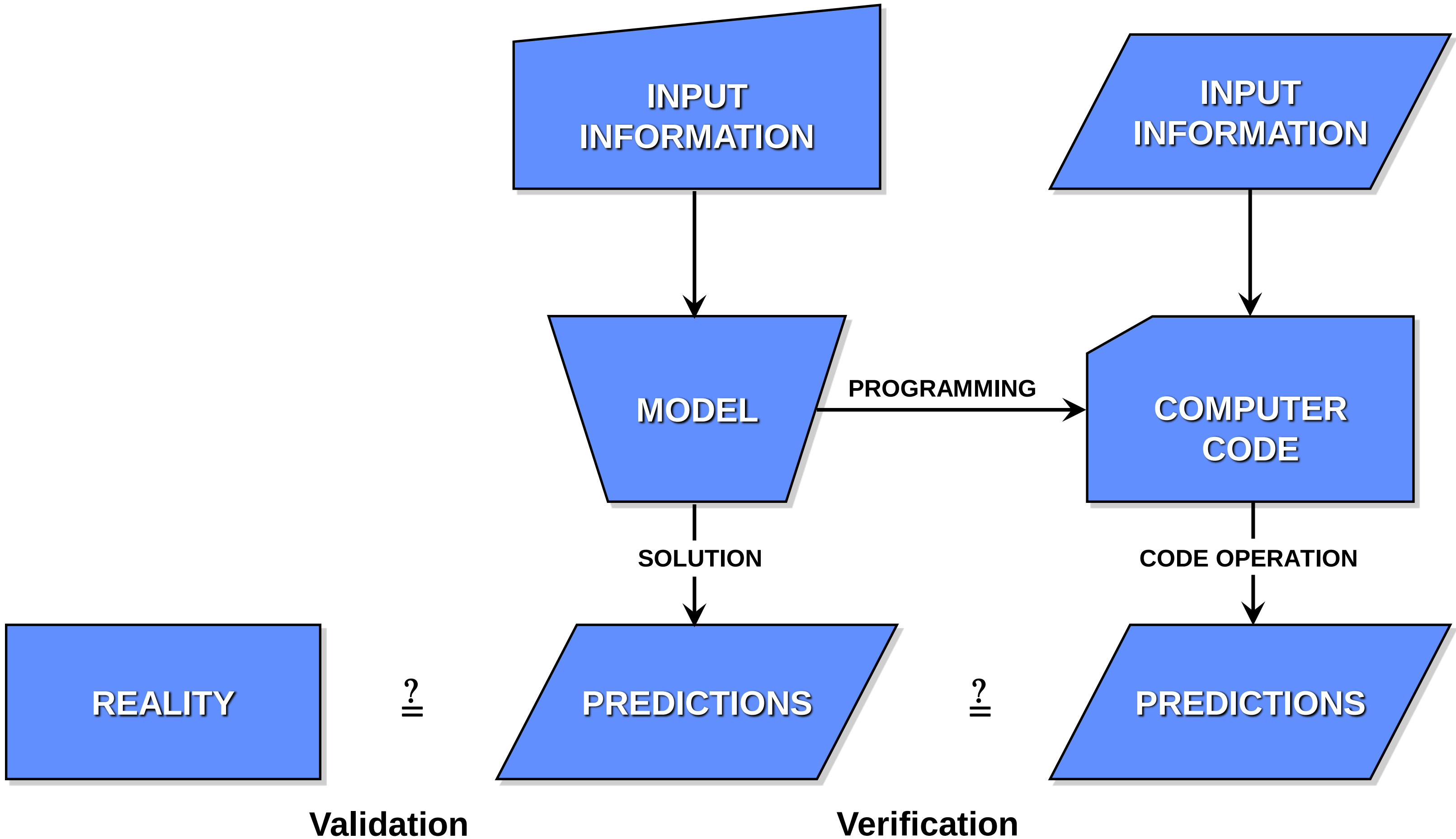
MACCS Modeling Diagram



Uncertainty And Sensitivity Analysis

- **Three Uncertainty Categories:**
  - **Stochastic - natural parameter variability**
    - **Can't reduce**
  - **Model - lack of complete information about phenomena**
    - **Incomplete knowledge of phenomena**
    - **Lower-fidelity model used to increase computational efficiency**
    - **Difficult to reduce**
  - **Parameter – input parameters are poorly quantified**
    - **Sensitivity analysis - identify the effect of input parameters on results**
    - **Uncertainty analysis – determine probability distribution for predicted results corresponding to input uncertainties**

Code Verification / Model Validation Relationship



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