ACCIDENT CONSEQUENCE ANALYSIS
P-301

June 8-12, 2009

United States
Nuclear Regulatory Commission

Sandia National Laboratories

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June 8-12, 2009

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Bethesda, MD

Accident Consequence Analysis
P-301

1. Purpose and Scope of Level-3 PRA Analysis

Objectives

- Discuss the 3 levels of PRA (PSA) and how Level 3 fits in
- Discuss the relationship between consequence and risk
- Discuss the characteristics of consequence analysis
- Discuss the overall course scope
- Discuss 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 gain knowledge that will:
  - lessen the chance (probability) of an accident
  - minimize the impact of such an accident

PRA vs. PSA

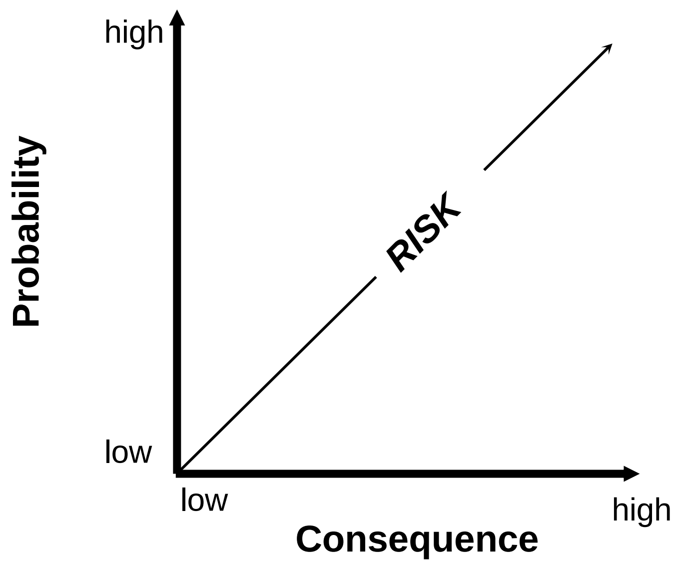
- PRA = Probabilistic Risk Assessment
- PSA = Probabilistic Safety Assessment
- Used interchangeably – no standard

Three Levels of PRA/PSA

- *Level 1* - The assessment of plant failures leading to core damage and the determination of **core damage frequency**.
- *Level 2* - The assessment of fission product release/transport and containment response which, together with the results of Level 1 analysis, leads to the determination of **release frequencies**.
- ➔ *Level 3* - The assessment of off-site consequences which, 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 a mishap.
- Probability = The likelihood of some event occurring.
- Risk = Consequence × Probability



Level-3 PRA (Consequences)

- Health and Economic Consequences

Release from Plant

↓

Transport to Public

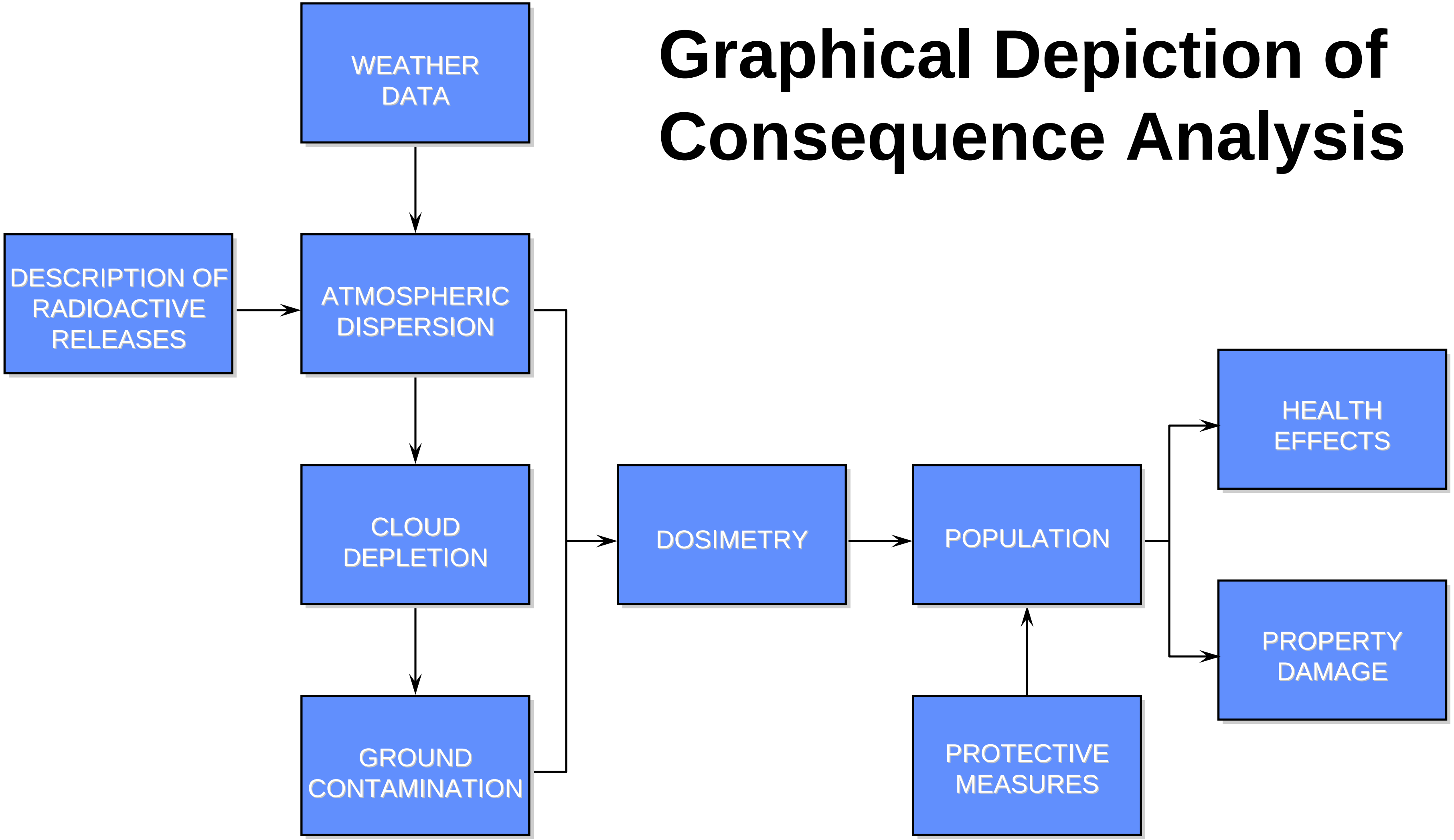
↓

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 & MACCS2 (US and worldwide)
  - ✓ COSYMA (European Commission)
  - ARANO (Finland)
  - CONDOR (UK)
  - LENA (Sweden)
  - MECA2 (Spain)
  - OSCAAR (Japan)
- Interest has been rejuvenated due to
  - Security investigations following 9/11
  - License extension for existing reactors
  - Certification and licensing of new reactors

Graphical Depiction of Consequence Analysis



Scope of Course

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

General Applications of PRA

- Predictions of public risk
  - Generic
  - Site specific
  - Societal
  - Individual
- Evaluation of alternative design features
- Environmental impact assessment
- Rulemaking and regulatory procedures
- Application of safety goals

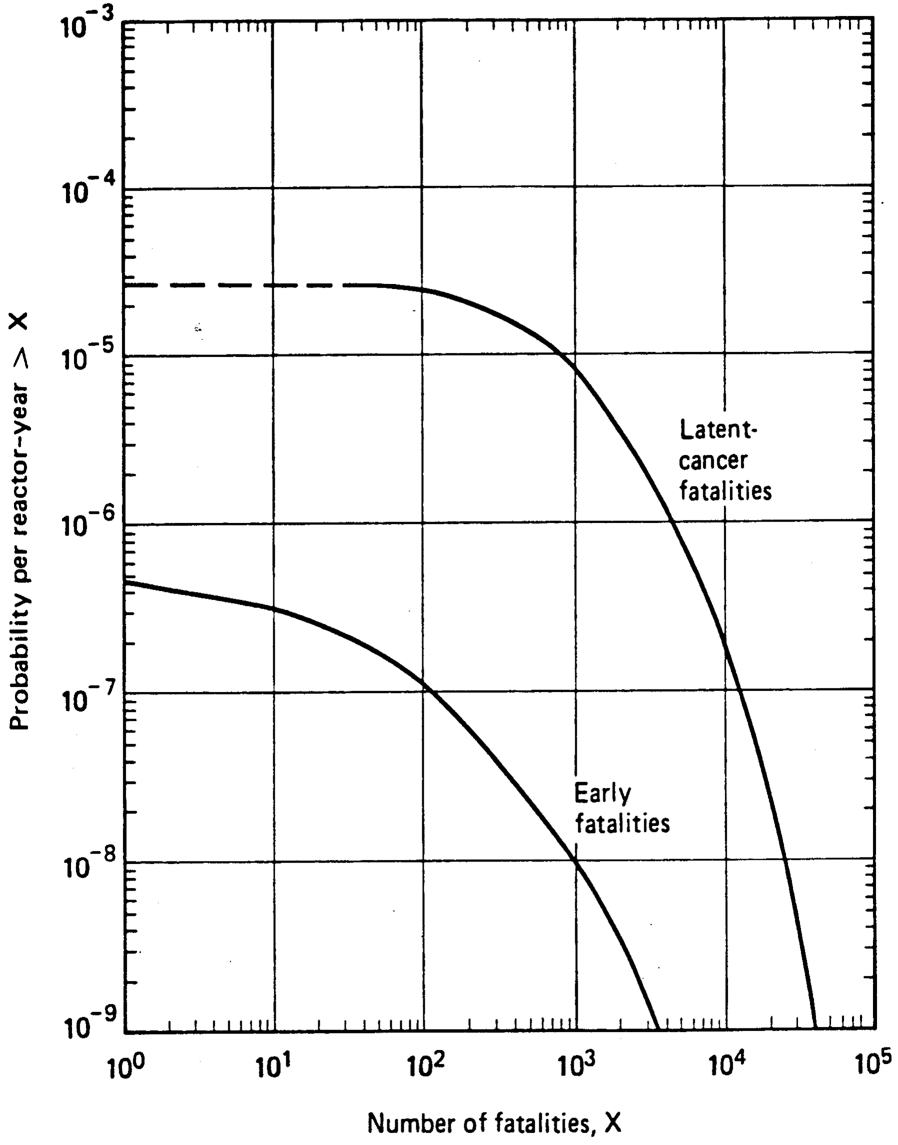
General Applications of PRA (cont.)

- Emergency planning and response
- Criteria for the acceptability of risk
- Focus for research needs
- Accident liability
- Instrumentation needs and dose assessment
- Cost/benefit analysis

Complementary Cumulative Distribution Function (CCDF)

- A distribution function calculated from a set of input parameters.
- With respect to PRA, it is a function that analyzes the relationship between Probability and Consequence (definition of risk).
- Graphical (WinMACCS) or tabular (MACCS2) in nature.

CCDF for Early and Latent-cancer Fatalities



Notes:

- From the Reactor Safety Study (USNRC, 1975)

Class Schedule

- June 8, Monday AM
  - Section 1 – Purpose and Scope of Level-3 Analysis
  - Section 2 - History of Consequence and Risk Analysis
- June 8, Monday PM
  - Section 3 - Interface with Level-2 Analysis
  - Section 4 - Overview of MACCS2
- June 9, Tuesday AM and PM
  - Section 5 - Atmospheric Transport and Dispersion
- June 10, Wednesday AM and PM
  - Section 6 - Health Effects and Economic Consequences
- June 11, Thursday AM
  - Section 7 - Protective Measures
  - Section 8 - Uncertainties, V&V, and Research
- June 11, Thursday PM
  - Section 9 - Course Summary and Exam Preparation
  - Section 10 – Exam
- June 12, Friday AM
  - Continuation of Unfinished Material
  - Additional Consequence Analyses
  - SECPOP2000 and MELMACCS

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
- 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
- Study of radium dial painters - [1945]

1940's (cont.)

- 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
- National Committee on Radiation Protection (NCRP) - [1946]
  - An independent body of scientific experts
  - Recommends limits for occupational exposure
- 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

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 formulae published - [throughout the 50's]
  - Publication of maximum permissible dose limits
  - National Bureau of Standards (NBS)
- 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" - [1961]
  - 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.)

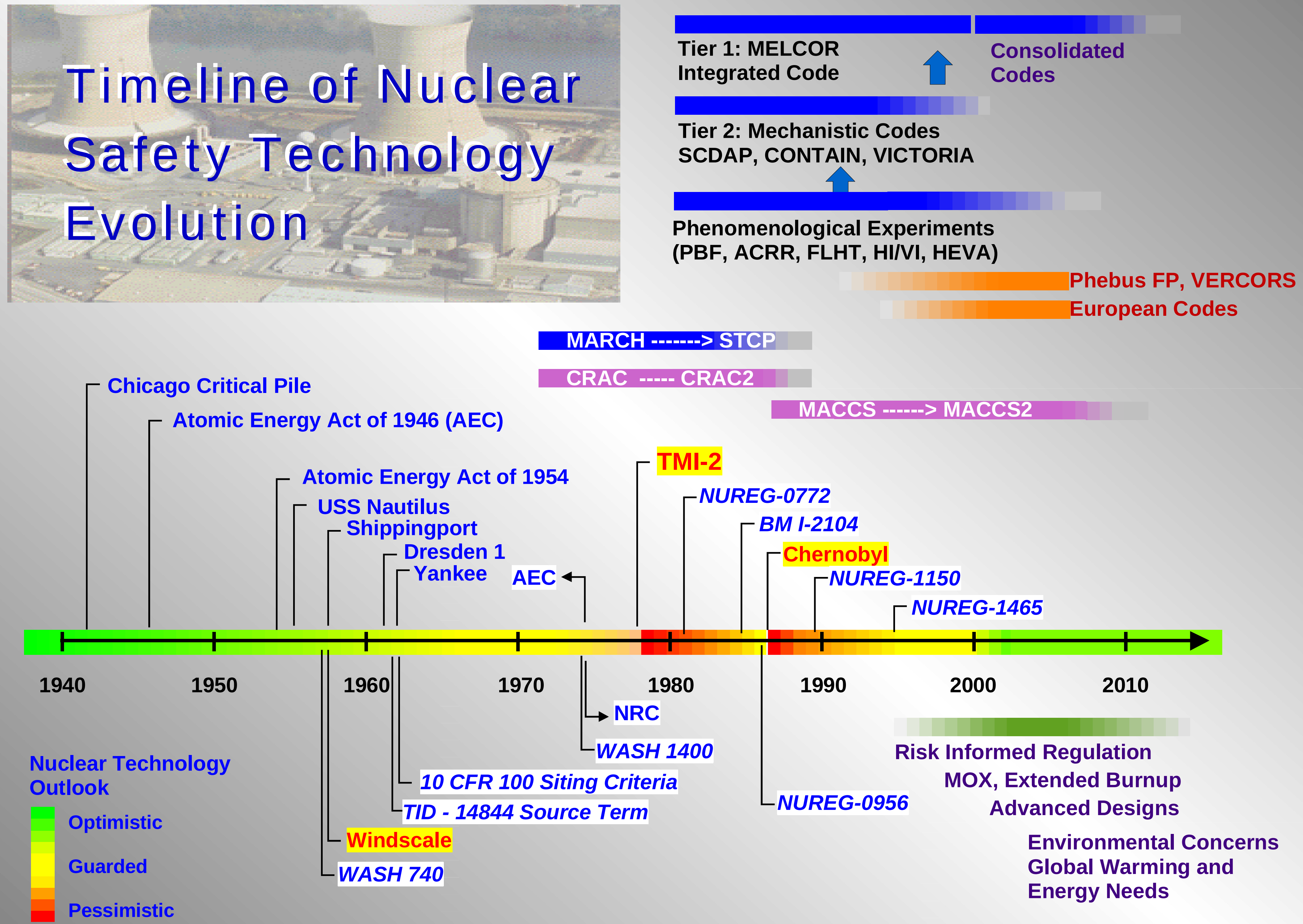
- Core Integrity investigation during a LOCA
  - Thermal-hydraulic safety related computer codes
  - Two-phase flow
  - LOFT
- TID Release assumptions used in Safety System design
  - Iodine releases recognized as conservative
  - Assumed to compensate for uncertainty
- Regulatory Guides 1.3 and 1.4 - [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"

1970's

- ECCS Concerns
  - Semi-Scale
  - AEC publishes "interim acceptance criteria"
- USAEC "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 Evolution
Tier 1: MELCOR Integrated Code
Consolidated Codes
Tier 2: Mechanistic Codes SCDAP, CONTAIN, VICTORIA
Phenomenological Experiments (PBF, ACRR, FLHT, HI/VI, HEVA)
Phebus FP, VERCORS
European Codes
MARCH -------> STCP
CRAC ----- CRAC2
MACCS ------> MACCS2
Chicago Critical Pile
Atomic Energy Act of 1946 (AEC)
Atomic Energy Act of 1954
USS Nautilus
Shippingport
Dresden 1
Yankee
AEC
TMI-2
NUREG-0772
BM I-2104
Chernobyl
NUREG-1150
NUREG-1465
1940
1950
1960
1970
1980
1990
2000
2010
NRC
WASH 1400
10 CFR 100 Siting Criteria
TID - 14844 Source Term
Windscale
WASH 740
NUREG-0956
Risk Informed Regulation
MOX, Extended Burnup
Advanced Designs
Environmental Concerns
Global Warming and
Energy Needs
Nuclear Technology Outlook
Optimistic
Guarded
Pessimistic

WASH-740

- USAEC, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants", March 1957
- 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.)
  - $2.3 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
    - 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.)

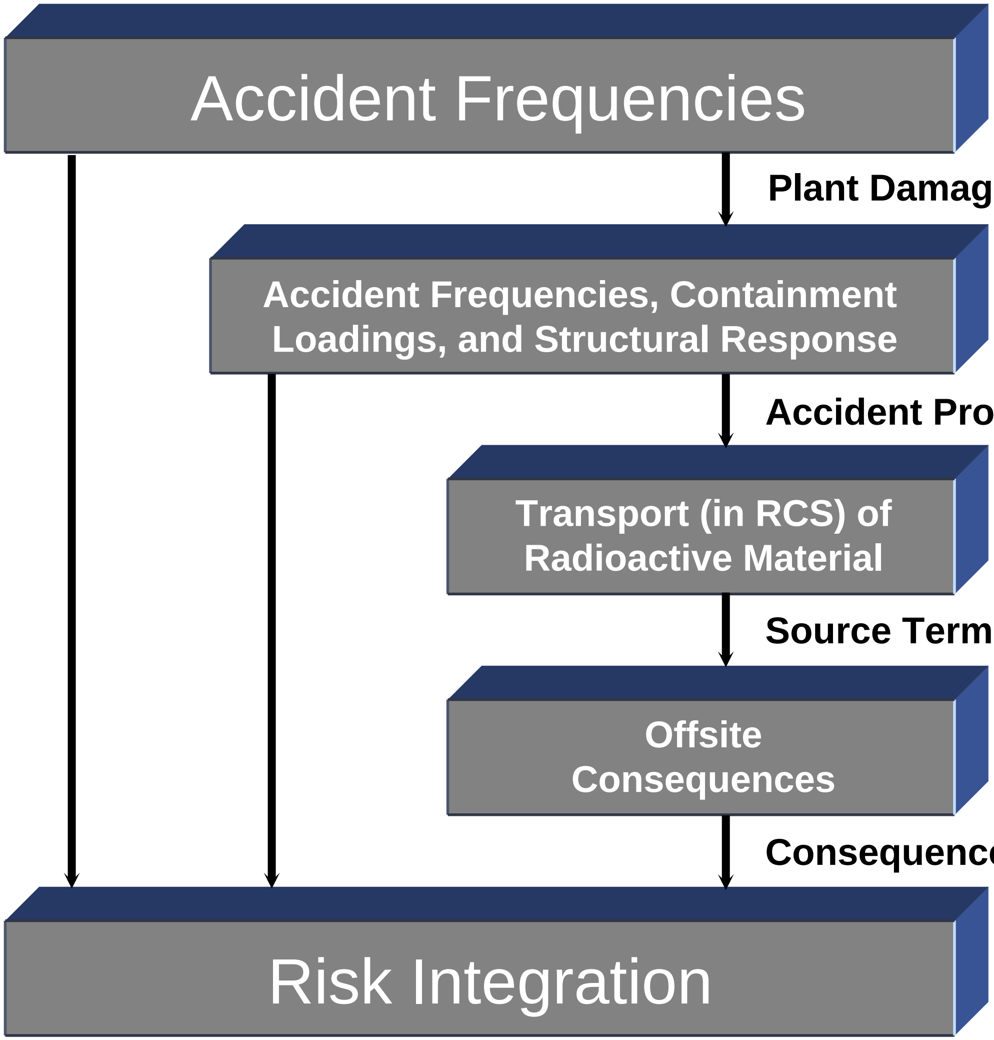
- Calculation of Reactor Accident Consequences (CRAC)
  - Assign probability distribution to key variables
    - release magnitude
    - weather conditions
    - population

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

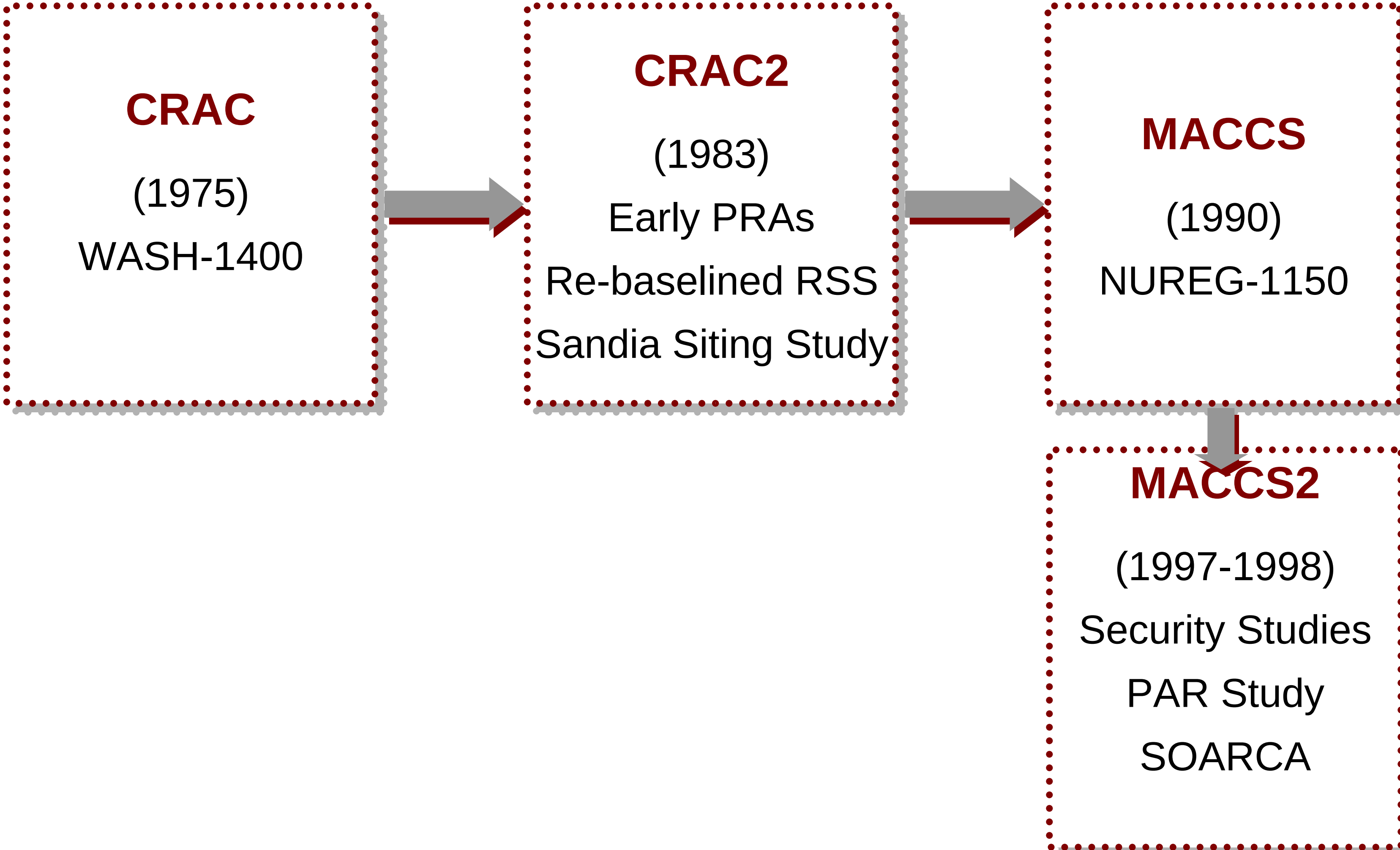
NUREG-1150

- "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 info first four steps

NUREG-1150 Risk Analysis Process



Consequence Code Evolution



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

⇩

- *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

⇩

- *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 which 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.

Outline

- Level-1/Level-2 interface (plant damage states)
- Level-2 PRA
- Introduction to source terms
- Importance of released radionuclides
- Source term release categories
- Structure of the NUREG-1150 analyses
- Structure of the NUREG-2300 analyses (IPEs)

LEVEL-1/LEVEL-2 INTERFACE

- Plant-Damage-State (PDS) characterization
  - Availability of functions to mitigate accident progression after core damage
  - Physical state of the reactor coolant system (RCS) and containment
- 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 (4)
  - SGTR (2)
  - Event V (Interfacing systems LOCA)
- Status of ECCS (5 modes)
  - Injection, recirculation, not operating, recoverable
- Containment heat removal (4 modes)
  - Operating, recoverable, sprays
- AC power (4 modes)
  - Available, recoverable, not recoverable

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

- Contents of reactor water storage tank (RWST) (4 modes)
  - Injection, availability
- Heat removal from steam generators (6 modes)
  - Auxiliary feedwater system (AFWS) status - steam and electric
  - Steam generator pressurization
- Cooling for reactor coolant pump seals (3 modes)
  - Operating status, recovery status
- There are potentially 11520 PDSs, but only a few dozen are of interest

Level-2 PRA

- Characterization of the core-melt accident progression
- Conditional probability of containment failure
- Source term
- Assessment of severe accident phenomenological ***uncertainties*** and containment challenges

Typical Core-Melt Accident Sequence

- Initiating event
- In-vessel:
  - Core uncovery
  - Core heatup
  - Core melt
  - Core slump and relocation into lower plenum
  - Fuel/coolant interactions (FCI) in lower plenum
- Vessel and/or RCS failure:
  - Overtemperature/overpressure failure of RCS piping, steam generator tubes possible before vessel breach, and/or
  - Vessel penetration, creep rupture 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:
  - Temperature and pressure rise from mass and energy additions
  - Hydrogen combustion
  - Steam explosions
  - Mitigating 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, failure, or valve)
  - Release into the environment via
    - Containment breach
    - Failure to isolate
    - Bypass of containment (SGTR, ISLOCA)

Level-2 Probabilistic Analysis

- Level-2 analyses extend 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 the containment event tree (CET)
  - Depicted on accident-progression event tree (APET) in NUREG-1150

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”) is an averaging process and causes loss of information detail
- Level-2 predictions are phenomenological in nature and therefore modeling uncertainty is intrinsic

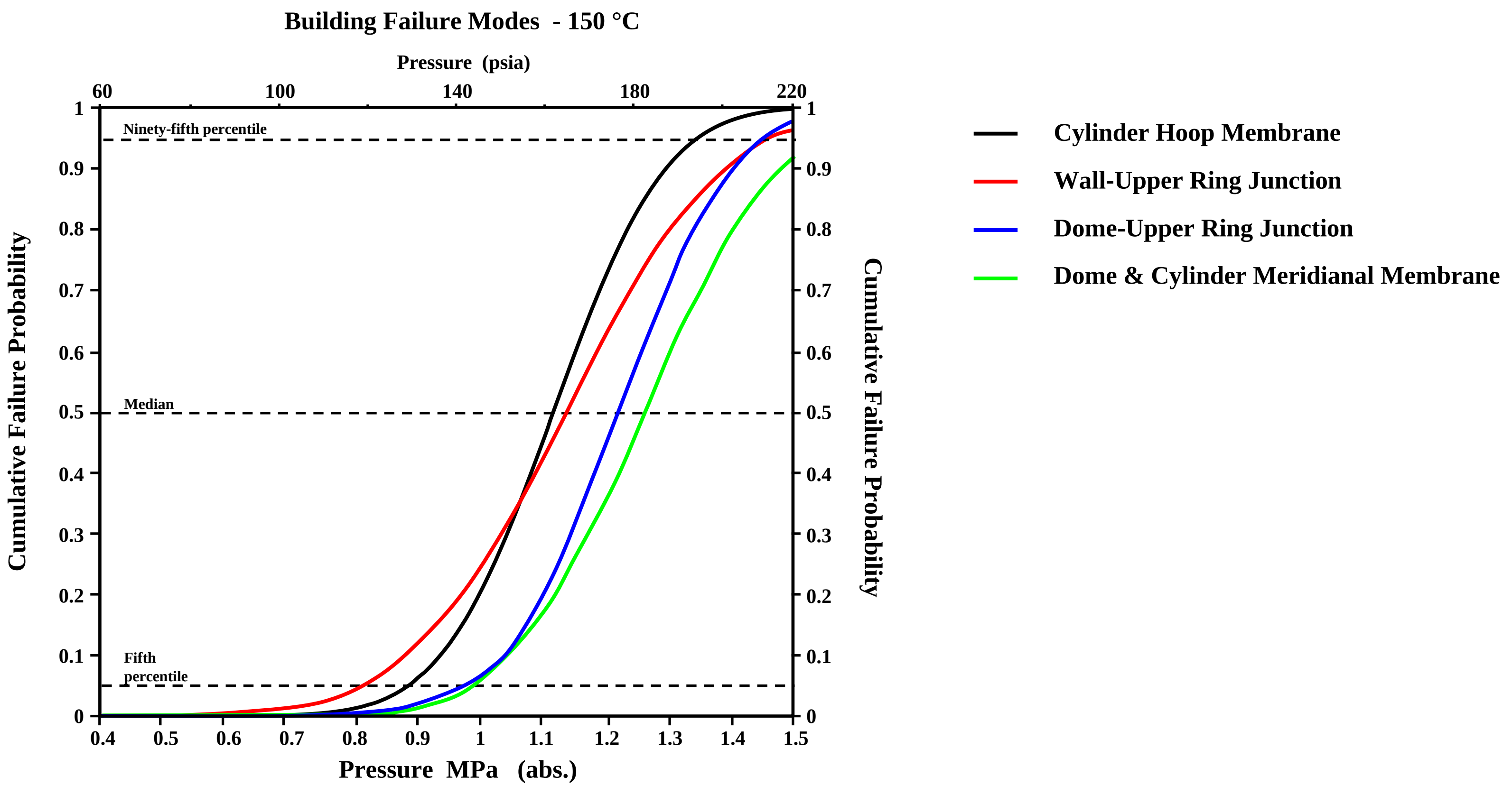
Accident-Progression Analysis

- 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 and Outcomes

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

Introduction to Source Terms

- The "Source Term" is the quantity and types of radionuclides released to the environment
  - Isotopic activities (Bq)
  - Rate and timing of release
  - Chemical and physical forms
  - Thermal energy
- Chernobyl (example of a 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
  - More than half of core inventory of iodine, one-third of core inventory of cesium and tellurium released
  - 3.5% of fuel released with late release due to core debris oxidation
    - low volatility elements such as cerium, zirconium and the actinides mainly retained in the fuel fragments
  - Ruthenium and molybdenum released in late phase probably because of oxidation to volatile forms

Example Source Term Grouping Parameters

- Containment failure modes:
  - Failure before core damage
  - Failure at time of vessel breach
  - Pre-existing leakage/isolation failure
  - Late rupture
  - Late leakage - precludes rupture
  - Bypass with/without submergence
  - Basemat penetration
  - No failure
- Spray system operation
- Auxiliary building release mitigation effective

Source-Term Release Categories

- Fission products escape path
  - From the fuel or the fuel rod
  - Through the primary system to the containment
  - From containment into the atmosphere
- Natural and engineered removal processes diminish the magnitude of release
- Similar sequences are grouped into release categories
  - Too many important sequences to perform the consequence analysis for each
  - Only important and distinguishable combinations are characterized

Factors Determining Importance of Radionuclides Released

- Total core inventory
  - Fission yields
  - Operating history
  - Half-life
  - Decay products
- Physical and chemical properties
  - Nature of radioactivity (alpha, beta, gamma)
  - Volatility
- Atmospheric transport factors (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 about 50% of fission yield.

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

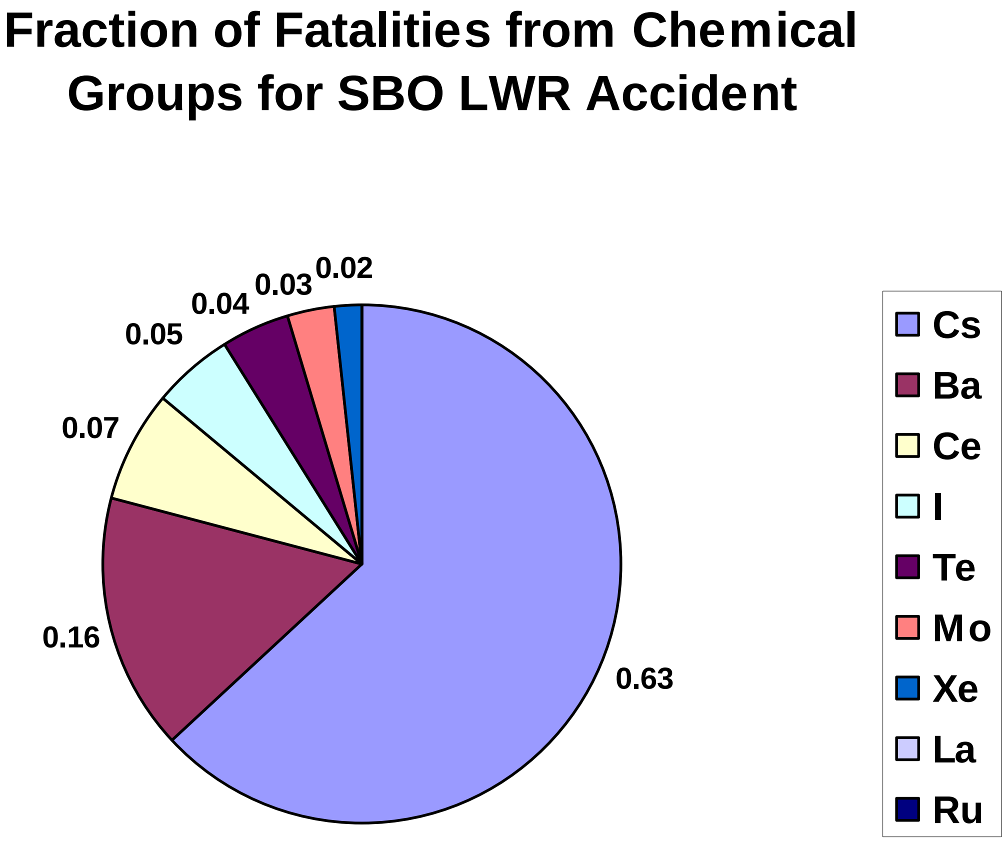
WASH-1400 First Day Doses at 0.5 Miles (Example to indicate important groups)

Radionuclide Group	Curies (3000 MWt)	Baseline Relative Dose[1]	Relative Dose with Indicated Attenuation	
			Attenuation Factor	Dose
Noble Gases[2]	3.4E+8	0.8	1.0	0.8
Iodines[3]	7.2E+8	54.8	10	5.5
Telluriums	1.8E+8	28.8	10	2.9
Cesiums	0.2E+8	1.0	10	0.1
Ceriums	3.7E+8	6.2	10	0.6
Rutheniums	2.1E+8	1.0	10	0.1
Others[4]	33.3E+8	7.4	10	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 Long-Term Doses Resulting in Latent Health Effects

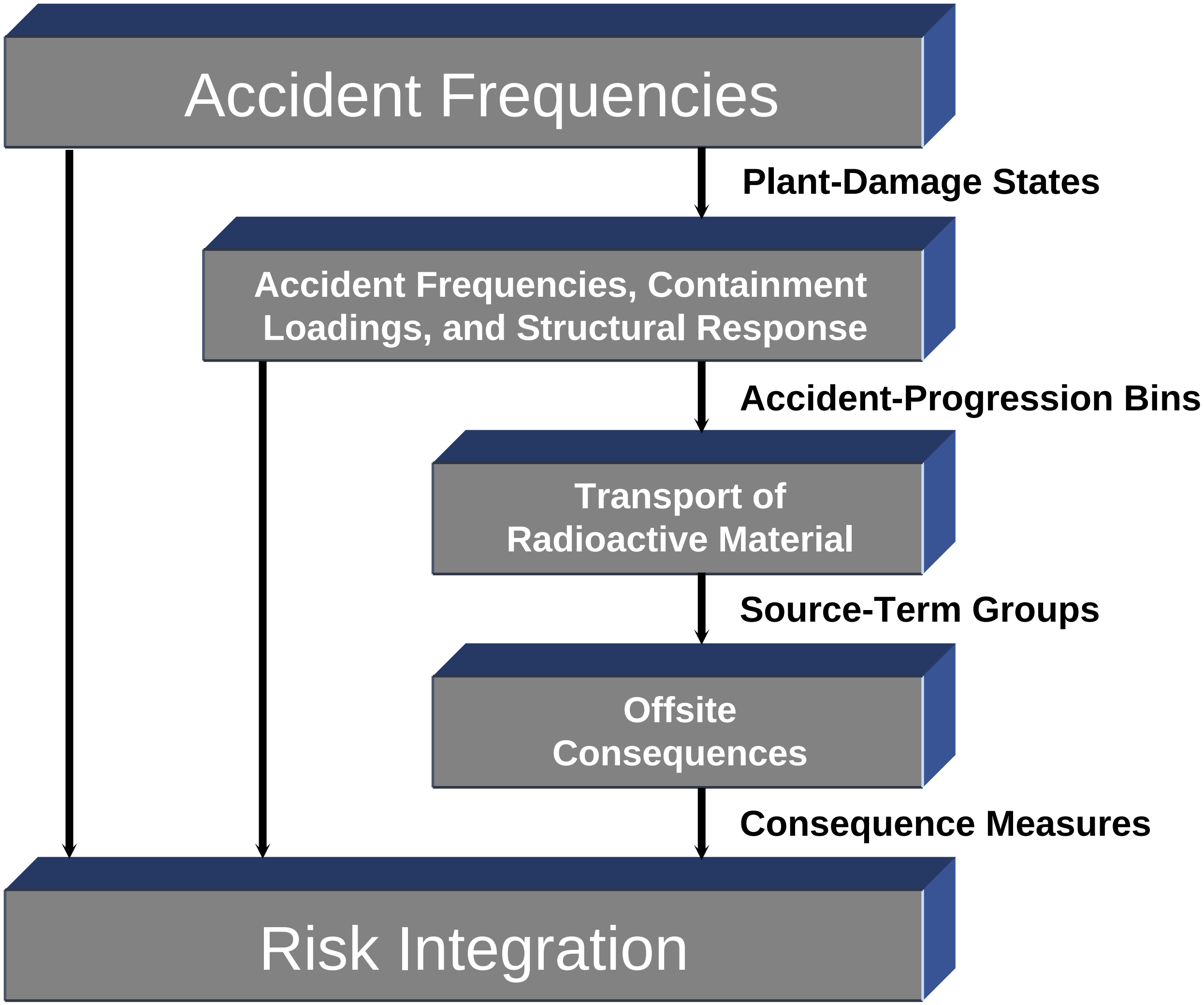
- Gamma radiation from the Cs group, primarily from Cs-137, produces most of the long-term dose
- Second largest contributor is the Ba group
- Ce, I, Te, Mo, and Xe each contribute less than 10% to the long-term dose



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 component phases 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 $\overrightarrow{\mathrm{PDS}}$ 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 $\mathrm{P(PDS \rightarrow APB)}$ such that

$$\overrightarrow{\mathrm{APB}} = \overrightarrow{\mathrm{PDS}} \cdot \mathrm{P(PDS \rightarrow APB)}$$

where $\overrightarrow{\mathrm{APB}}$ 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 Source Term Groups (STGs) where each group is a collection of source terms that define similar conditions for consequence analysis
  - Transition matrix representation is

$$\overrightarrow{STG} = \overrightarrow{APB} \cdot P(APB \rightarrow STG)$$

where $\overrightarrow{APB}$ 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 so that the source terms in them had similar health effect impacts
- Grouping done with PARTITION code based on
  - Early health effect (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)
  - Evacuation 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 Group Source Terms

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

$$\vec{C} = \overrightarrow{STG} \cdot P(STG \rightarrow C)$$

where $\vec{C}$ 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

$$\vec{C} = \overrightarrow{PDS} \cdot P(PDS \rightarrow APB) \cdot P(APB \rightarrow STG) \cdot P(STG \rightarrow C)$$

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,

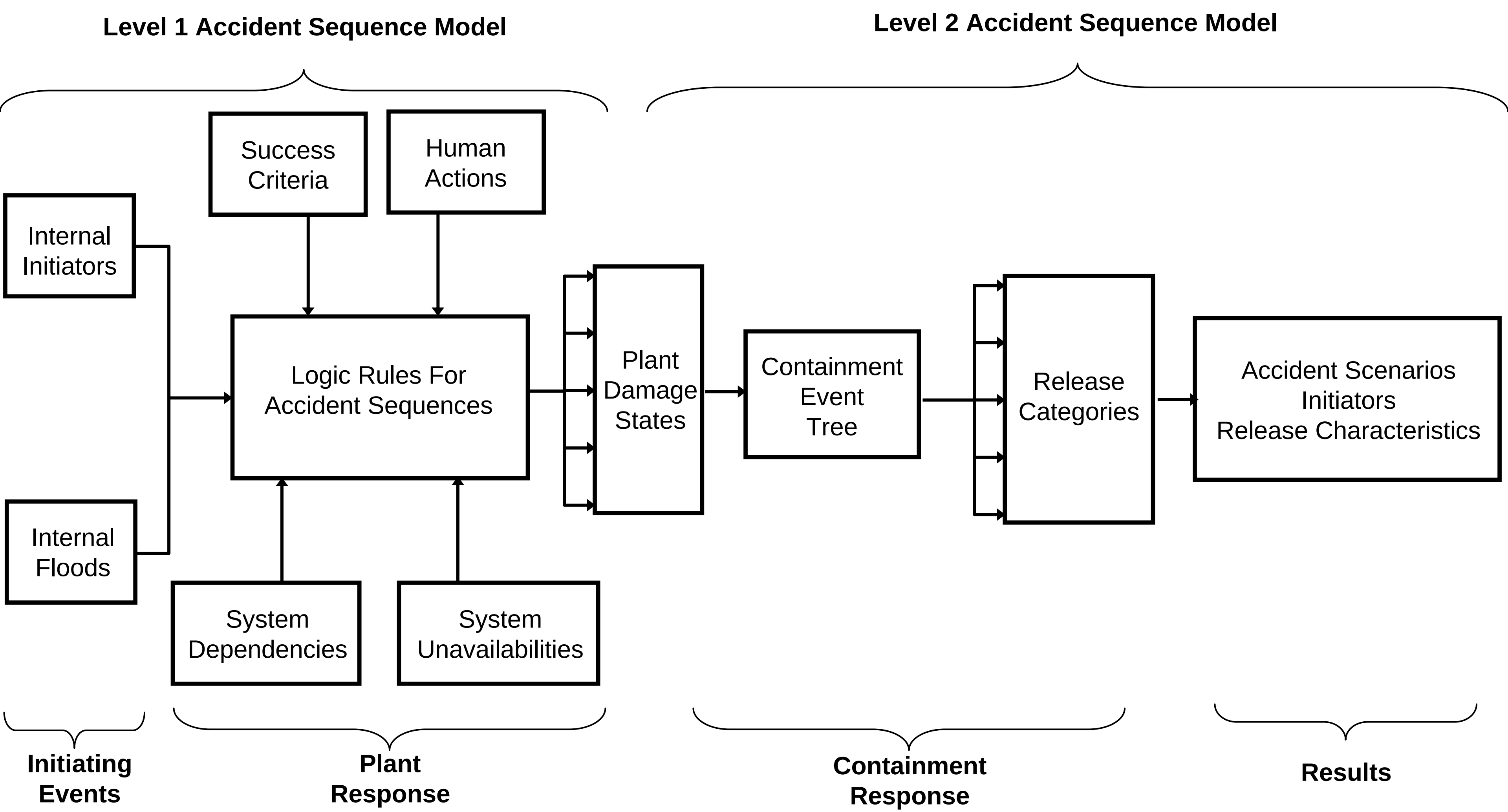
$pSTG_{kl}$ = conditional probability that APB_k will be assigned to STG_l,

$cSTG_{lm}$ = 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 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

References

- Radiological Assessment: A Textbook On Environmental Dose Analysis, NUREG/CR-3332
- 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

4. MACCS2 Overview

Objectives

- **Develop a basic understanding of**
  - **Atmospheric radioactive release and related potential for exposure**
  - **Code structure and applicability**
  - **Code outputs**
  - **Code limitations**

Basic Concepts I

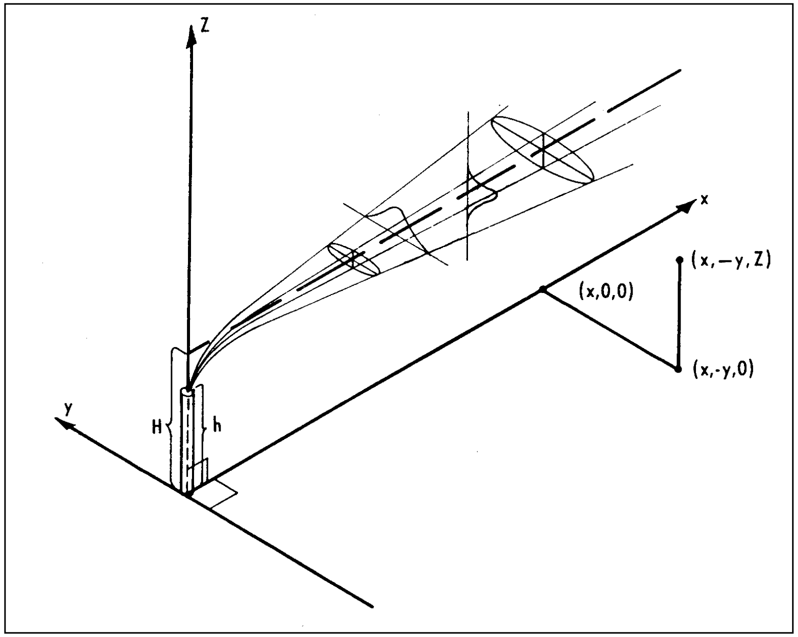
- **Source term**
  - **Defines the magnitude and timing of release of radionuclides**
  - **Characterized by the following parameters**
    - **Initial time of release**
    - **Release rate as a function of time (by radionuclide)**
    - **Initial height**
    - **Buoyancy (heat content)**
    - **Aerosol size distribution (by radionuclide)**
  - **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
    - Advection (material moves downwind at the speed of the wind)
    - Dispersion (stochastic motion from diffusion and turbulence)
    - Buoyancy (tendency to rise because of lower density)
    - 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**
  - **Valid solution for a point source in a 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

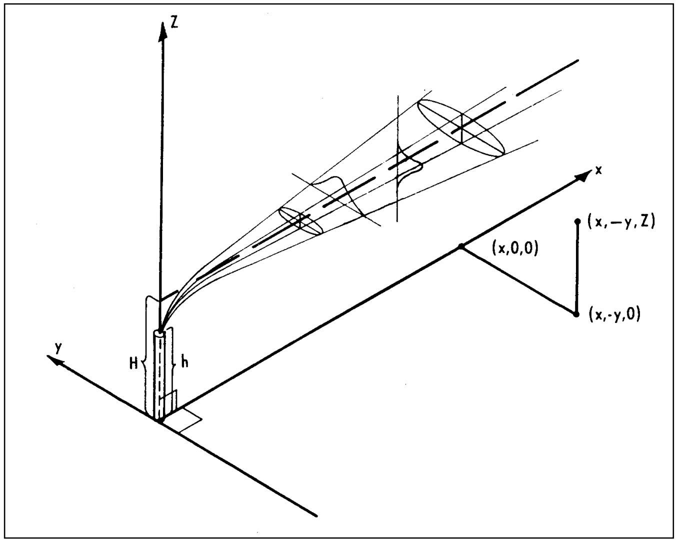
- **Types of dose**
  - **Absorbed dose – energy deposited in a specific organ (Gy)**
  - **Equivalent dose or dose equivalent – biological effect of dose to a specific organ (Sv)**
  - **Effective dose – weighted average of doses to a set of organs (represents entire body)**
  - **Committed dose – time 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

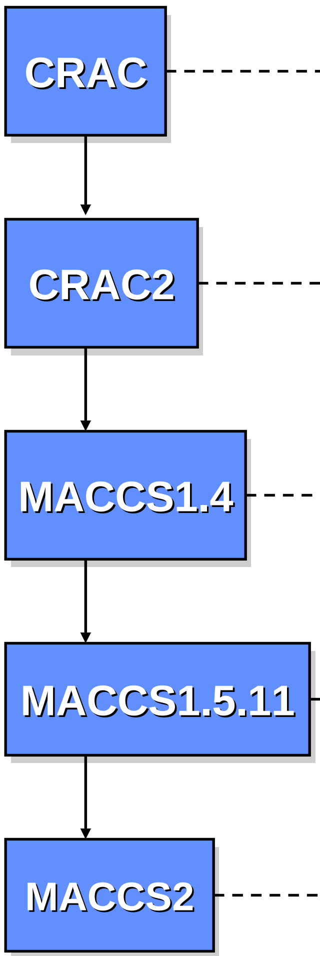
- **Dose conversion factors (now dose coefficients) are used to calculate doses from exposures**
  - **Exposure is a measure of the rate times the duration to which a receptor is exposed for each**
    - **Radionuclide**
    - **Pathway**
    - **Organ**
  - **Exposures are expressed in terms of intake (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)**
- **Risk factors are used to calculate health effects from doses**

Basic Concepts IX

- Types of ATD models
  - Gaussian plume (MACCS2)
    - One-dimensional wind field (x)
    - Empirical dispersion model
    - Very fast (seconds to minutes)
  - Gaussian puff (RASCAL)
    - Two- or three-dimensional wind field (x, y) or (x, y, z)
    - Empirical dispersion model
    - Moderately fast (minutes to hours)
  - State-of-the-art models (LODI from NARAC)
    - Three-dimensional wind field (x, y, z)
    - Monte-Carlo particle tracking model
    - Very slow (days to weeks)



MACCS2 Evolved From RSS



1975: WASH-1400 (Reactor Safety Study)

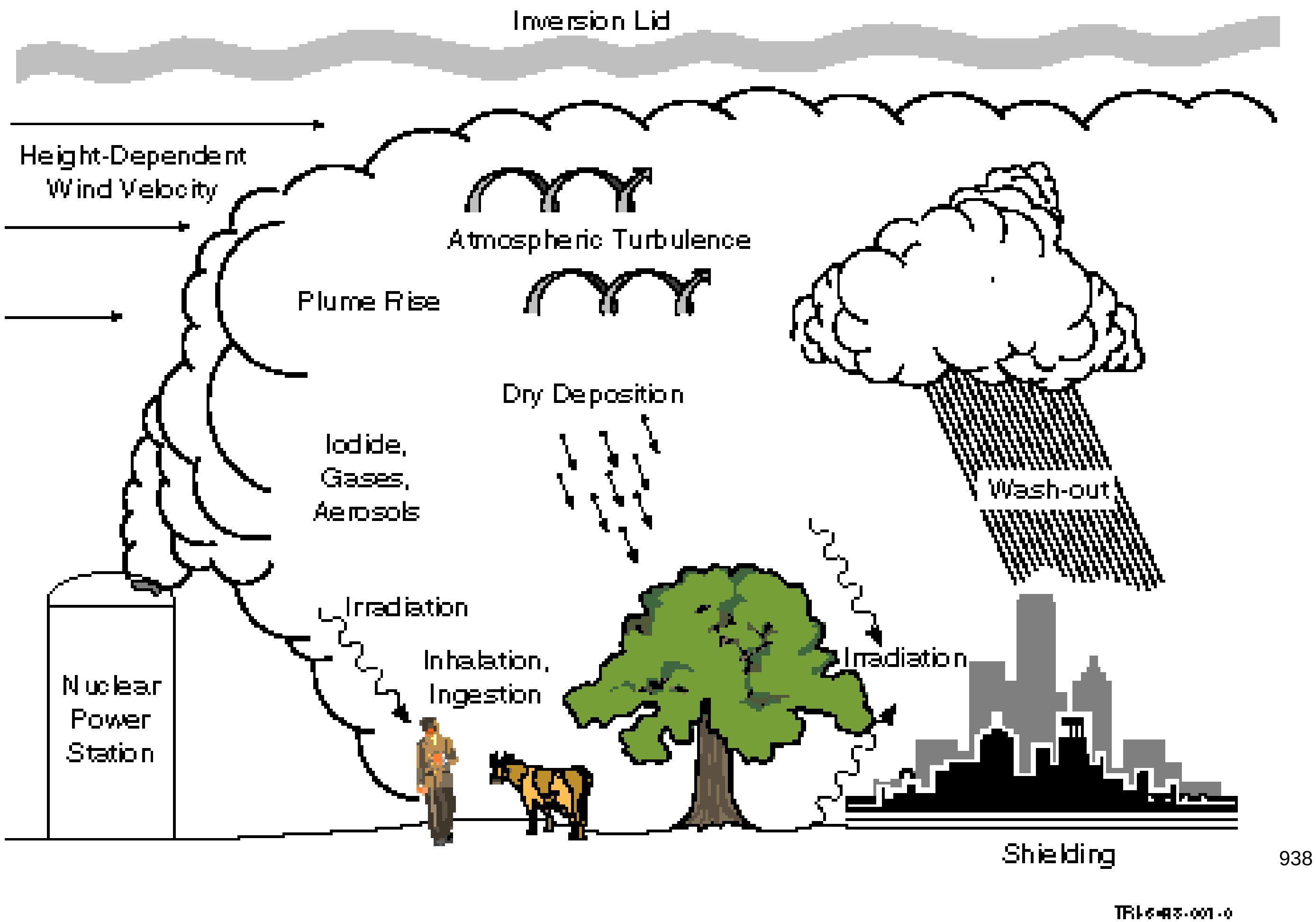
1983: Early PRAs

1987: Draft NUREG-1150 (never released to the public)

1990: NUREG-1150

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

Pathways to Receptors From Atmospheric Release



MACCS2 Estimates Consequences of Airborne Radioactive Releases

- **Consequences considered by MACCS2 (MELCOR Accident Consequence Code System Version 2)**
  - **Doses**
  - **Health effects**
  - **Economic impacts**
- **Consequences altered by mitigative actions including**
  - **Sheltering, evacuation, and relocation**
  - **Decontamination, interdiction, and condemnation**

Key Features of MACCS2

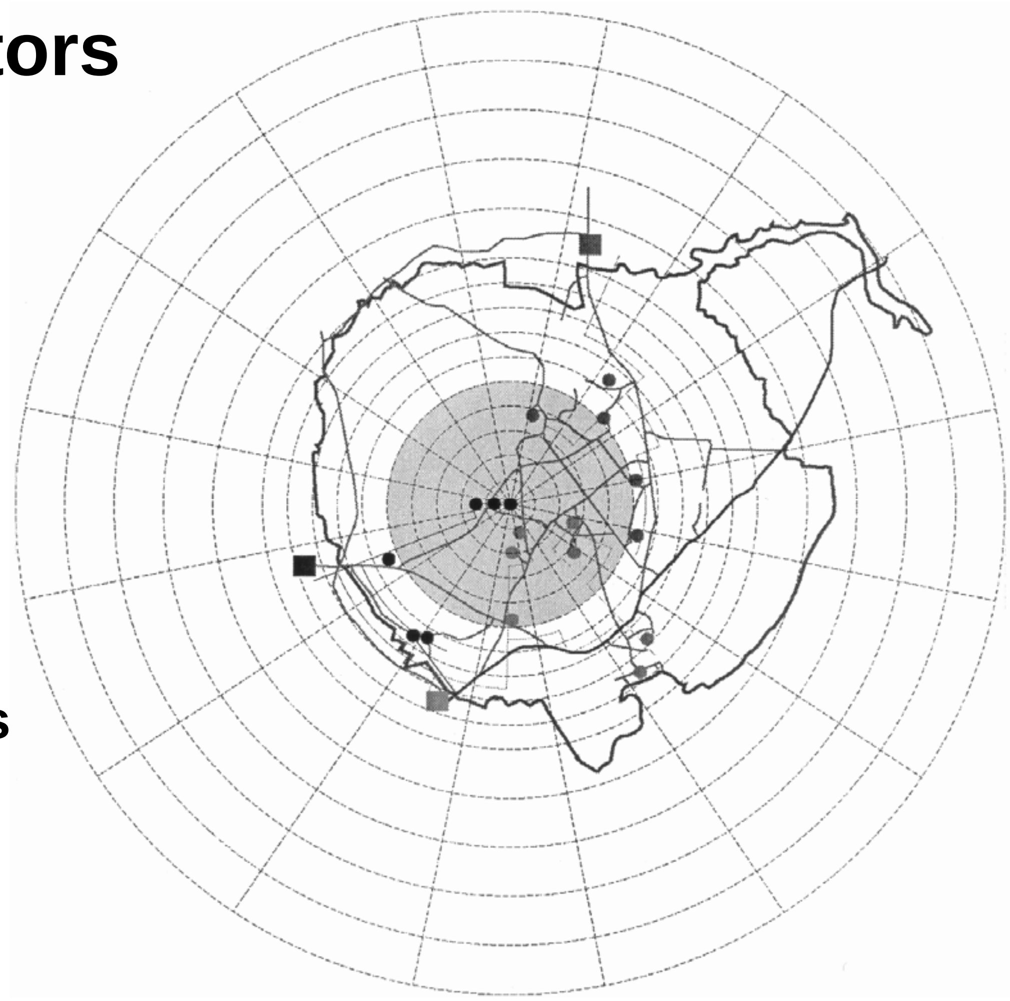
- **Polar coordinate spatial discretization**
  - **Up to 35 radii**
  - **16, 32, 48, or 64 compass directions**
- **Phases consistent with existing EPA protective action guides (PAGs)**
- **Architecture allows user to invoke the following modules as needed (to determine results of interest)**
  - **ATMOS – 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 (which are functions of atmospheric stability) and increase with downwind distance**
- **σ_z differs from σ_y because of temperature gradients in the atmosphere**

Spatial Division Based on Compass Sectors

- Illustration shows 16 22.5°-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 7 days**
  - **Dose pathways**
    - **Direct inhalation**
    - **Cloudshine**
    - **Groundshine**
    - **Resuspension inhalation**
    - **Deposition onto skin**
  - **Possible mitigative actions**
    - **Sheltering**
    - **Evacuation**
    - **Dose-dependent 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 dose-dependent 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**
    - **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 (MACCS2 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 plumes (i.e., up to 200 plumes)
- Dispersion based on
  - Gaussian plume 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 start times randomly selected from each day)
    - Weather bin sampling

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)

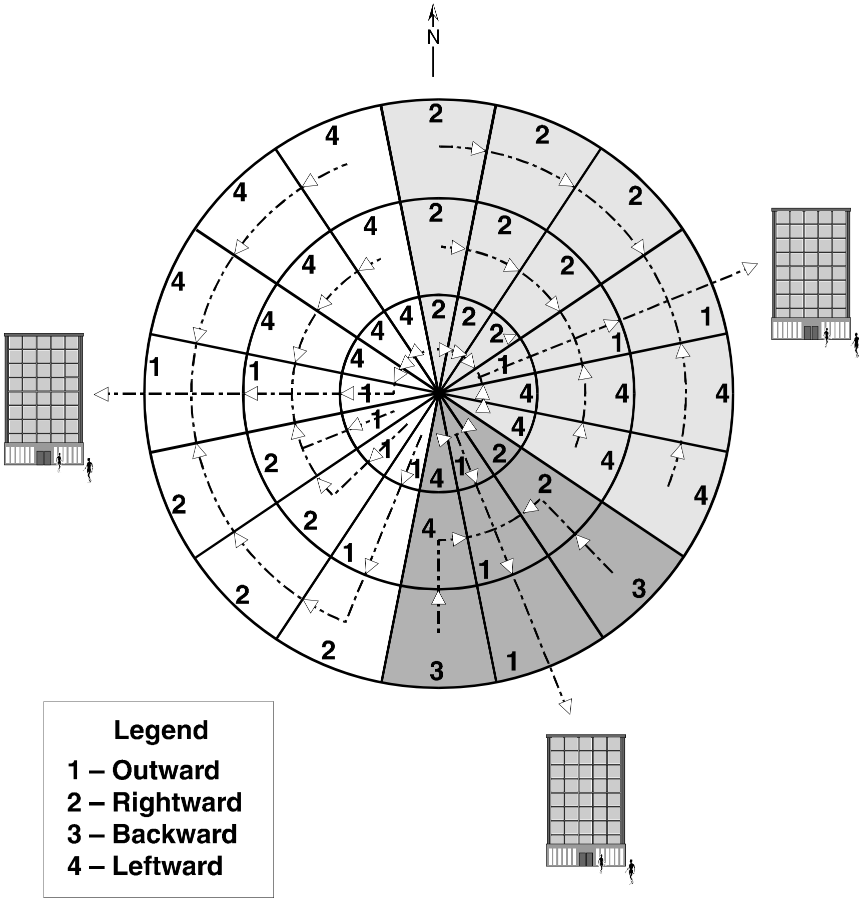
EARLY Module
Emergency Phase II

- **Dose-dependent relocation**
  - **Only outside user-specified sheltering/evacuation region**
  - **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 in early, middle, and late phases**
  - **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 includes a scaling factor and effects of decay/weathering during decontamination period (1-year maximum)**
- **Decay/weathering continue (if necessary) during interdiction periods (8 years maximum for farmland and 30 years maximum 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 (including those incurred in early 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**
  - **Site data (SECPOP2000)**
  - **Dose conversion factor data (DOSFAC2, FGRDCF)**
  - **Food chain data (COMIDA2)**
- **Site data optionally needed by EARLY to define population and regional economic data**
- **Dose conversion factors required by EARLY and CHRONC**
- **Food-chain data optionally used by CHRONC**

SECPOP2000
Based on Census Data

- For each MACCS2 grid section (within continental US)
  - Block-level data (1990 or 2000 census) used to estimate population
  - County-level data for 1992, 1997, and 2002 used to estimate
    - 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)

Preprocessors Available to Modify Dose Conversion Factor Files

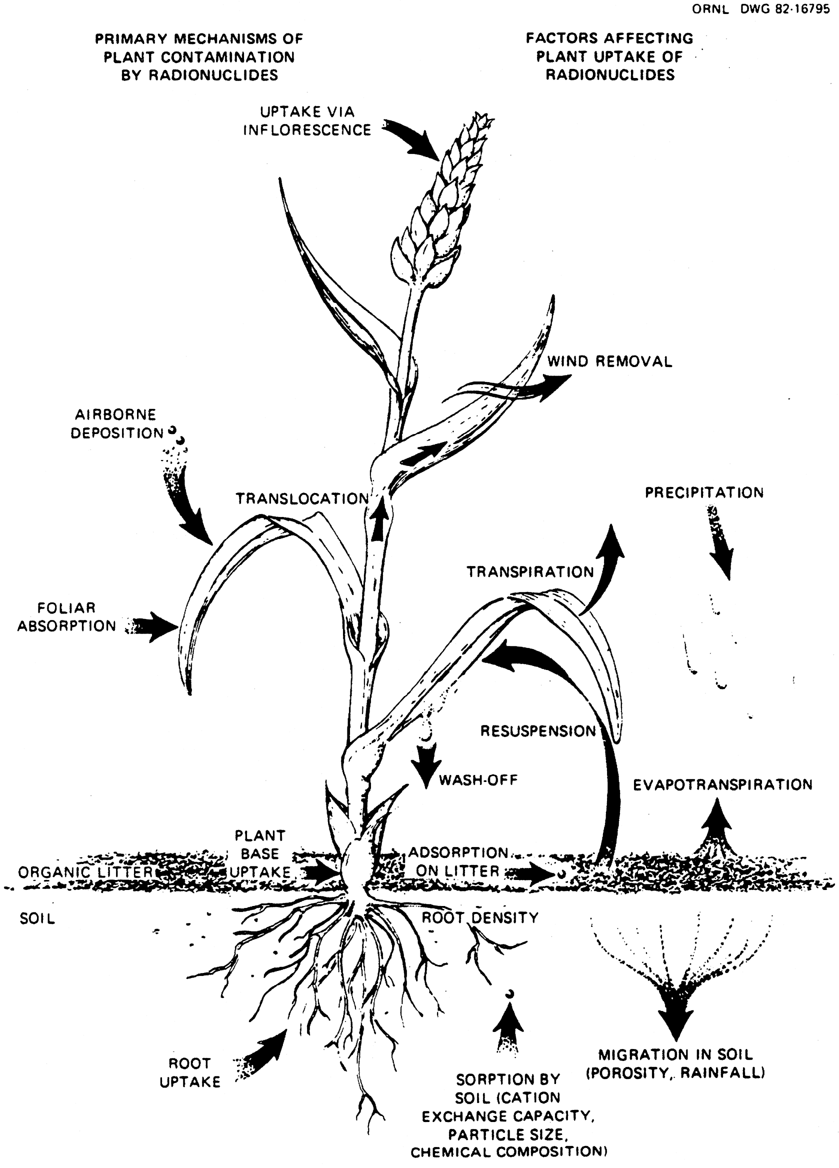
- **Dose conversion factor (DCF) files accompany MACCS2 release (adequate for most applications)**
- **Preprocessors allow replacement of released files for specific analyses (*with limitations*)**
  - **DOSFAC2 - 60 nuclides only based on DOSD87 & DOE/EH-0070**
  - **FGRDCF - 500 nuclides for inhalation/ingestion and 825 nuclides for cloudshine/groundshine based on Federal Guidance Reports 11 and 12 without acute capabilities**
- **New FGR-13 DCF file includes 825 nuclides and acute capabilities**

Three Options for Food Chain Modeling

- **Options include:**
  - **Transfer-factor model (MACCS)**
  - **COMIDA2**
  - **No ingestion pathway**
- **Transfer-factor model**
  - **Requires numerous unitless transfer factors (difficult to determine)**
  - **"Static"; consisting of growing season and long term submodels**
  - **Neglects radioactive decay and ingrowth - limited to 6 nuclides**
- **COMIDA2**
  - **Provides dose conversion factors versus deposition (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

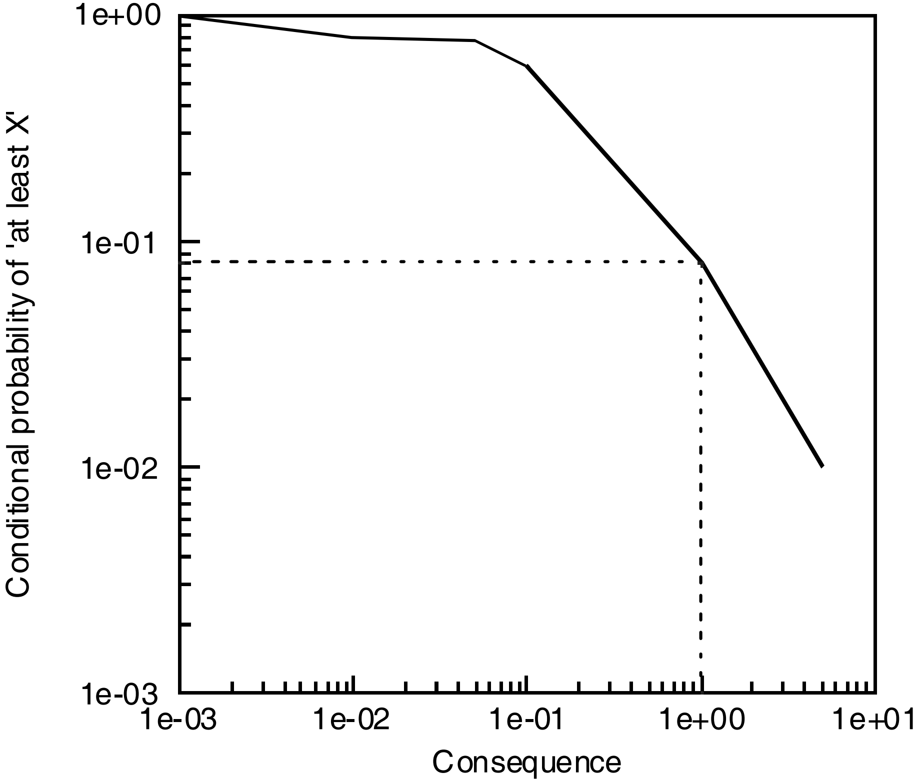


Extensive Output Available

- **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)

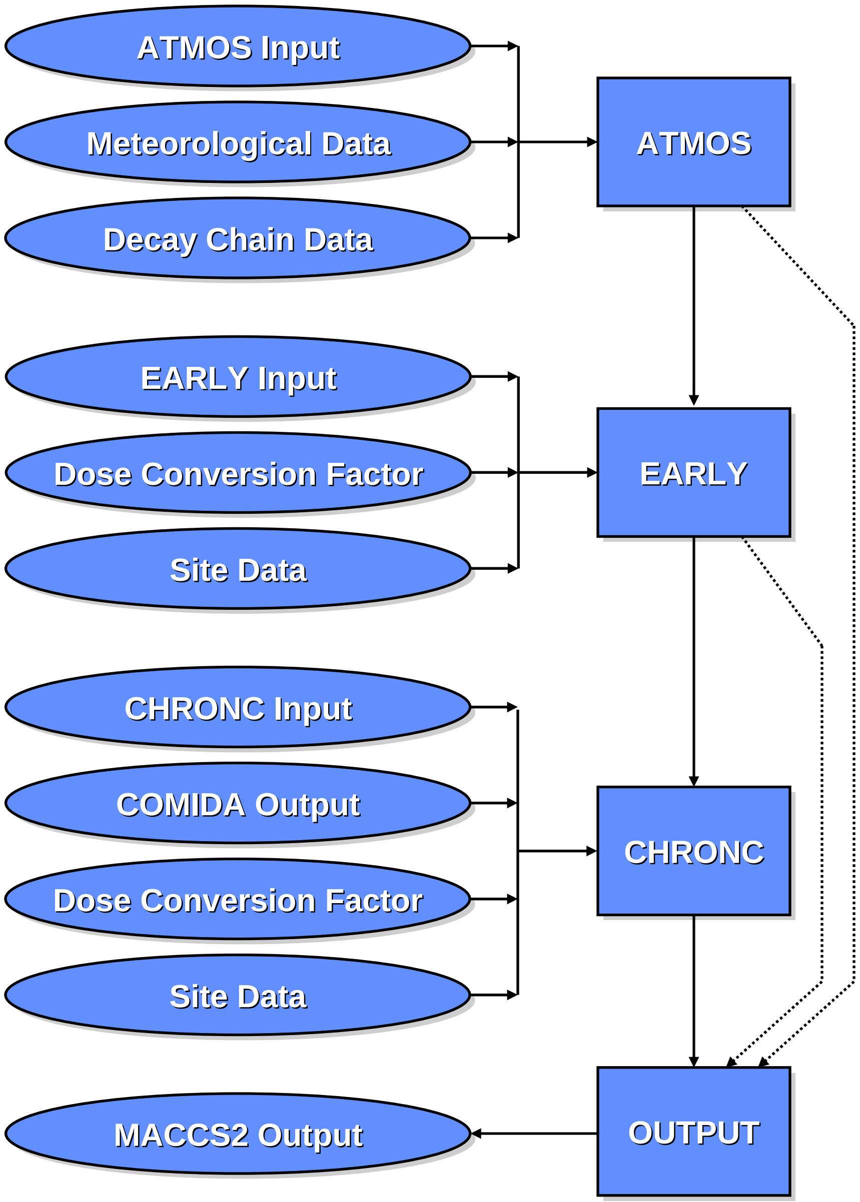
Any Result can be Outputted as a CCDF

- 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



MACCS2 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 MACCS2 (without user modification)



Summary

- **MACCS2 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**
  - **Full 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**

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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***
- **Become familiar with WinMACCS**

Complex Processes That Affect a Released Contaminant

- **Release mechanisms and characteristics**
- **Dilution and transport**
- **Reactions - chemical, nuclear (decay)**
- **Washout by cloud droplets and precipitation**
- **Deposition onto the underlying surface cover**

Algorithms Estimate Environmental Release Process

- **Emission of contaminants**
  - **Quantity**
  - **Rate**
  - **Height**
  - **Energy content**
- **Atmospheric transport and dispersion (ATD)**
- **Deposition**

DISPERSION

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

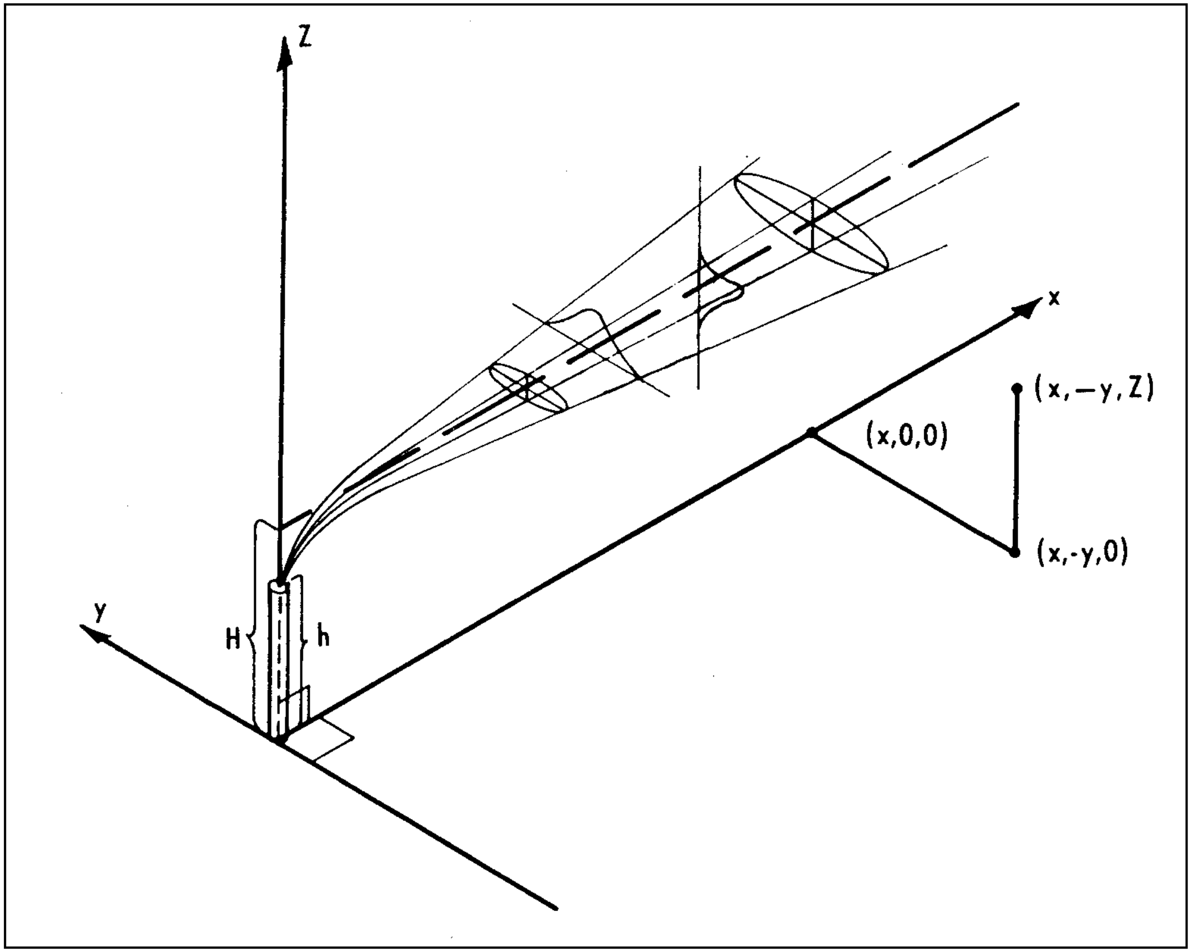
Straight-Line Gaussian Model (Standard Model)

- **Derived from Fickian diffusion equation**

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

- **Simple domain**
- **Good approximation out to first major terrain feature**

Coordinate System for Atmospheric Transport and Dispersion



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/m³)

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

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

z = Vertical distance from plume centerline (m)

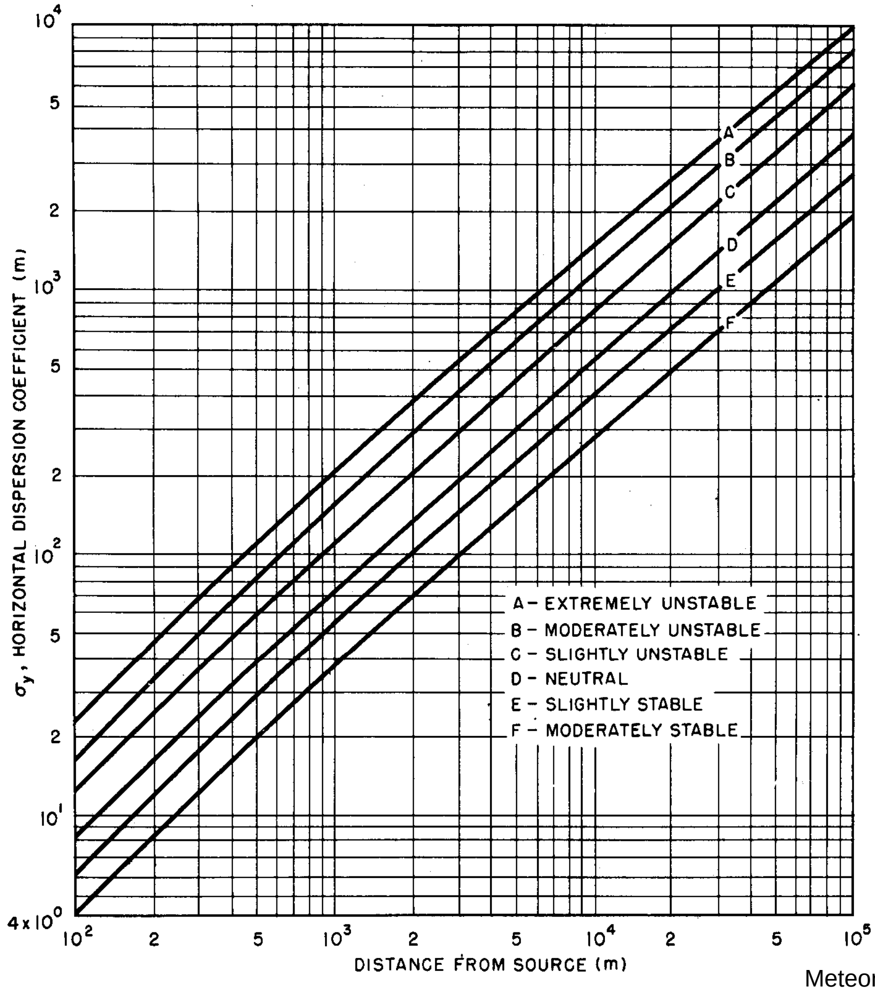
σ_y = Standard deviation of plume in the y direction as a function of x (m)

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

u = Average wind speed along plume centerline (@ height of release)

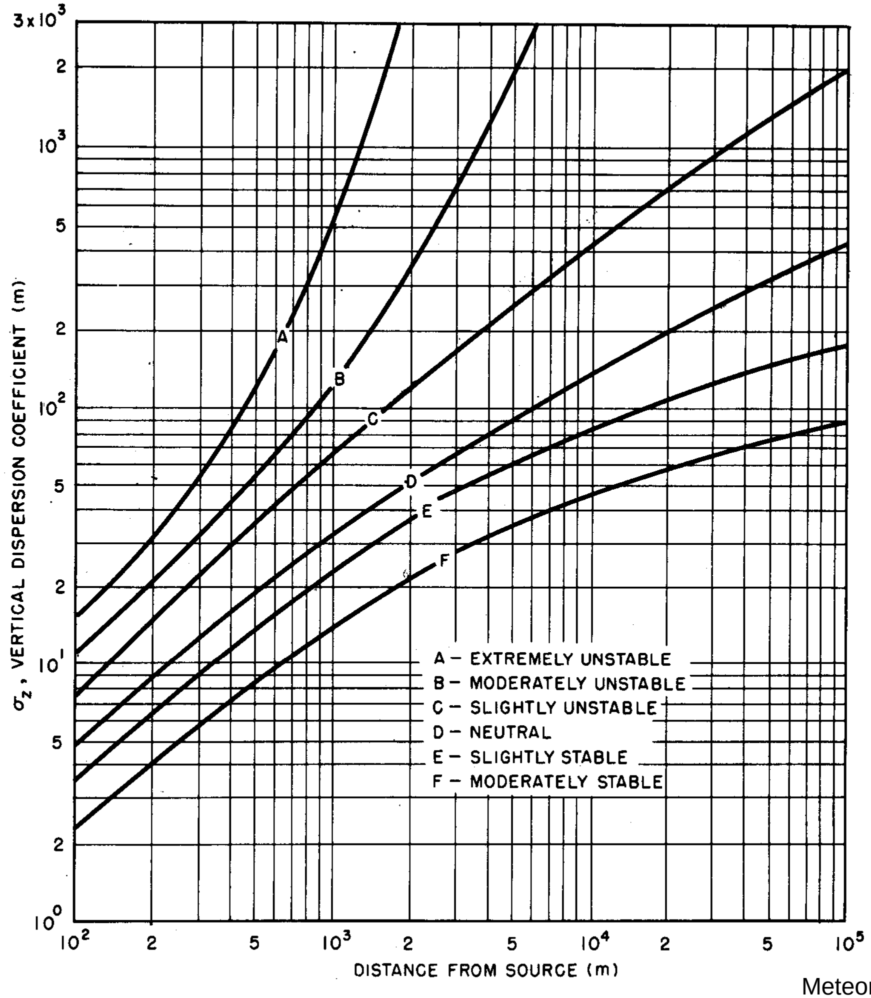
$$u\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} C\,dy\,dz = \dot{Q}$$

Lateral Dispersion, σ_y, vs. Downwind Distance From Source



Meteorology and Atomic Energy, 1968

Vertical Dispersion, σ_z, vs. Downwind Distance From Source



Meteorology and Atomic Energy, 1968

Power-Law Representation of Dispersion

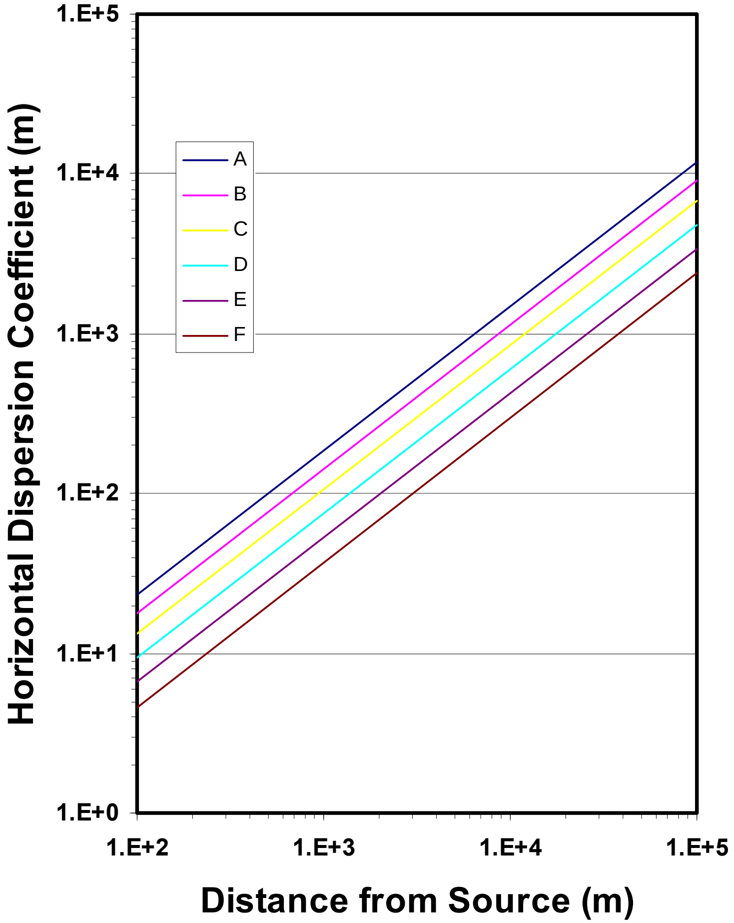
- **Power-law representation**

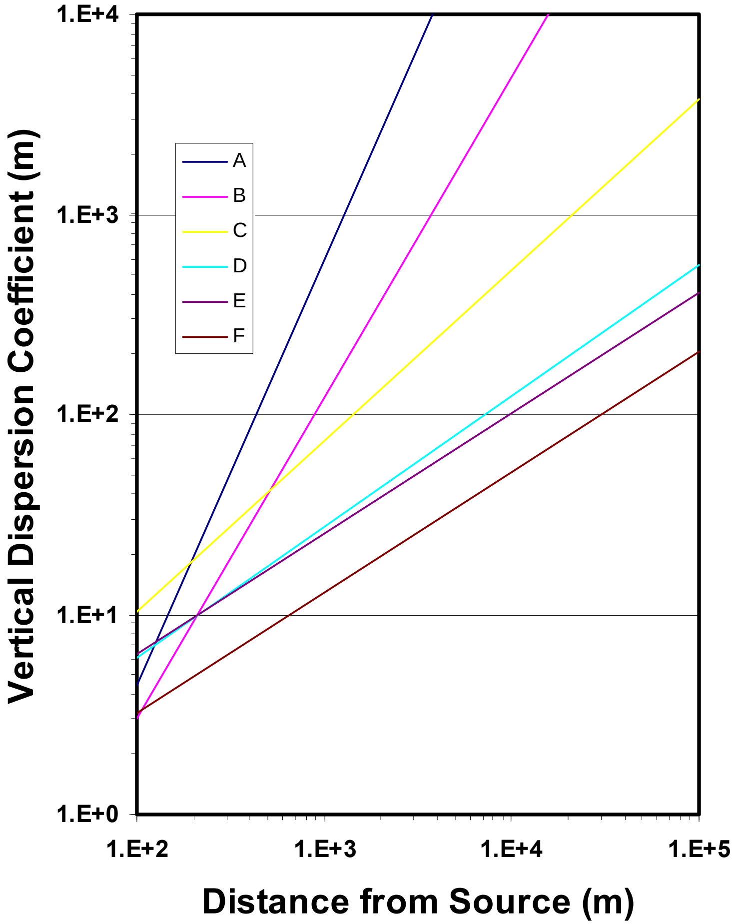
$$\sigma_y = a \cdot x^b \qquad \sigma_z = c \cdot x^d$$

- **Excellent representation for σ_y**
- **Good enough for σ_z at distances ≥ 1 km**

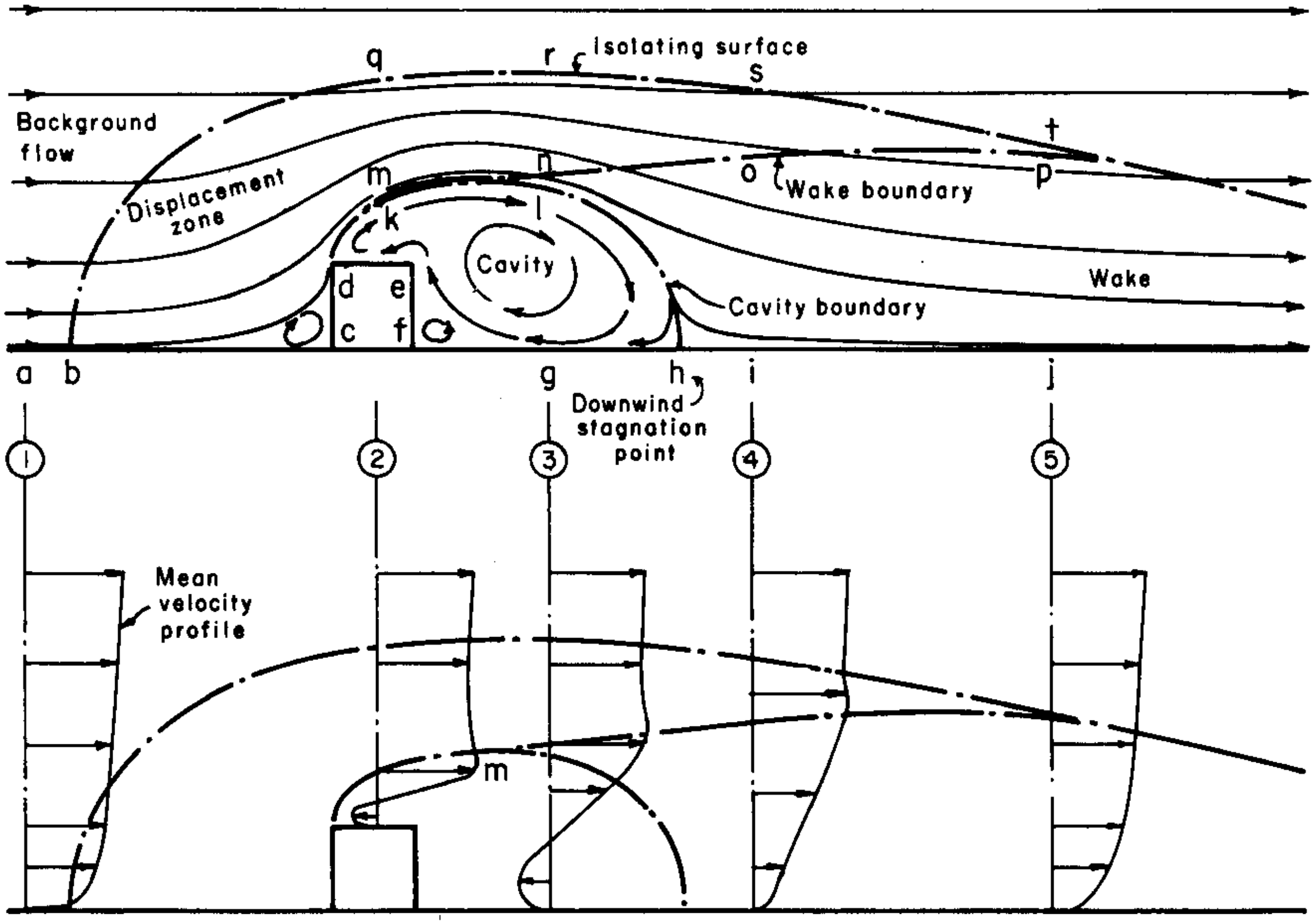
Stability Class	A	B	C	D	E	F
a	0.36580	0.2751	0.2089	0.1474	0.1046	0.0722
b	0.90310	0.9031	0.9031	0.9031	0.9031	0.9031
c	0.00025	0.0019	0.2000	0.3000	0.4000	0.2000
d	2.12500	1.6021	0.8543	0.6532	0.6021	0.6020

Plots of Power-Law Functions





General Arrangement of Flow Zones Near a Sharp-edged Building



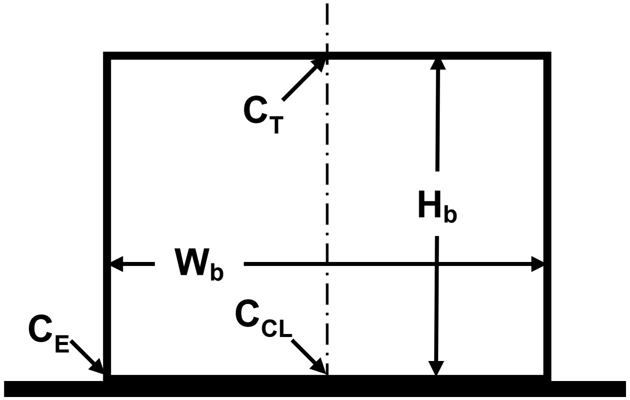
Meteorology and Atomic Energy, 1968

Building Wake - Area Source

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

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

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

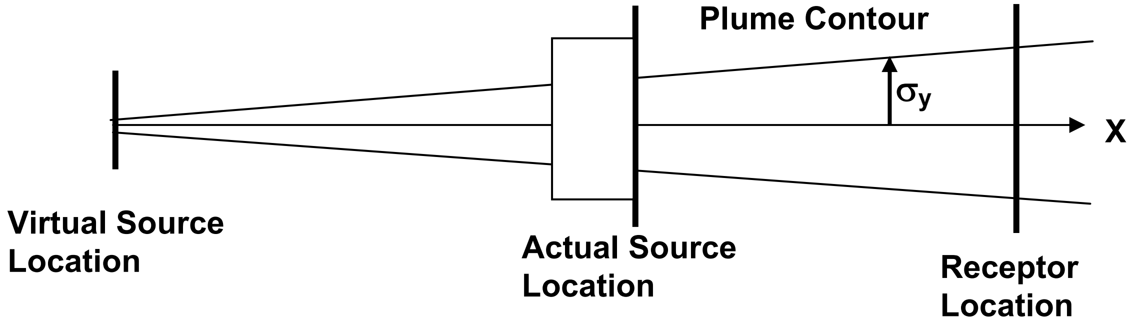


For f = 0.1, $\sigma_{y_0} = 0.23\ W_b$ and $\sigma_{z_0} = 0.47\ H_b$

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

Virtual Sources

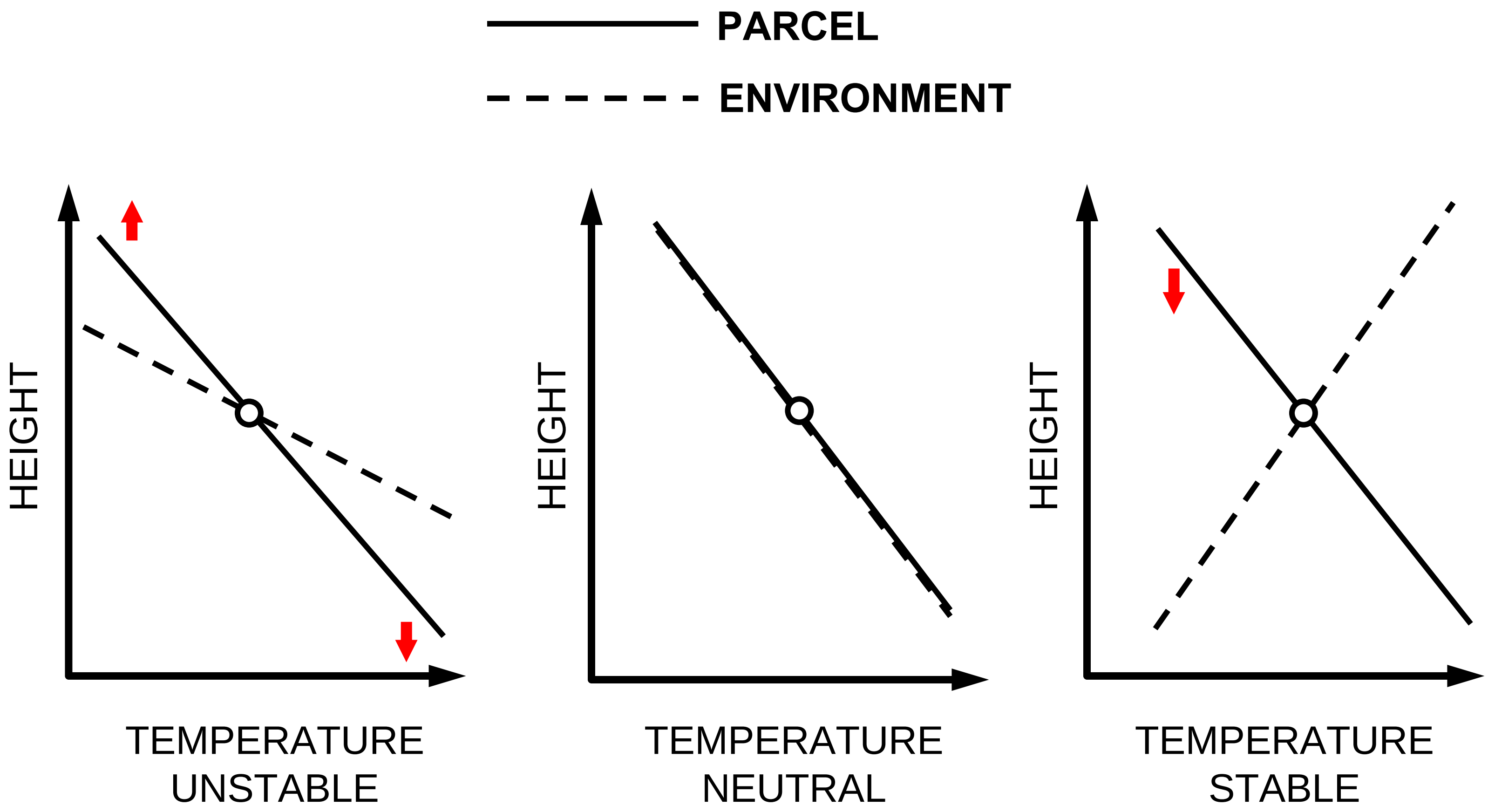
- Virtual source is the location of a "point" source that produces an equivalent plume
- Actual source location corresponds to a finite distance downwind from the virtual source
  - X_{y0} for crosswind dispersion
  - X_{z0} for vertical dispersion
- Receptor locations are relative to actual source location



Planetary Boundary Layer

- **Region of atmosphere between earth's surface and geostrophic flow**
- **Radioactive materials are released into this layer**
- **Ranges in height from 50 m – 5000 m**
- **Ground surface effects are important**
- **Wind speed tends to increase with height**
- **Wind direction tends to vary with height**
- **Stability of atmosphere within PBL determines turbulence intensity (dispersion effects)**

Illustrations of PBL Stability Conditions

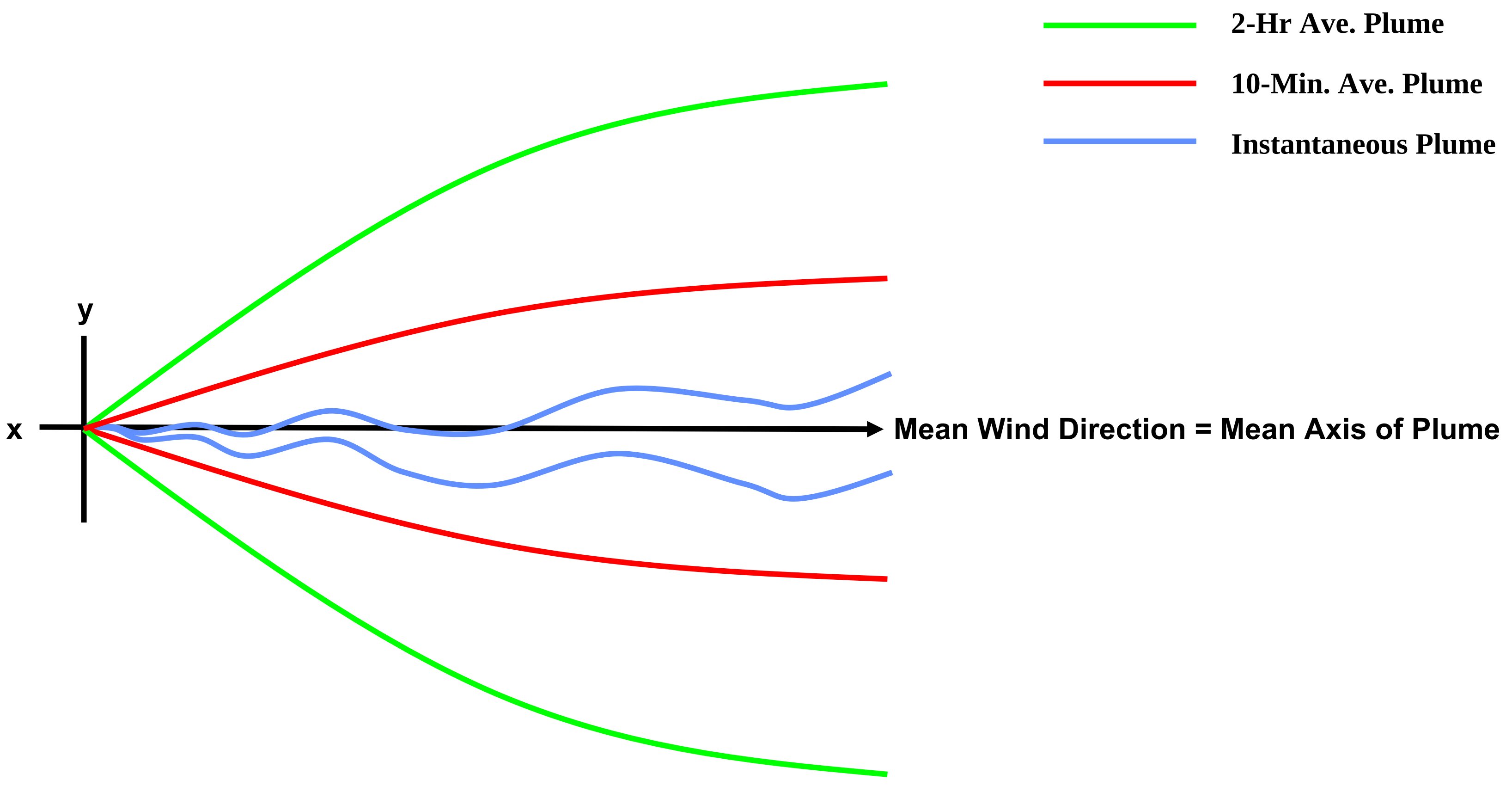


ORNL-DWG 83-10939

Atmospheric Stability Classifications by Vertical Temperature Difference

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*	$4.0 < \Delta T/\Delta z$

Effect of Diffusion 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)

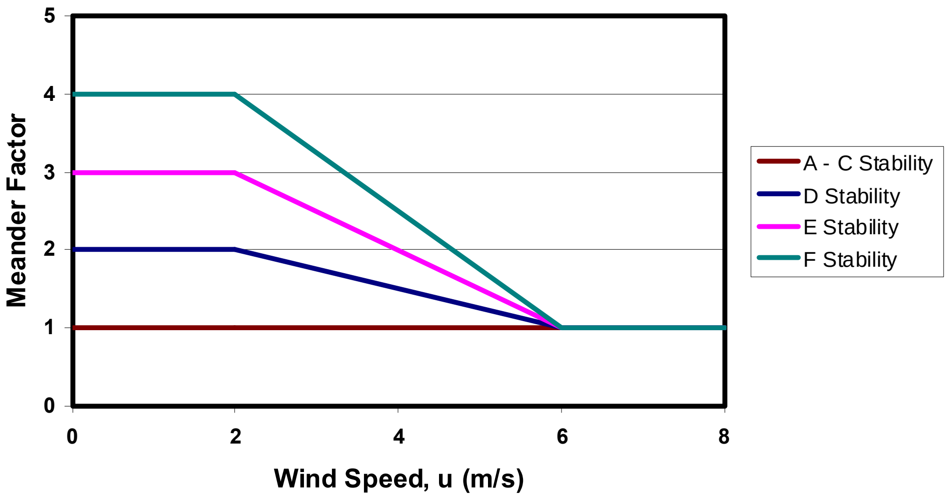
Δt_{ref} = 600, the experimental duration of the Prairie Grass tests (s)

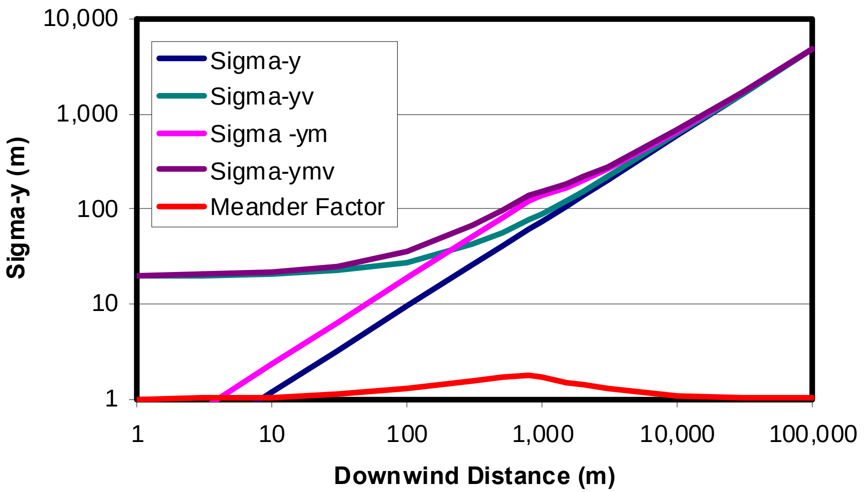
m = an empirical exponent

= 0.2 when $\Delta t < 1$ hr

= 0.25 when $\Delta t > 1$ hr

Regulatory Guide 1.145 Plume Meander Model



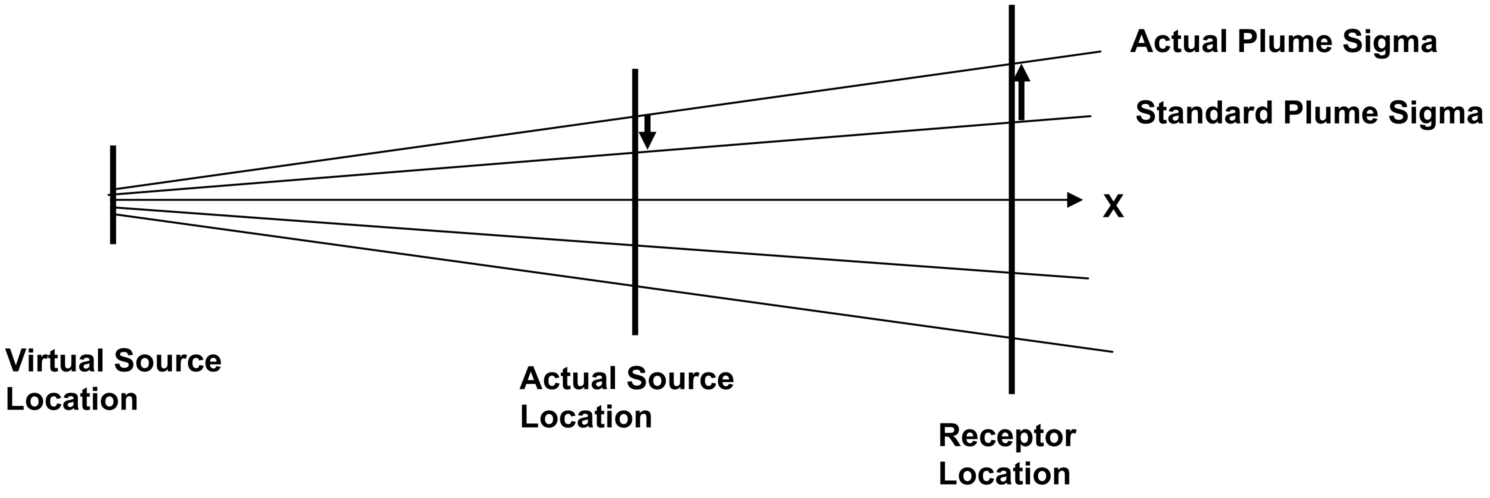


- Meander factor depends on stability class and wind speed
- Model is based on a 1-hr plume duration
- Effect of plume meander diminishes beyond 800 m from source
- Plot shows
  - Unscaled σ_y for a point source
  - Unscaled σ_y for a finite source, accounting for a virtual source location
  - Scaled σ_y for a point source
  - Scaled σ_y for a finite source
  - Ratio of scaled to unscaled σ_y for a finite source

Adjustments to Virtual Source Locations

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

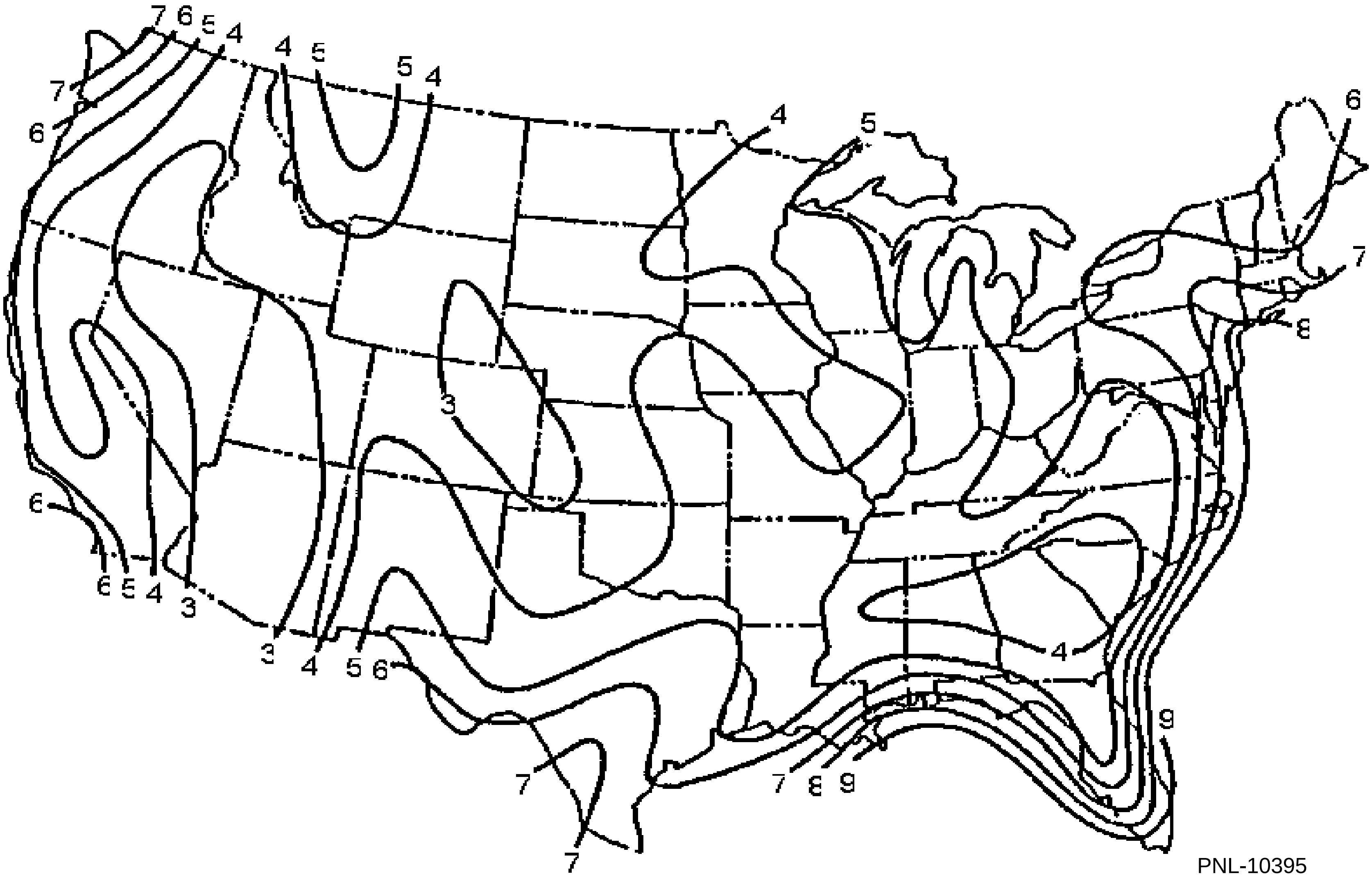
Actual plume is standard plume times the meander factor



Mixing Layer

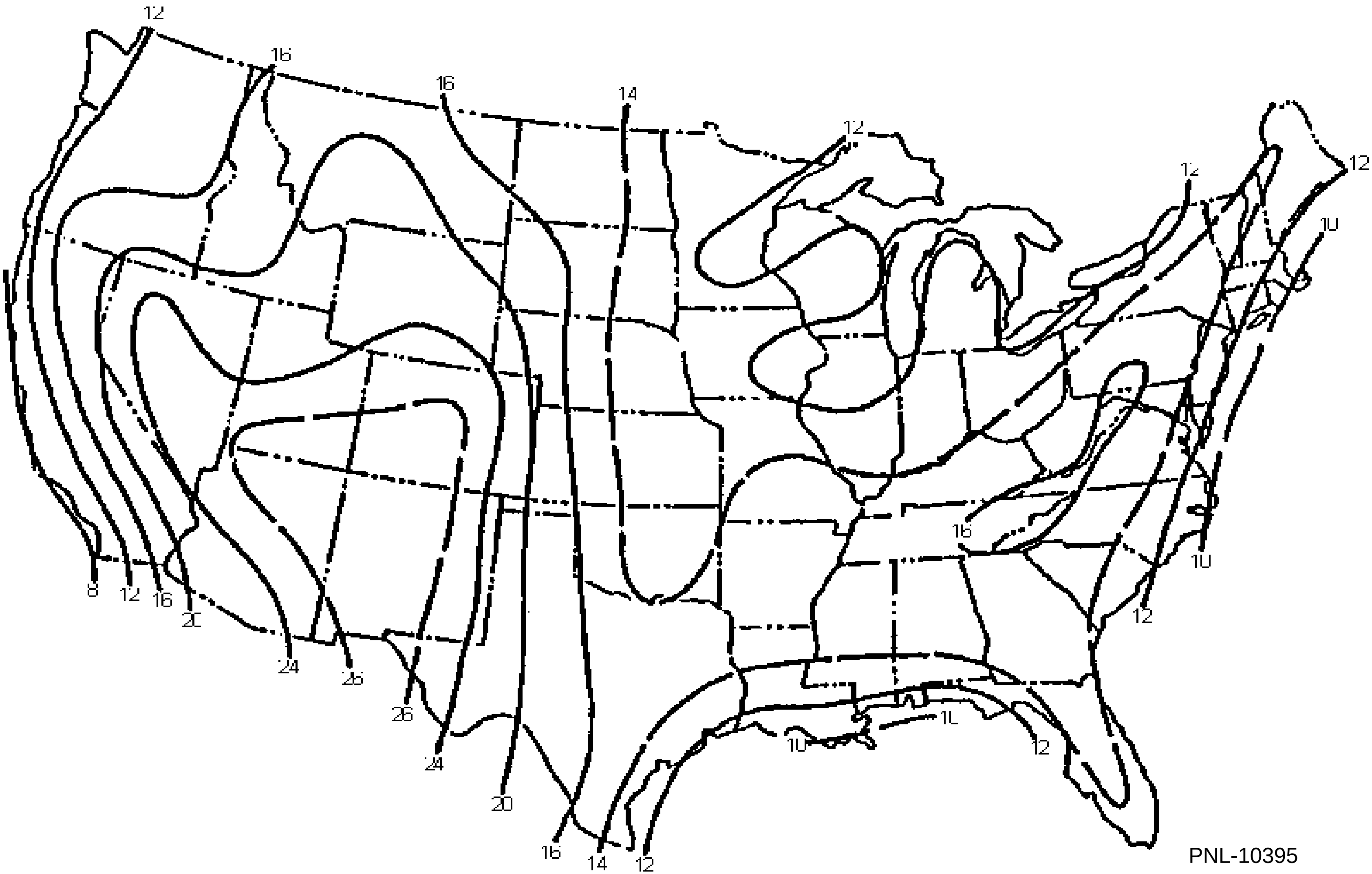
- Height is defined by a temperature inversion
- Varies continuously (hour to hour, day to day, season to season)
- Usually lowest at night and early morning
- Usually highest in afternoon
- Inhibits plume rise (here we assume that it is an absolute barrier)

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



PNL-10395

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

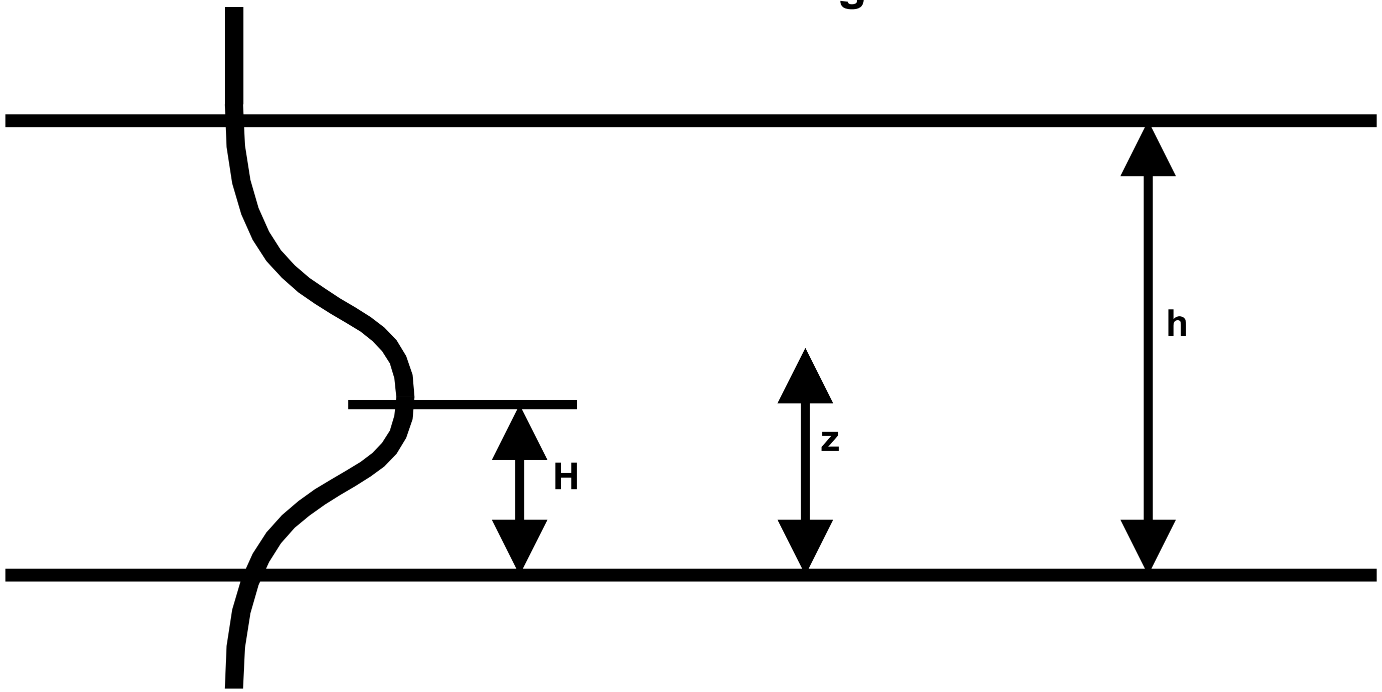


Vertical Boundaries
Ground and Mixing Layer

H = release height 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)**

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

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)**

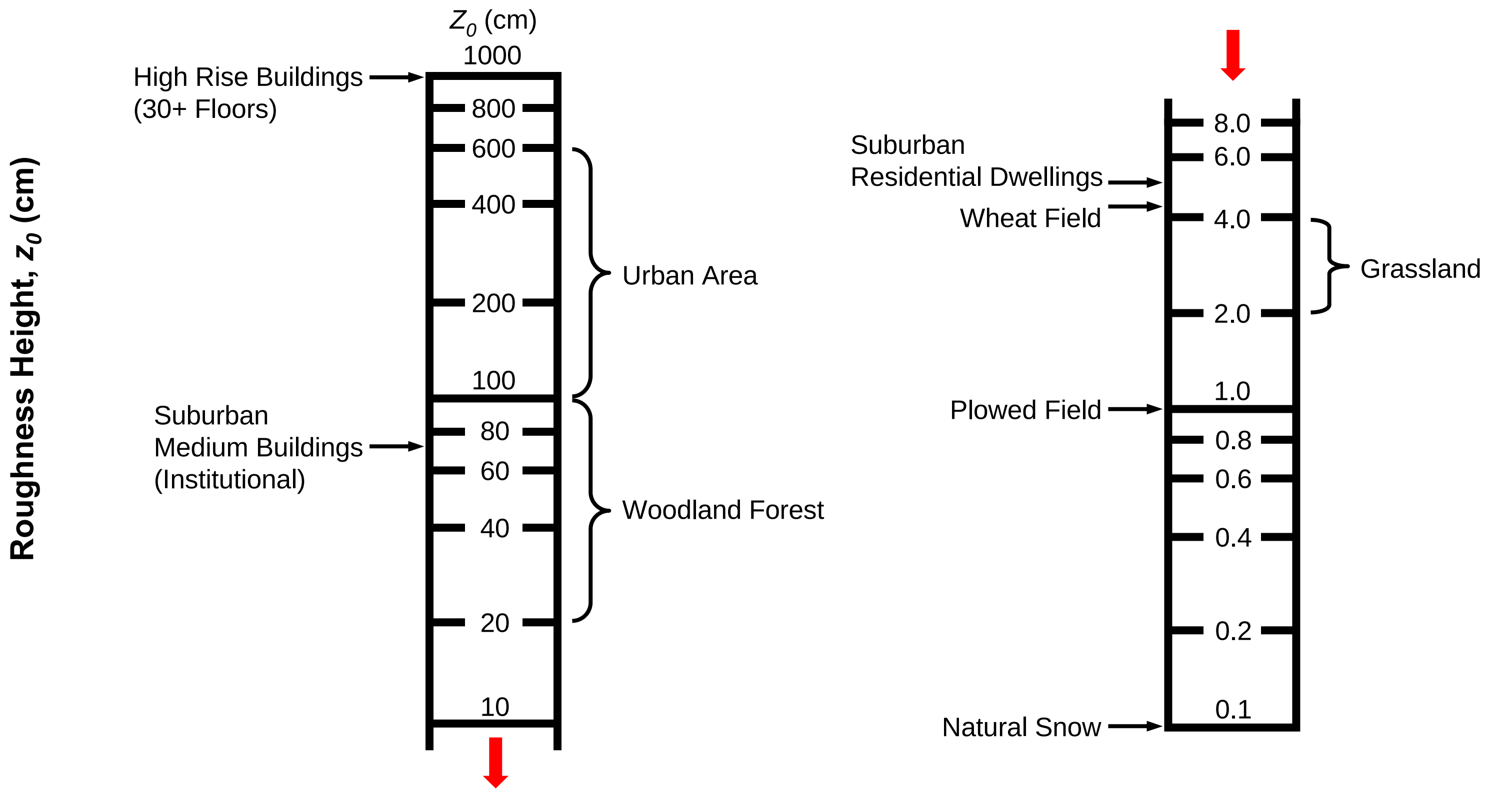
- **A trapped plume is**
  - **Released at the level of the initial release point**

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 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



DOE/RL/87-09

Workshop Example 1 (Characterizing a Release)

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 (cont.)

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

Roughness: $\sigma_{z,z_0} = \sigma_z \left(\frac{100}{3}\right)^{0.2} = 2\sigma_z$

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 (cont.)

Receptor Distance (m)	σ_y (m)	σ_z (m)
	$8.6/1.25 = 6.9 \Rightarrow X_{y_0} = 180$	$28/2 = 14 \Rightarrow X_{z_0} = 1100$
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

Reflections:

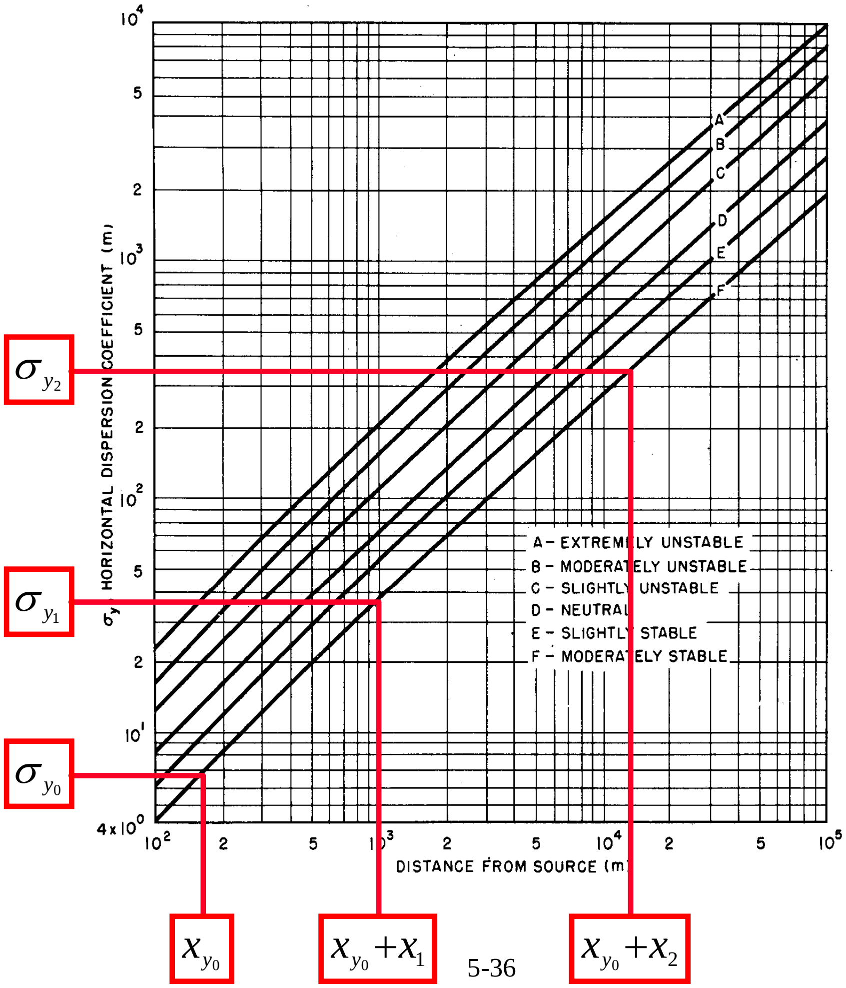
$$\sum_{n=-\infty}^{\infty} 2e^{\left[-2\left(\frac{n1500}{\sigma_z}\right)^2\right]}$$

Z=0
H=0

σ_z \ n	0	-1	+1
42	2	0	0
106	2	0	0

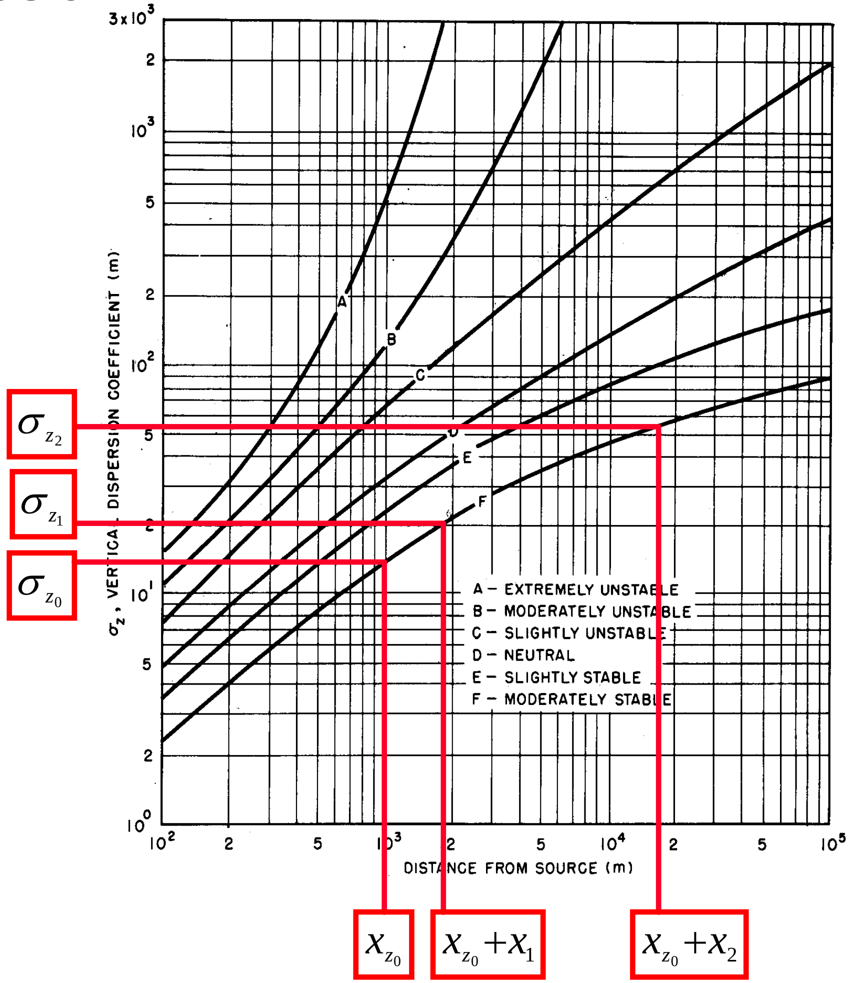
WORKSHOP EXAMPLE 1 (cont.)

Lateral Diffusion, σ_y, vs. Downwind Distance From Source for Pasquill's Stability Classes



WORKSHOP EXAMPLE 1 (cont.)

Vertical Diffusion, σ_z, vs. Downwind Distance From Source for



WORKSHOP EXAMPLE 1 (cont.)

1/2 mile

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

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

8 miles

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

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

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

dist	σ_y σ_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 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 which 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.

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

Deposition Processes

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

Dry Deposition

- **Continuous and slow**

$$D = C V_d \Delta t$$

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

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

V_d = deposition velocity (m/s)

Δt = plume duration (s)

- **Approximate formula for deposition losses**

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

Where Q is the material suspended in the plume (Bq) and Σ represents the summation term in the expression for σ_z

MEPAS - Case Examples of Average Deposition Velocities (cm/s)

Pollutant Type	Surface Roughness Type					
	Water	**Bareland**	**Lowgrass**	**Wheat**	**Residential**	**Trees**
Particles, Large	0.875	1.812	2.550	3.344	4.857	9.125
Particles, Middle	0.184	0.667	1.061	1.548	2.399	5.338
Particles, Small	0.005	0.040	0.057	0.073	0.113	0.231
Gas, Reactive	0.324	0.622	0.719	0.776	0.843	0.910
Gas, Nondepositing	0.000	0.000	0.000	0.000	0.000	0.000
Gas as a Particle	0.005	0.040	0.057	0.073	0.113	0.231
Gas Maximum Rate	0.478	1.649	2.559	3.461	5.386	10.151

Pacific Northwest Laboratory

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 Man

- **Internal**
  - **Direct inhalation**
  - **Ingestion**
  - **Resuspension inhalation**
- **External**
  - **Cloudshine**
  - **Groundshine**

Internal Pathways

- **Inhalation**
  - **Breathing rate (20m^3/day - 30m^3/day, 23m^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**
    - **Irrigation**
  - **Aquatic Food**
  - **Crops**
    - **Deposition onto leaves (leafy vegetables)**
    - **Root uptake (other vegetables)**
  - **Animal products**
    - **Meat**
    - **Milk**

Workshop Exercise 3 - Internal Exposure (Inhalation & Drinking)

- **Continuing the workshop example, what is the dose to an individual located on the mall who is present at the time the plume is passing?**

Ingestion (Aquatic Food)

- **Usage factor (consumption rate)**
  - **0.0065 kg/d finfish**
  - **0.0027 kg/d shellfish**
- **Concentration of water, Bq/l**
- **Bioaccumulation factor, l/kg**
- **Decay (harvest to consumption)**

Ingestion (cont.)

- **Crop ingestion**
  - **Direct deposition onto plants**
  - **Deposition of irrigation water onto plants**
  - **Root uptake**
- **Animal products (milk and meat)**
  - **Feed consumption by animal**
  - **Water consumption by animal**

Resuspension Inhalation

- **Contaminated soil resuspends in atmosphere from wind (function of particle size, surface roughness, vegetative cover, wind speed)**
- **Mechanical (vehicles, walking)**
- **Inhalation**
- **Resuspension coefficient, k (m^{-1})**

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

- **Weathering (removal by overland runoff, leaching, covering)**

Emergency Phase

C_1 (m^{-1})	H_1 (yr)
10^{-4}	0.05

Long-Term Phase

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

- **Radioactive decay**

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?**

Cloudshine

- **Betas (short path length) and gammas**
- **Point source**

$$D'\left(\frac{\text{rad}}{\sec}\right)=\frac{.04\mu_a Q\overline{E}\left(1+K\mu r\right)e^{(-\mu r)}}{r^2}$$

μ_a = **gamma attenuation coefficient (absorbed by electrons), m^{-1}**

Q = **source strength, Ci**

$\overline{E}$ = **average gamma energy emitted at each disintegration, MEV/dis**

$1+K\mu r$ = **buildup factor**

μ = **total gamma attenuation coefficient (absorbed by electrons + scattered in photons), m^{-1}**

r = **distance to source**

Cloudshine (cont.)

- **Infinite cloud**
  - **Totally immersed in large cloud**
  - **$D' = .51\,\overline{E}\,\chi$ (.25 $\overline{E}\,\chi$ at ground)**
  - **χ = Ci/m^3 of cloud**
  - **$D = \int D'\,dt$**
  - **DCF compiled**

    (^{134}Cs: DCF=8010 mrem/yr per μCi/m^3, EDE)

- **Finite cloud**
  - **Integrate point solution over space or finite cloud dose correction factors**

Finite Cloud Dose Correction Factors

Diffusion Parameter $\sqrt{\sigma_y \sigma_z}$ (m)	Distance to Cloud Centerline Parameter $\sqrt{y^2+z^2}/\sqrt{\sigma_y \sigma_z}$ (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.

MACCS

Groundshine

- **Buildup on ground as plume is passing (deposition)**
- **Decay**
- **Weathering**
- **Dose conversion factors (^{134}Cs: 158 mrem/yr per μCi/m^2, EDE)**

6. Health Effects and Economic Consequences

Outline

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

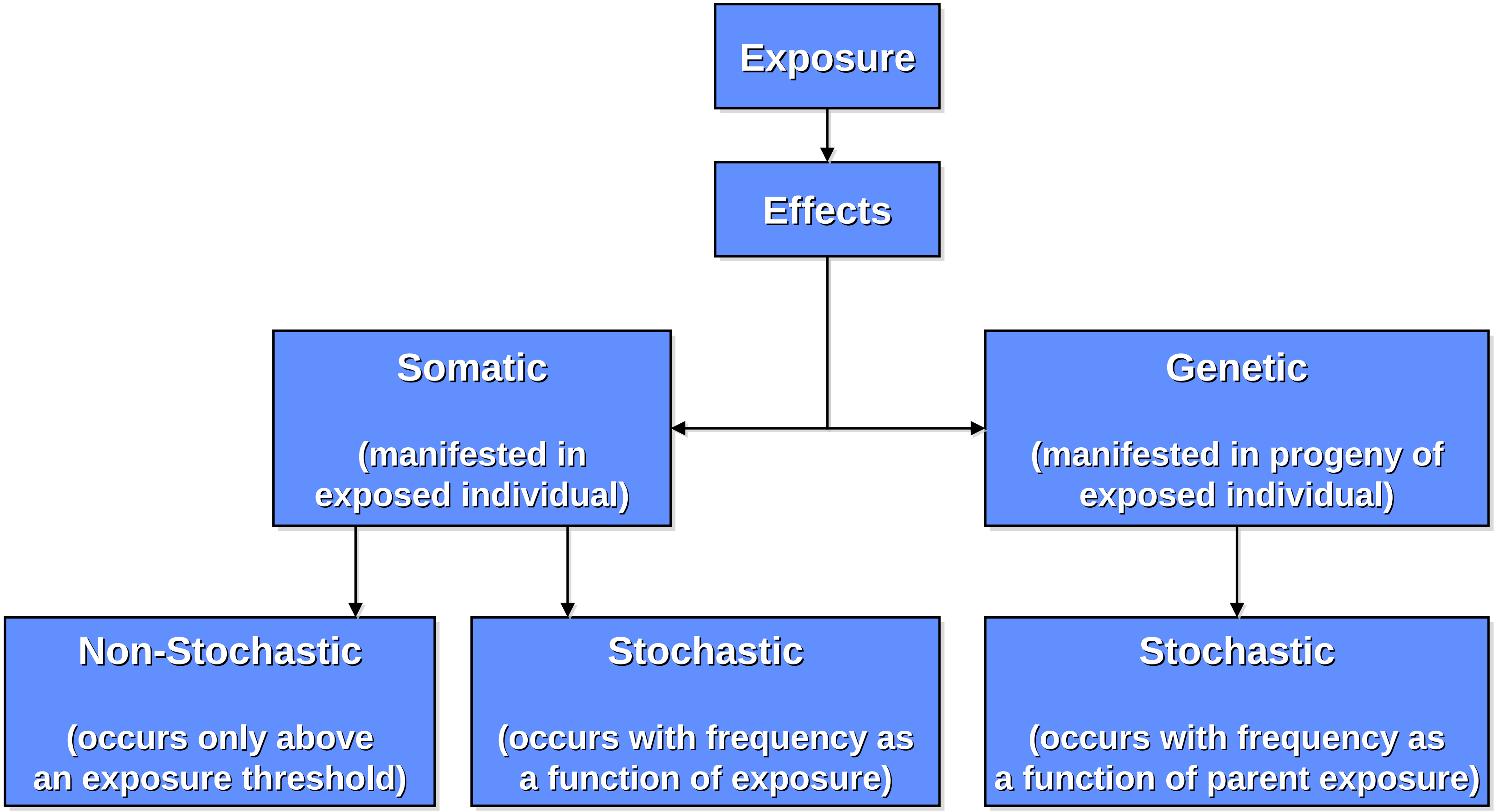
Objectives

- **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 MACCS2**
- **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



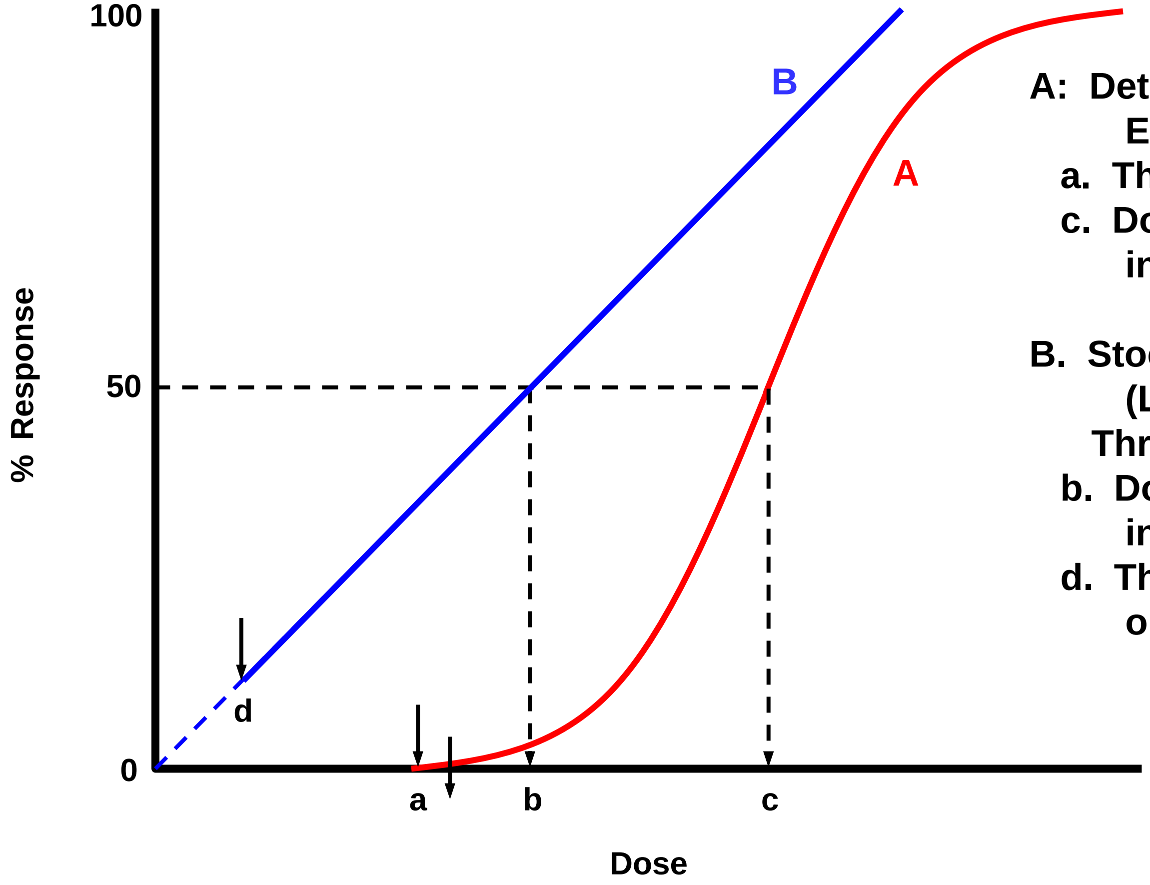
Dose-Response Curves

Graphical depiction of 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,**
- **Quality Factor of Radiation**
- **Dose Rate**
- **Sex**
- **Age At Exposure**
- **Other**

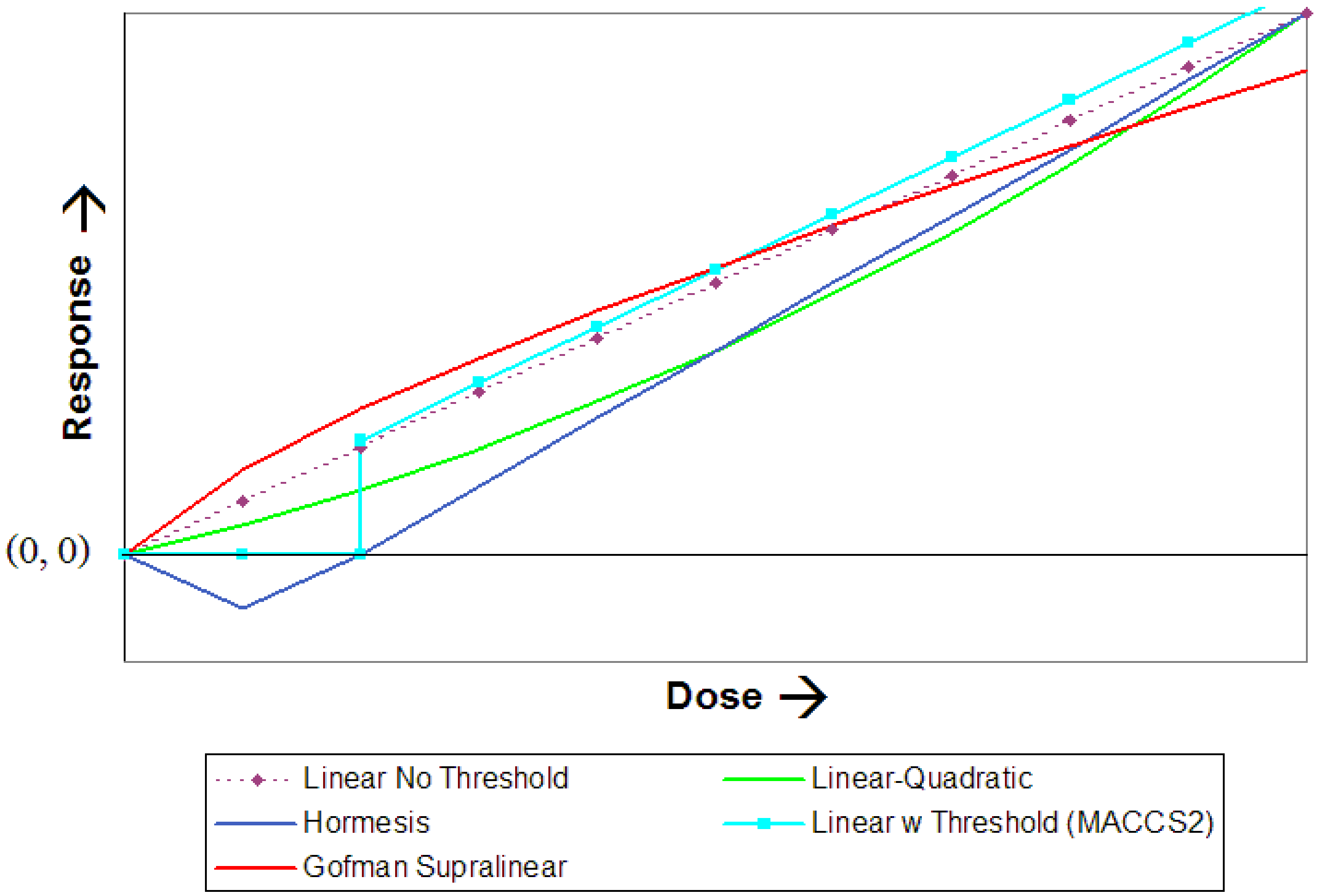
Dose-Response Curves



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



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 MACCS2 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)	Frequency (%)	Whole Body Absorbed Dose (rad)	Frequency (%)
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

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 cancer rate background in the general population → Lack of statistical power in low dose region**
    2. **Missing or inadequate radiation dosimetry and bioassay data & primitive analytical methods during 1940s – 1970s → Inadequate historical data**

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 Systems

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 61, 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 Systems (continued)

Date	Publication	Remarks
1991	ICRP-60	Revision of the system of dose limitation, tissue-weighting scheme introduced by ICRP-26. DOE is proposing to modify 10 CFR 820 & 835 to adopt; see FR 71, No 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 is proposing to modify 10 CFR 820 & 835 to adopt ICRP 68; see FR 71, No 154, p. 45996.

Dosimetry Systems (continued)

Date	Publication	Remarks
1999	Federal Guidance Report 13	Updates to ICRP 72 by ORNL with changes approved by US EPA
In press (2008?)	ICRP xxx	Replacement models for ICRP-60 and ICRP 68 et seq.

Dose Factor Files in MACCS2

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 MACCS2

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 MACCS2

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
- 1 μm particle size, but data are available for other sizes
- Acute, annual, and 50-yr DCFs

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	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.

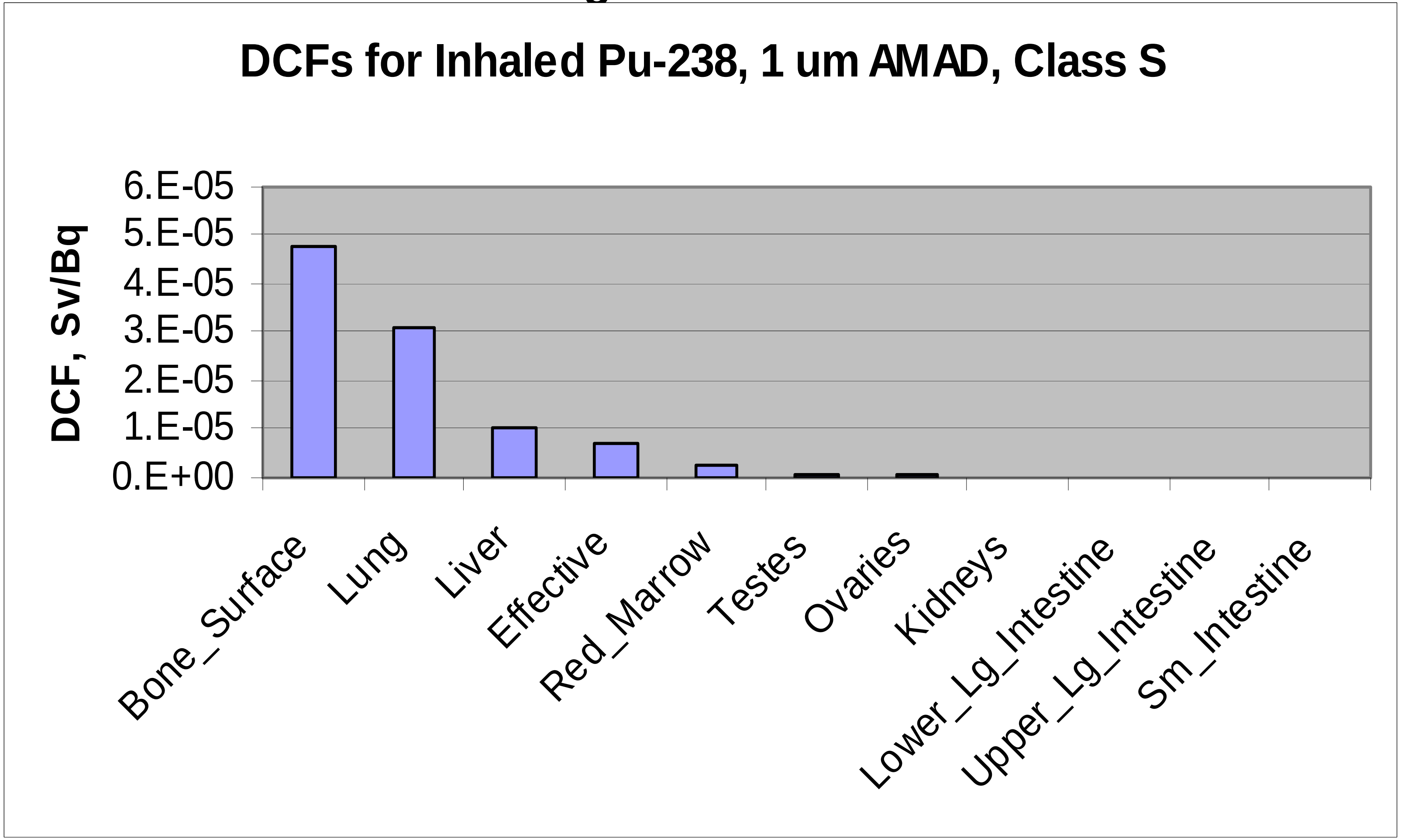
- **Equivalent dose to a tissue needed to determine stochastic health effects**
- **Radiation weighting factor, $W_{R,}$ from ICRP 60:**

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

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

Non-Uniform Irradiation

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



Non-uniform Irradiation

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

$$H_E = \Sigma H_T * W_T$$

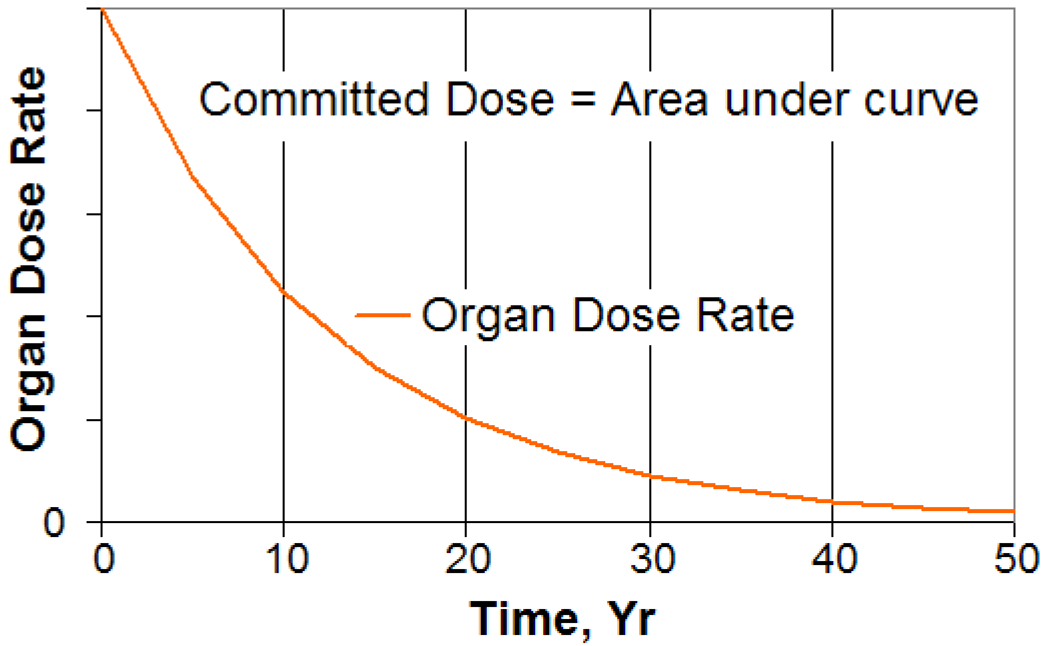
- **ICRP 60: Effective Dose** (E)

$$E = \Sigma H_T * W_T$$

- **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**

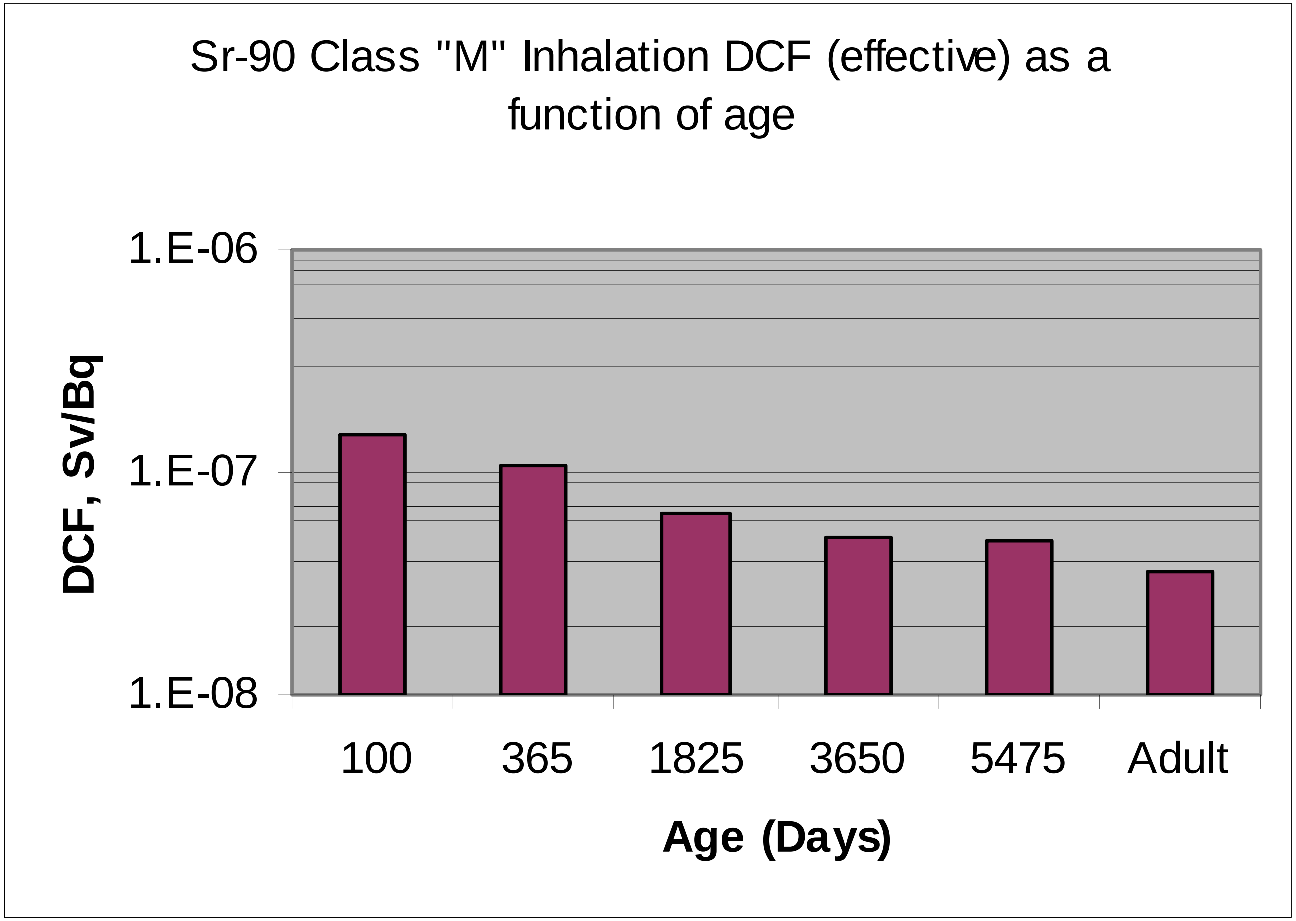
Doses from Inhalation and Ingestion

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



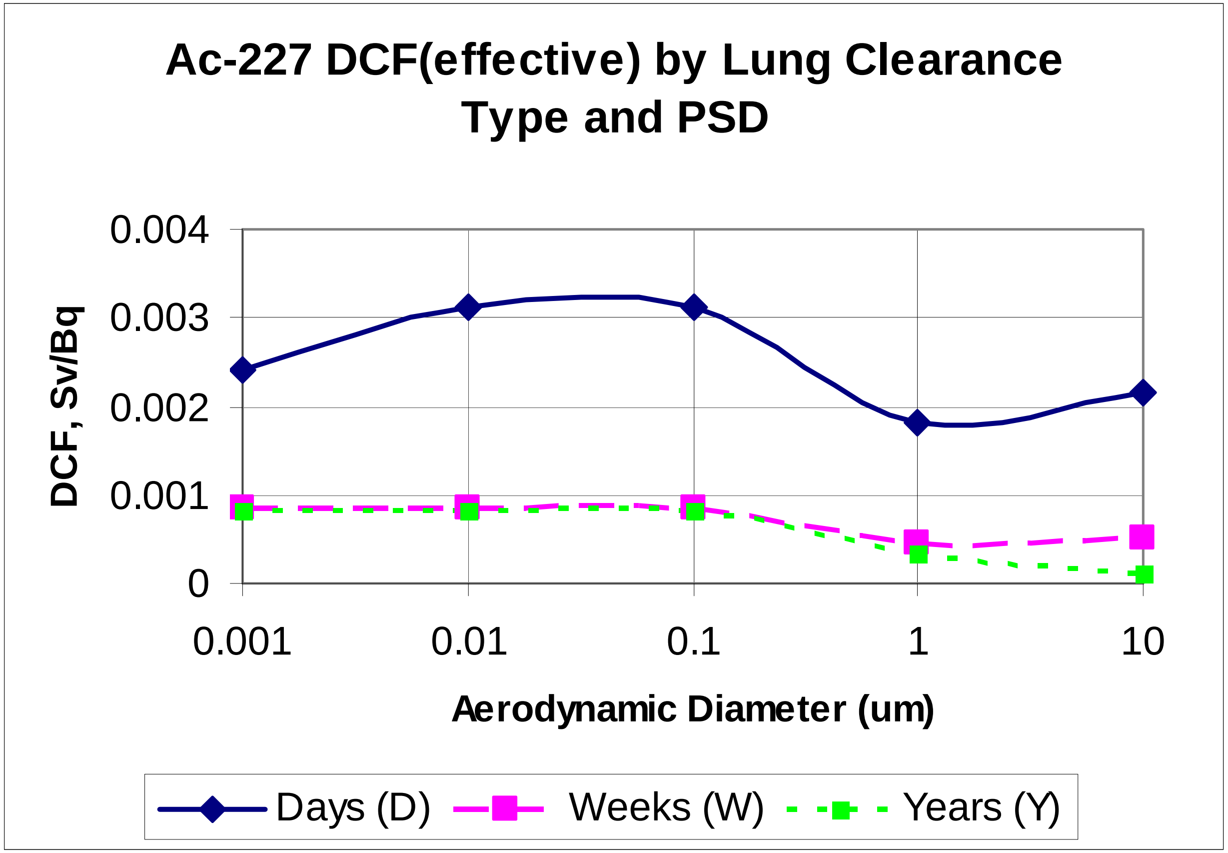
Doses from Inhalation and Ingestion

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



Doses from Inhalation

- **Effect of particle-size distribution and lung clearance class**



Doses from Inhalation and Ingestion

- **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)**

Doses from Inhalation and Ingestion

Acute Organ Dose Coefficients

- ***ICRP database*** **(ICRP 1998). Q=20 for high LET. Not recommended for acute health calculations. Workers and several age groups. ICRP-68, ICRP-72.**
- ***DOSFAC2.*** **Limited to workers, 60 isotopes, ICRP-30 based. Used by MACCS2. Uses high LET Q=10 for acute coefficients.**
- **MACCS2 dose factors based on Federal Guidance Report 13, Adults only. Uses high LET Q=10 for acute coefficients.**
- **Federal Guidance Report 13, Several ages. Unweighted absorbed dose rates. Calculated using ORNL's DCAL software package.**

Tissue Weighting Factors

	Tissue weighting factor (w_T)	
Organ or tissue	ICRP Pub. 26	ICRP Pub. 60
Gonads	0.25	0.20
Bone marrow (red)	0.12	0.12
Colon	--	0.12
Lung	0.12	0.12
Stomach	--	0.12
Bladder	--	0.05
Breast	0.15	0.05
Liver	--	0.05
Esophagus	--	0.05
Thyroid	0.03	0.05
Skin	--	0.01
Bone surface	0.03	0.01
Remainder	0.30[a]	0.05[b,c]

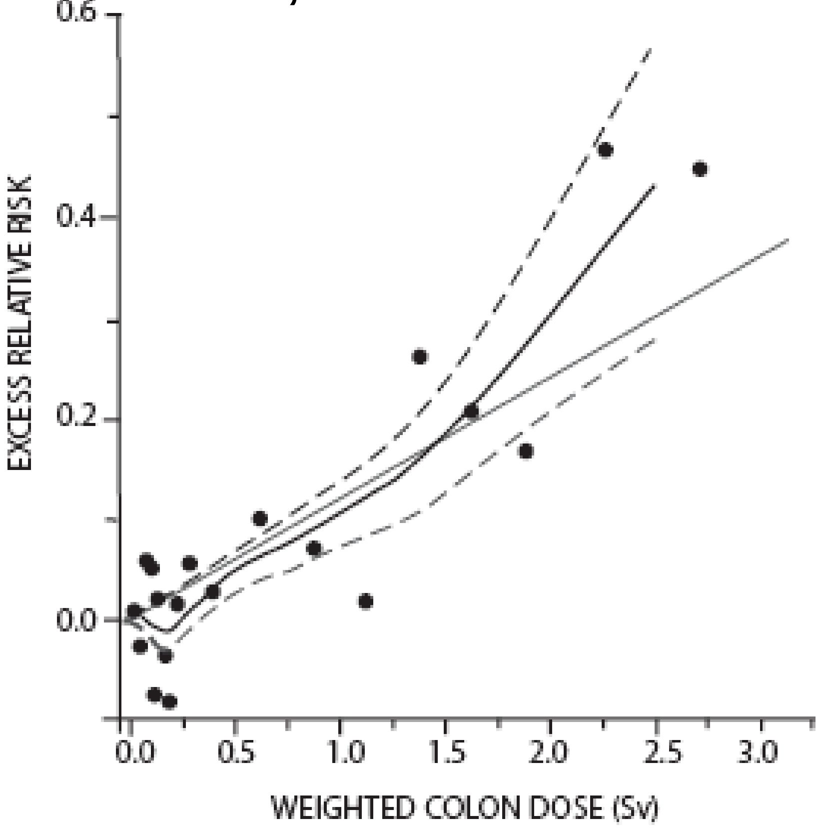
Radiation Epidemiology

- **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 including 1988, 2000, 2006.**

Health Effects

- **Development of Cancers**
- **Somatic effects: irradiation of Embryo or Fetus (ICRP-49, ICRP-90)**
  - **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*)**

Excess risk of mortality in atomic bomb survivors from non-cancer disease in LSS cohort, 1968-97 .



Health Effects

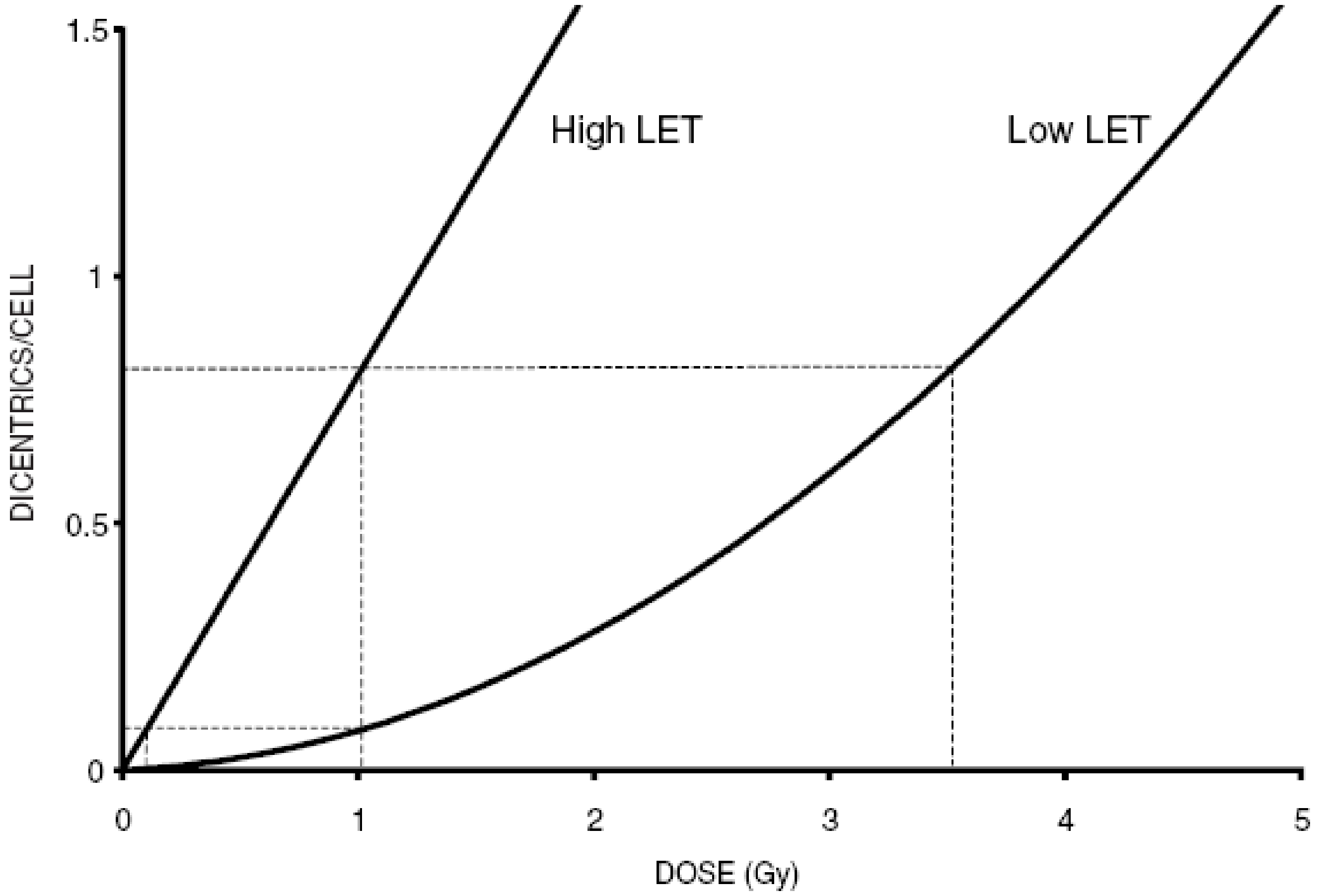
- **Early Acute Effects:** ***hematopoietic, gastro-intestinal, pulmonary, early transient incapacitation***
- **Genetic Effects**
  - **Chromosome abnormalities: rings, di-centrics, and translocations.**
  - **Heritable: mutation doubling dose ~ 1Gy (100 rad) per BEIR VII, trisomies, spontaneous abortion,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

Health Effects

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

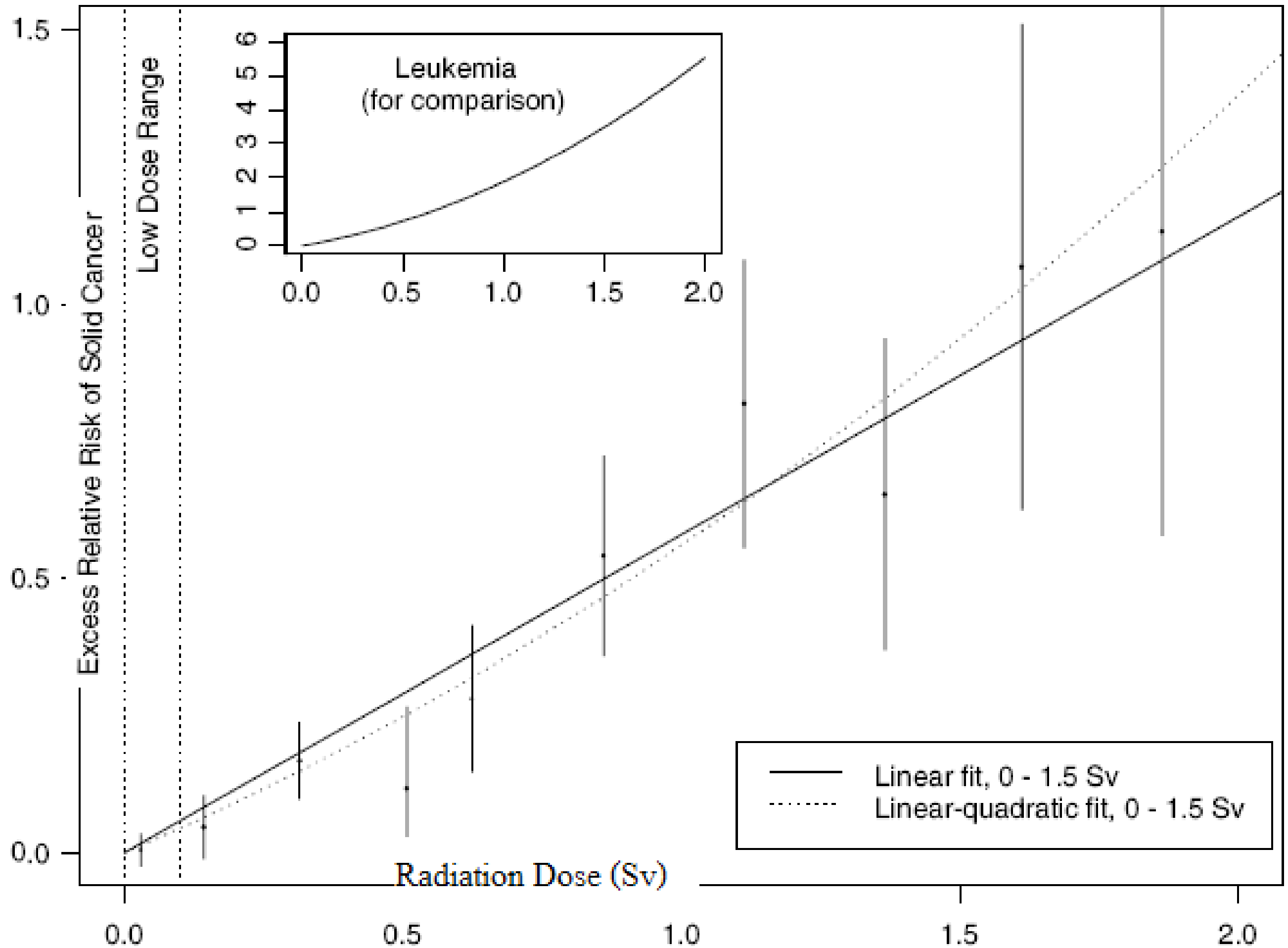
IAEA Report 405.

Health Effects



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



Carcinogenic Effects

- BEIR VII uncertainty estimate: +100%/-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 Dose and Dose Rate Effectiveness Factor by a factor of 2 (BEIR V) or 1.5 (BEIR VII).

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) excluding DDREF	Average Mortality (per Gy) excluding DDREF
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.

Exercise

- **Open WinMACCS Projects/SOARCA/SurryR7/SurryISLOCA…**
- **Go to "Latent Cancer Parameters" under "Early" and:**
  - **Update the zero values in the Cancer Incidence Risk (CIRISK) column with BEIR VII values (previous slide) for Leukemia, Lung, and Other.**
  - **Update the CIRISK value for GI based on the ICRP60 assumption that**

$$\frac{CFRISK_{GI}}{CIRISK_{GI}} = 0.55$$

  - **Update the DDREFA values for Leukemia, Lung, GI and Other to the BEIR VII assumption that DDREFA=1.5.**
  - **Under Early>Output Control>Health Effect Cases, add "CAN INJ/LEUKEMIA, "CAN INJ/LUNG","CAN INJ/OTHER" and "CAN INJ/GI.**
- **What is the maximum value of "peak dose on spatial grid" for cohort 1?**
- **Answer: 742 Sv. Since above ~0.4 Sv, some of the BEIR VII risk coefficients (Leukemia) shouldn't have been treated as linear.**

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:** $R = \propto D + \beta D^2$
  - ***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**

General Risk Findings (Continued)

- **Piecewise Linear Model:**
  - **BEIR V**
  - **BEIR VII- most solid cancers**
  - **Stochastic Risk $\propto$ D For Dose $>$ 20 rad or Dose Rate $>$ 10 rad/hr**
  - **At low dose rates: R $\propto$ D/DDREF**
- **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.**

MACCS2 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				

MACCS2 Early Health Effects Model

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

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

$$x_T = \textit{normalized dose to organ "T" for a particular effect} = \left[\sum_t D_t / D_{50,t} \right]$$

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

MACCS2 Early Health Effects Model

Early Health Effect and Dose Threshold (Sv)	LD_{50} or D_{50} (Sv) Time Period End Point (days)							
	1	**7**	**10**	**14**	**21**	**30**	**200**	**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	-	-	-

MACCS2 Early Health Effects Model

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

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

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

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

- **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 (Sv)
	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:**

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

$$\beta_{PV} = 3$$

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

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

Solution to Health Effects Sample Problem Continued

- **Probability of Diarrhea:**

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

$$\beta_D = 2.5$$

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

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

Solution to Health Effects Sample Problem Continued

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

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

$$H_D \text{ was } 0.693$$

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

Overview of Economic Consequences

- **Economic models estimate direct offsite costs resulting from a reactor accident**
  - **Costs arising from emergency response actions**
  - **Costs from intermediate- and long-term protective actions**
- **Costs not included**
  - **Some categories of business and personal income**
  - **Reactor and onsite damage**
  - **Replacement power**
  - **Medical**
  - **Life-shortening**
  - **Litigation costs**

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 condemnation of property

General Cost Formulas

- **Evacuation, Relocation Cost General Formula**

$$C_{epa} = n_i \times \Delta t \times C_d$$

where

$C_{epa} =$ Cost of early protective action

$n_i =$ number of individuals involved

$\Delta t =$ Duration of action (days)

$C_d =$ Daily cost ($/person-day)

General Cost Formulas (cont.)

- **Cost of Long Term Protective Action**

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

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} = Farmland area

Non-Farm Cost Formula

- **Non-farm costs**

$$C_p = \mathrm{C_d} + C_r + C_c$$

where

$$C_p = \text{Cost of long-term protective action}$$

$$C_d = \text{Cost per person for decontamination}$$

$$C_r = \text{Cost per person for relocation}$$

$$C_c = \text{Cost per person for loss of property usage}$$

Loss of Property 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

V_w = per person value of nonfarm wealth, including land, buildings, infrastructure, and non-recoverable equipment and machinery

F_{im} = fraction of wealth resulting from improvements

r_{dp} = depreciation rate

r_{ir} = inflation adjusted rate of investment return

Summary

- **Stochastic (random) vs. non-stochastic (predictable) health effects**
- **Acute exposure vs. chronic exposure**
- **MACCS2 acute health effects model**
- **Committee on the Biological Effects of Ionizing Radiation (BEIR)**
- **Cost categories modeled by MACCS2**
- **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 has 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.

Use 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
- Evacuation
- Sheltering
- Relocation
- 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 (usually reactor SCRAM)**
  - **Protective actions are called emergency-response actions**
    - **Evacuation**
    - **Sheltering**
    - **Temporary relocation**

Introduction to Protective Measures (cont.)

- **MACCS2 Mitigative Actions (cont.)**
  - **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 - lower ingestion of contaminated food**
    - **Decontamination***
    - **Temporary interdiction***
    - **Condemnation***
    - **Restricted crop production**

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

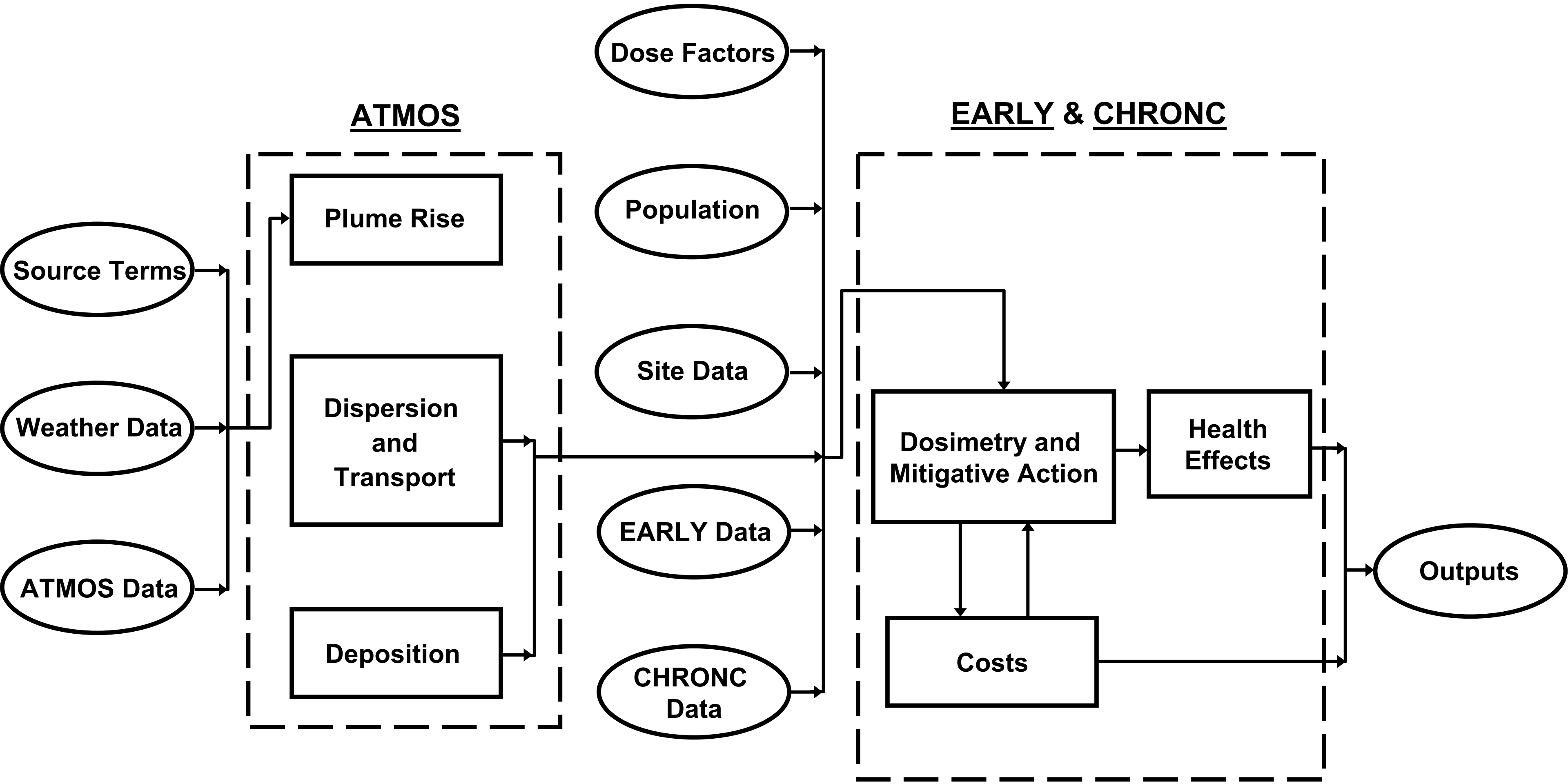
MACCS2 Modeling of Phases

- **The ATMOS module 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 calculations are modeled by the EARLY module.**
  - **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 different emergency response scenarios (cohorts)**
  - **EARLY results are combined by population fractions, time fractions, or using individual populations for each scenario**
  - **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 scenario**

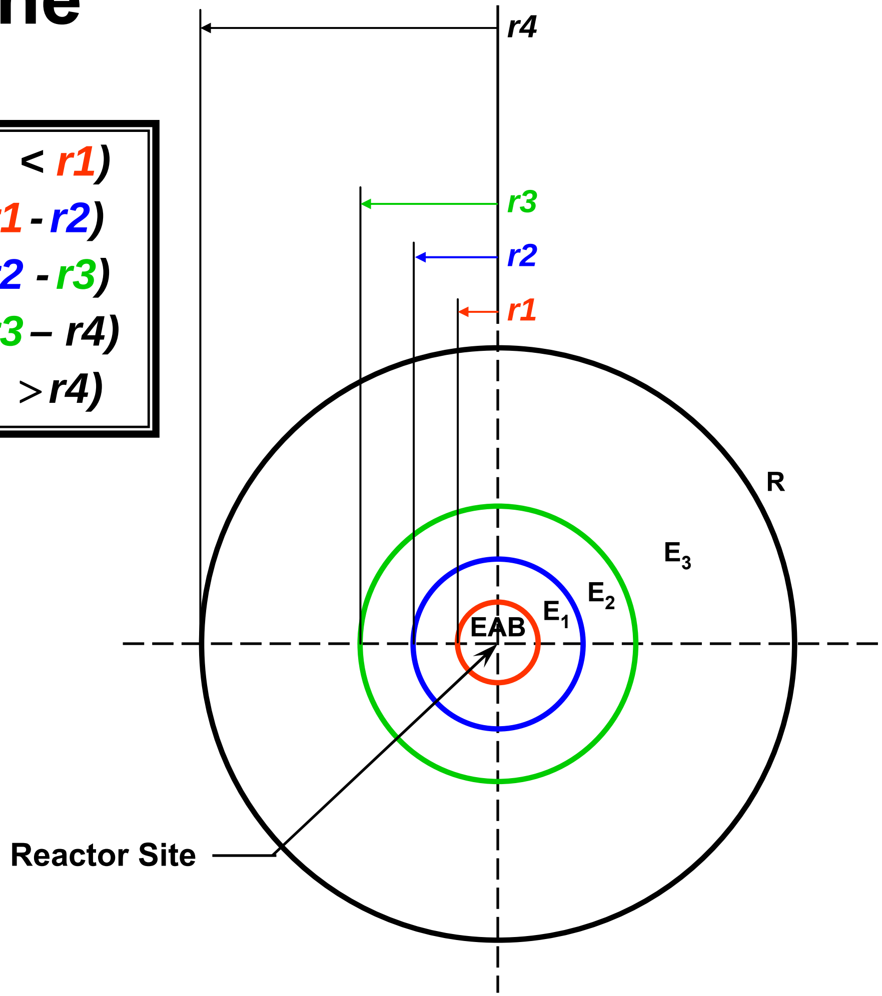
MACCS2 Modeling Diagram



Emergency Planning Zone

Exclusion Area Boundary	(< r1)
↗ E_1: Evacuation and Sheltering Zone 1	(r1 - r2)
↗ E_2: Evacuation and Sheltering Zone 2	(r2 - r3)
↗ E_3: Evacuation and Sheltering Zone 3	(r3 – r4)
↗ R: Relocation Zone	(> r4)

- **The exclusion area boundary is bounded by *r1*.**
- **Evacuation and sheltering zones are optional and need not be included.**
- **The relocation zone 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
  - Speed is user specified and is same for all evacuation zones
  - Three times periods can be defined with different evacuation speeds
  - All people in zone move as a group
  - Evacuation is to (user-specified) distance from reactor site
  - Evacuating shielding factors apply
  - Radial position of evacuees is compared to position of front and back of plume as function of time to determine period of exposure to airborne radionuclides
- Fourth period: After evacuation
  - Upon reaching evacuation distance, the evacuees are assumed to avoid further exposure in EARLY

Sheltering and Evacuation (cont.)

- Fifth period: After end of Emergency Phase
  - Evacuees moved back to original spatial element if habitability criterion satisfied.
  - Those people in evacuation spatial elements over which plume did not pass effectively are never 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 hrs)**
  - **Normal**
    - **Lower dose limit (e.g., 0.01 Sv over 1 week)**
    - **Longer delay to relocate (e.g., 24 hrs)**
  - **Critical organ is user specified (usually TEDE)**

Relocation (cont.)

- Total dose projection
  - Normal activities
  - Entire emergency phase
  - Pathways
    - Cloudshine
    - Groundshine
    - Direct and resuspension inhalation
- Individuals relocated if projected dose commitment exceeds specified limit
- Relocated individuals
  - Receive no further exposure during emergency phase
  - May return after intermediate phase if long-term habitability criterion is met

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
  - 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 dose 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 (unfarmable)**
  - **Disposal of milk and/or crops during growing season**
- **The user specifies the maximum allowable food doses that are allowed**
  - **Short-term milk dose**
  - **Short-term food dose (other than dairy)**
  - **Long-term dose from all food**

Long-Term Ingestion Doses (cont.)

- **Land 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 wholly 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 And Sensitivity Analysis

"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:
  - Stochastic - natural parameter variability (e.g., Meteorological data)
  - Model - lack of complete information about phenomena
  - Parameter - lack of complete information about system

1. Stochastic uncertainty (e.g., weather)
   - Irreducible
2. Model uncertainty (e.g., Gaussian plume model)
   - Quantified by comparing with data
   - Not easily quantified in many cases

Uncertainty and Sensitivity (cont.)

❸ 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)

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 of consequence measure m (e.g. early fatalities)

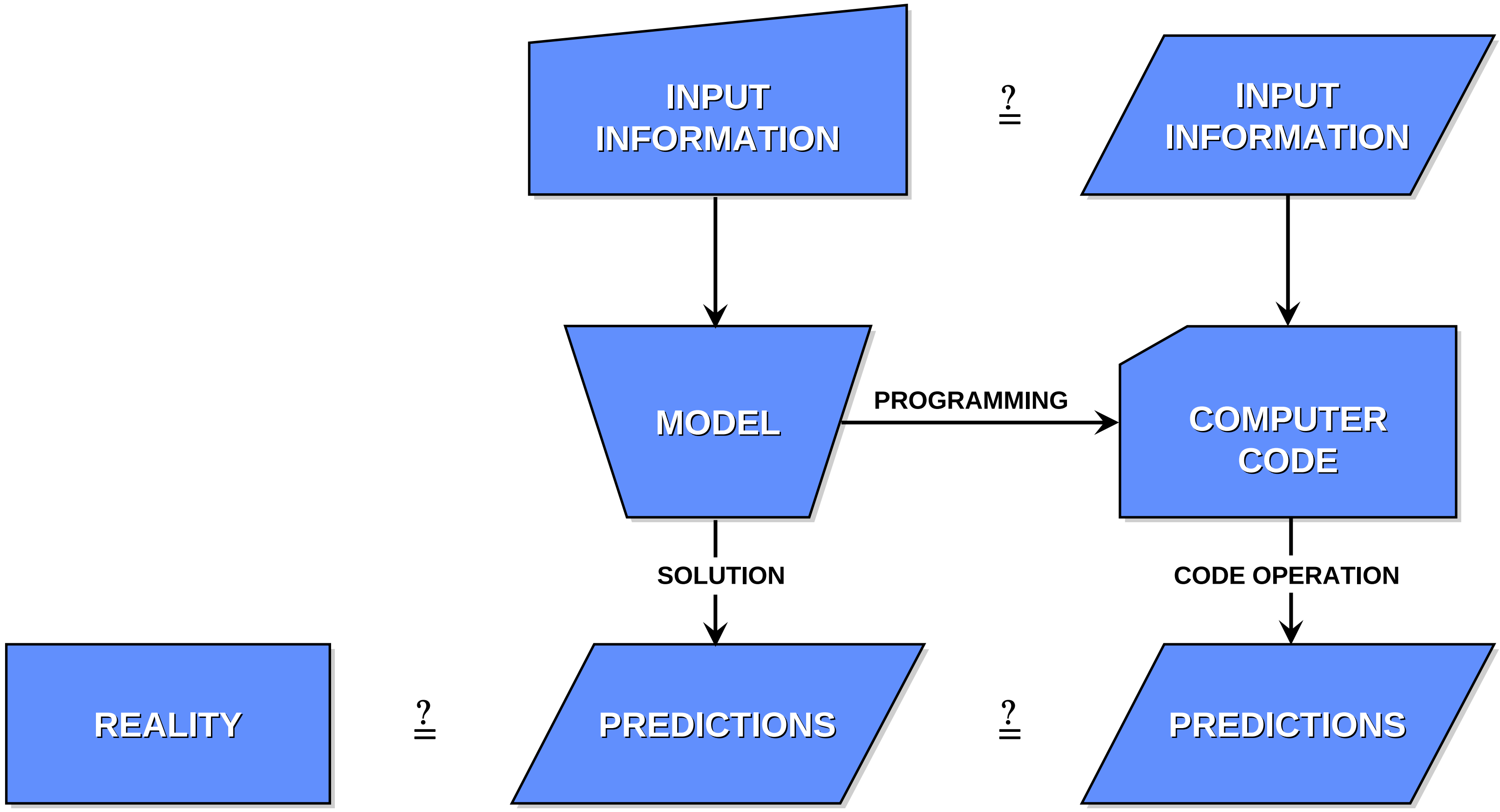
$fPDS_j$ = frequency (per year) of plant damage state j

$pAPB_{jk}$ = 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 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
- 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

MACCS2 Developments

- Major development efforts
  - WinMACCS
    - User-friendly interface
    - Simplify analysis and minimize user errors
    - Reduce effort to perform uncertainty analysis
  - SECPOP2000
  - MELMACCS
- Code Verification
  - Ad hoc by core group of DOE users
  - University of New Mexico
  - Ongoing testing of new model developments

Recent MACCS2 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 MACCS2 Model Developments - II

- Emergency response
  - Map layer for network evacuation screens
  - 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 options to include dose threshold

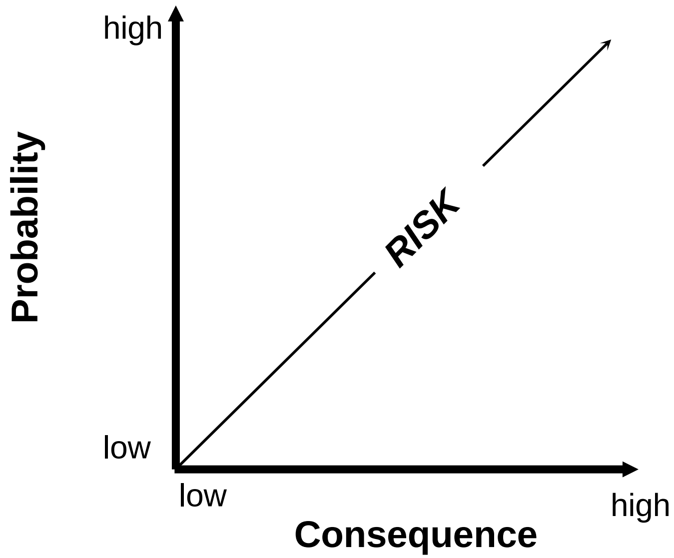
9. Course Summary & Test Preparation

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.**
- ***Level 2* - The assessment of fission product release/transport and containment response which, together with the results of Level 1 analysis, leads to the determination of release frequencies.**
- ➔ ***Level 3* - The assessment of off-site consequences which, 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 a mishap**
- **Probability = the likelihood of an event occurring**
- **Risk = Consequence × Probability**



Level-3 PRA (Consequences)

- **Health Consequence**

RELEASE FROM PLANT

↓

TRANSPORT TO PUBLIC

↓

EFFECT OF TRANSPORTED RELEASE ON PUBLIC HEALTH

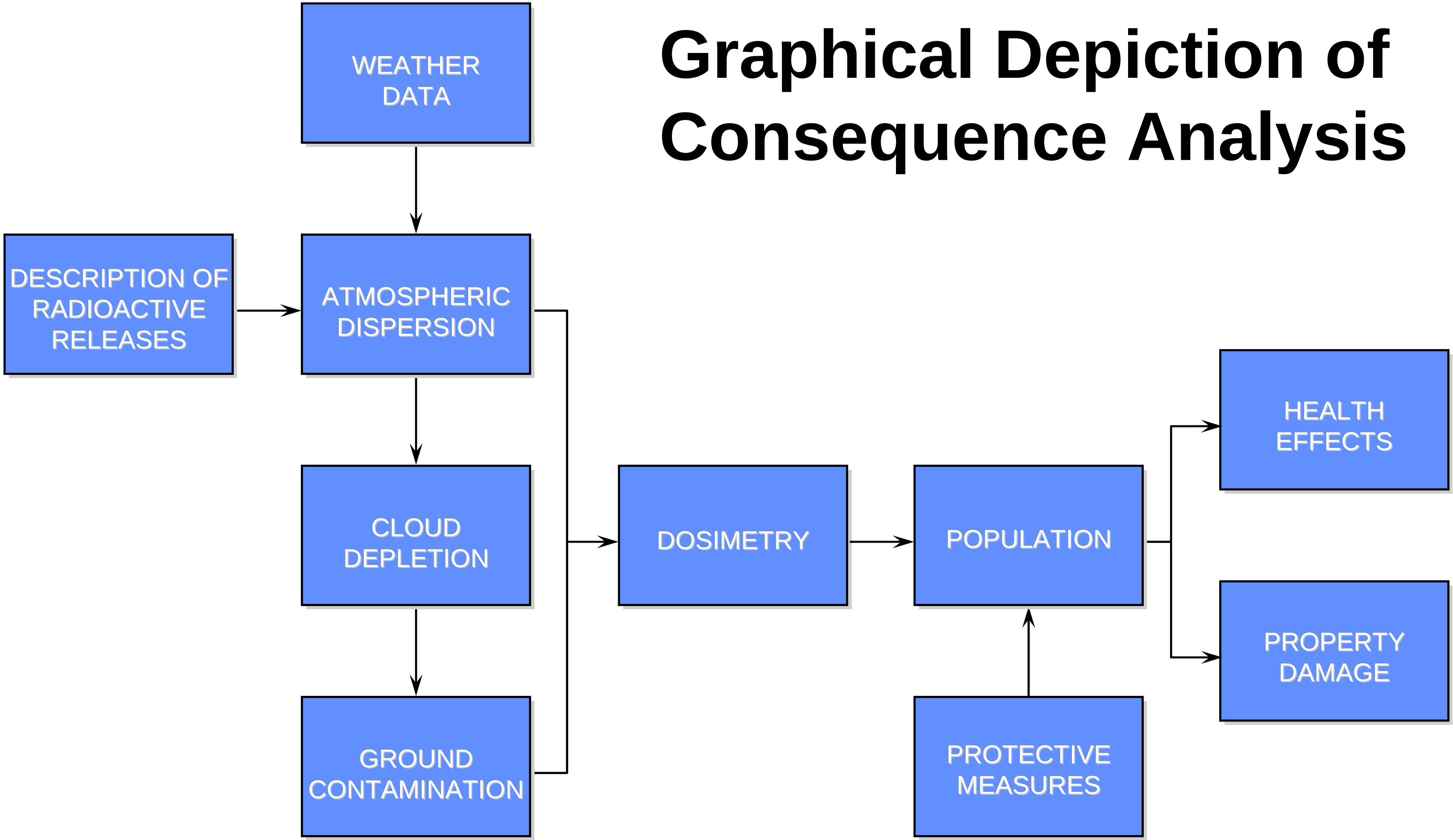
- **Economic Consequence**

  Only different in last term

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 & MACCS2 (US)**
  - ✓ **COSYMA (European Commission)**
- **Interest being rejuvenated following 9/11 and by renaissance of nuclear power**

Graphical Depiction of Consequence Analysis



Consequence Code Evolution

CRAC

(1975)

WASH-1400

→

CRAC2

(1983)

Early PRAs

Rebaselined RSS

Sandia Siting Study

→

MACCS

(1990)

NUREG-1150

↓

MACCS2

(1997-1998)

Security Studies

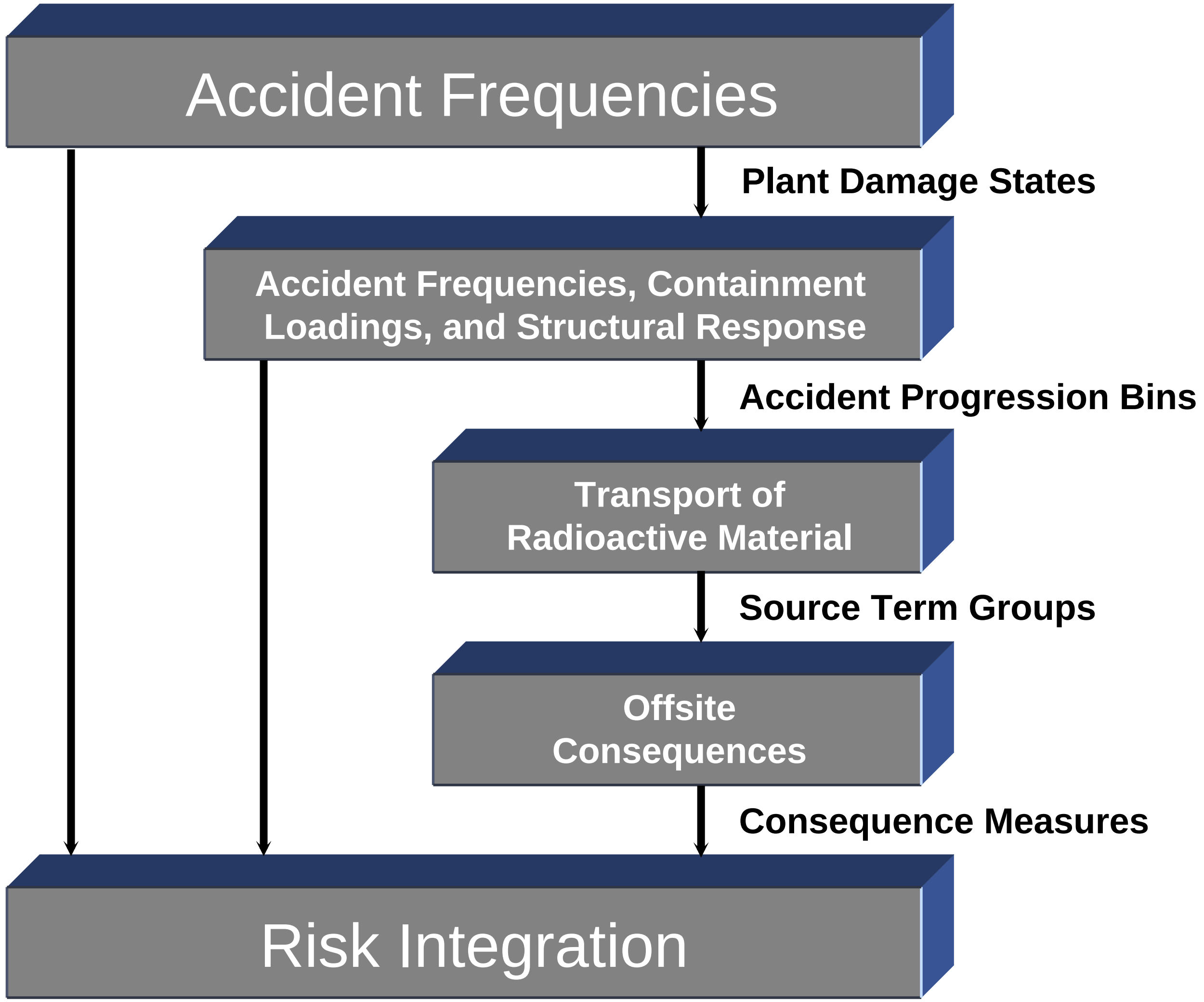
PAR Study

SOARCA

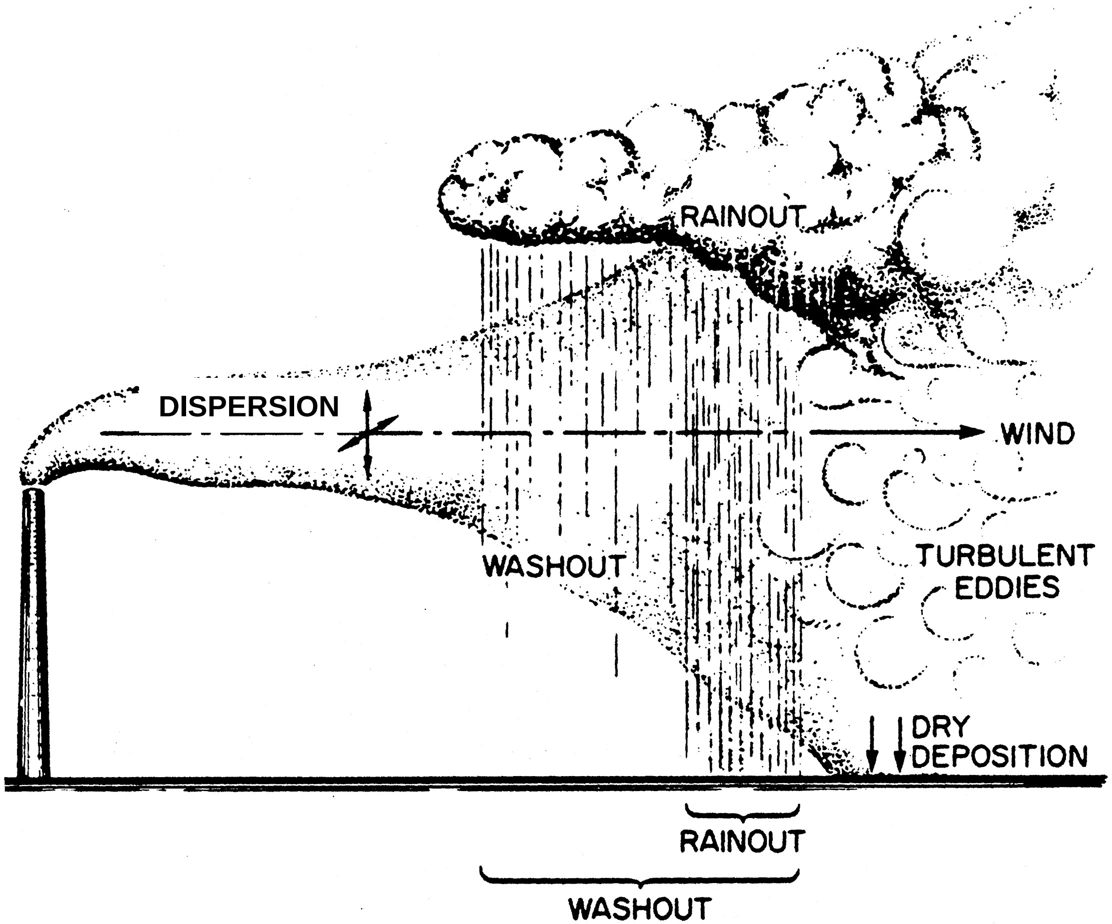
Level-2 PRA Results

- **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**
    - **amounts of various radionuclides**
    - **variation of release with time**
    - **energy in released cloud and release elevation**

NUREG-1150 Risk Analysis Process



Atmospheric Dispersion Consists of Dispersion, Transport, and Depletion Processes



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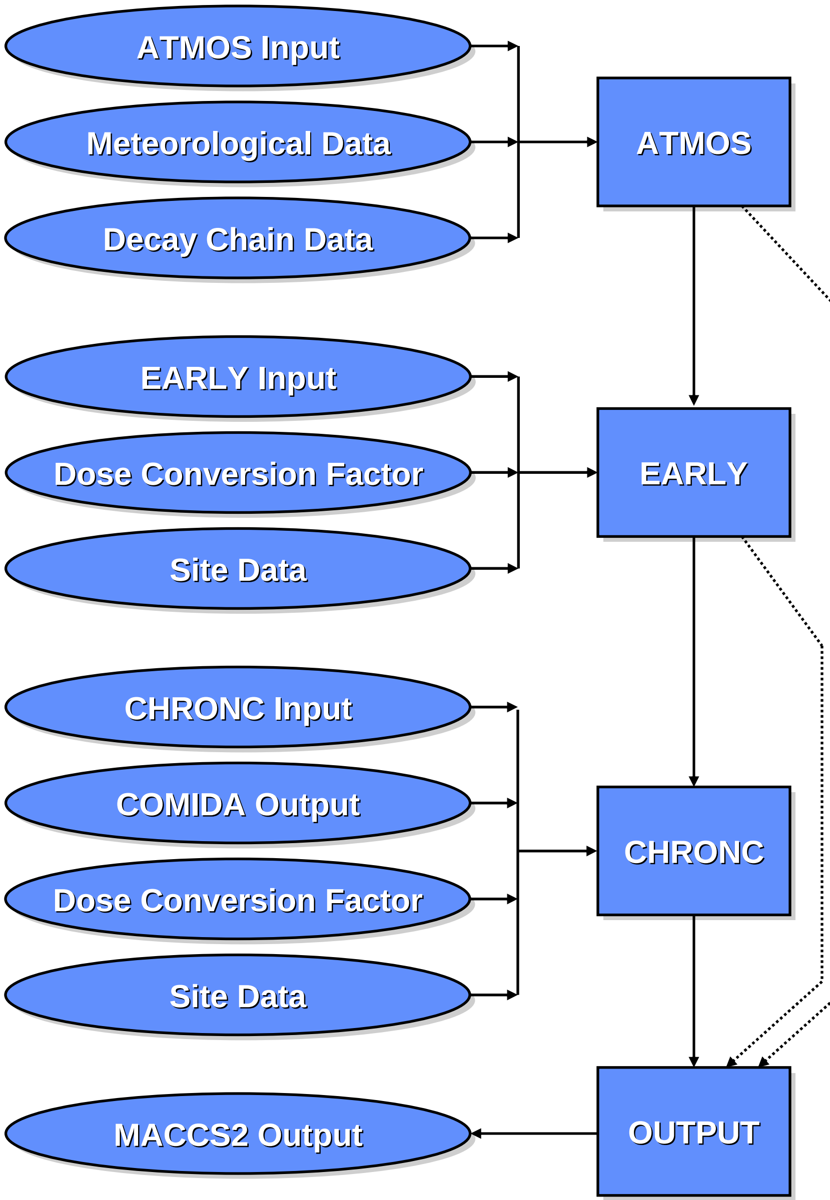
MACCS2 Data Flow

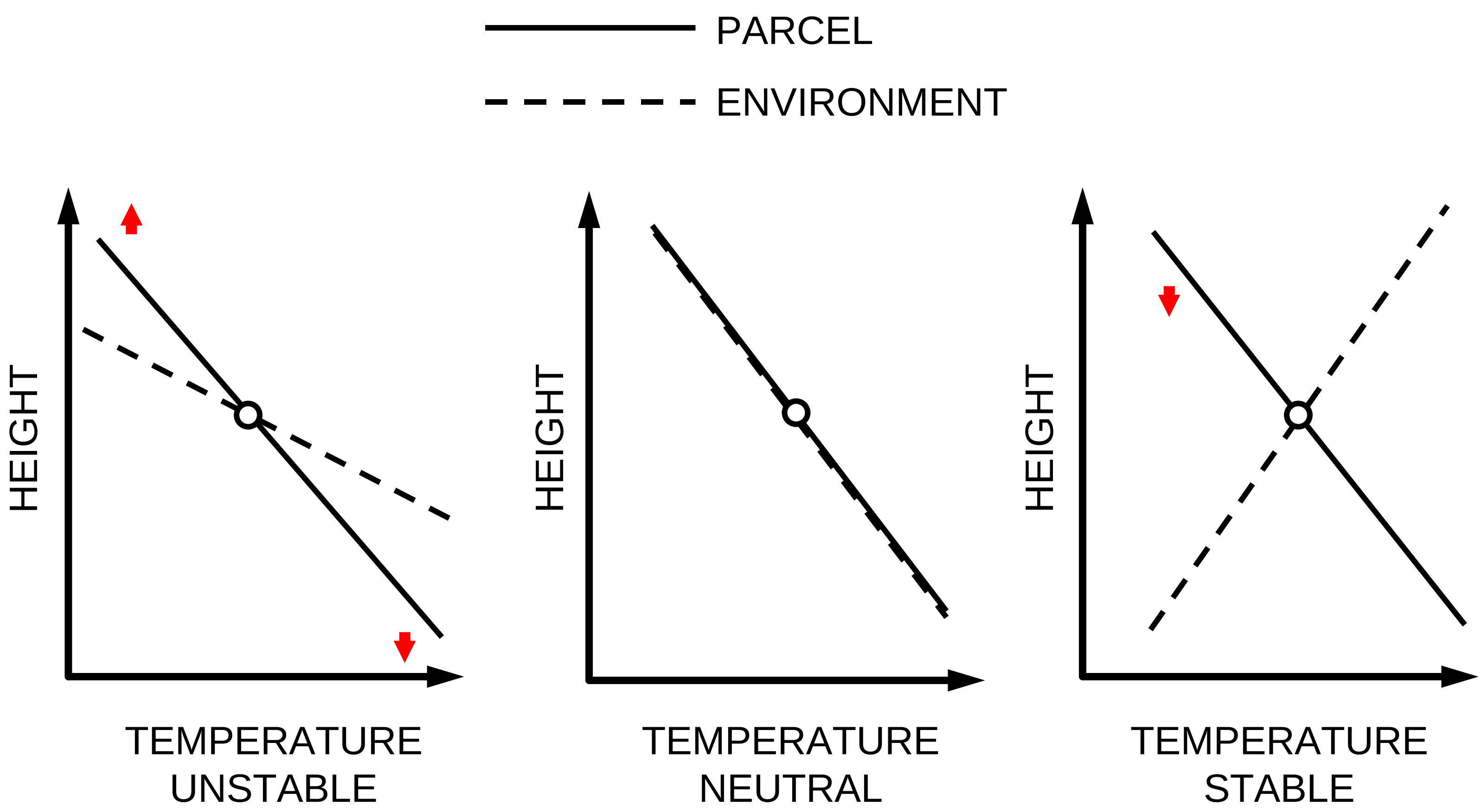
- User activates modules only as needed to determine results of interest
- Activated modules determine input files that are required
- Some required input files can be used as transmitted with MACCS2 (without user modification)



MACCS2 Overview

- **MACCS2 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**
  - **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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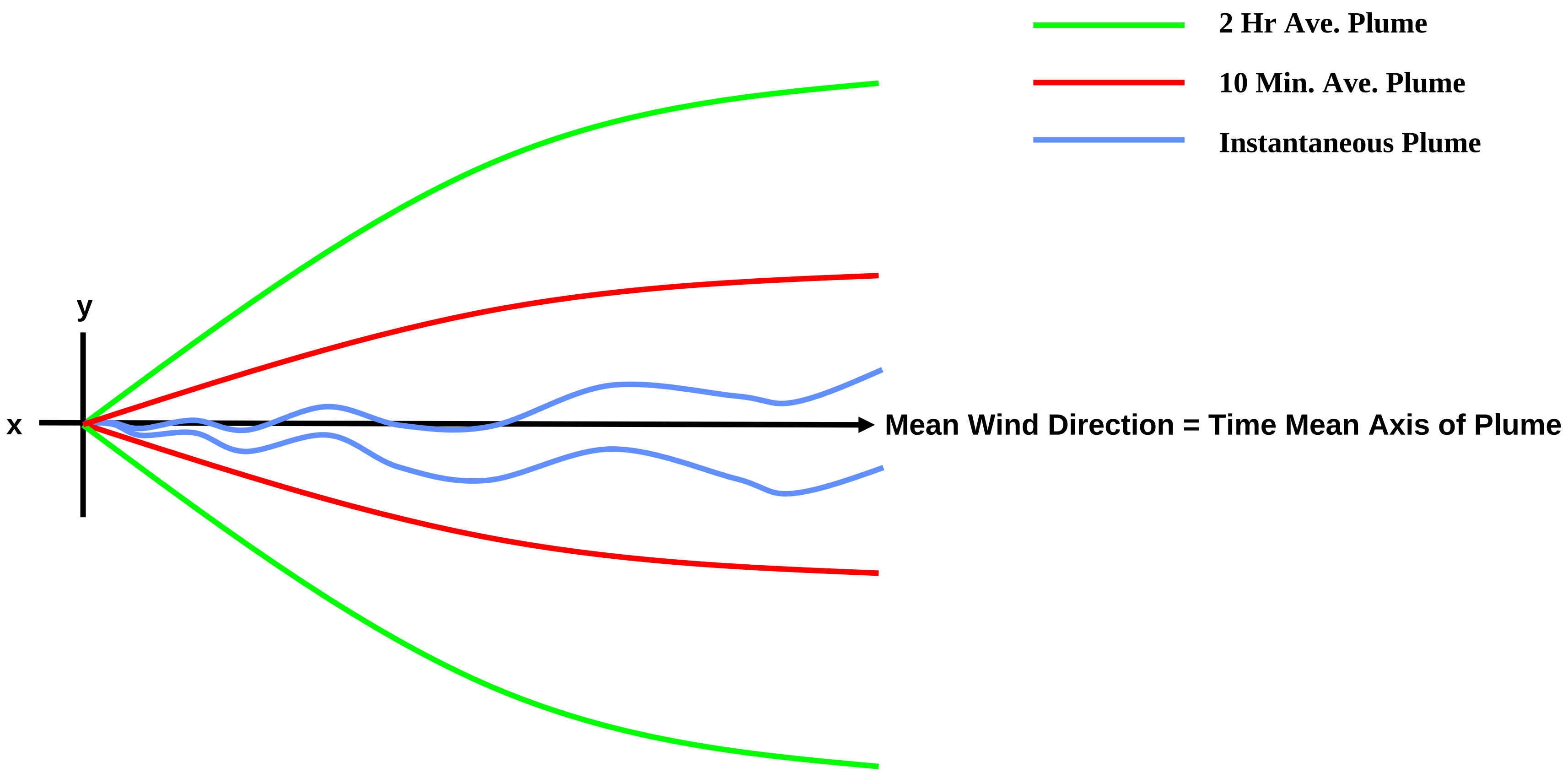
Effect of Diffusion Times

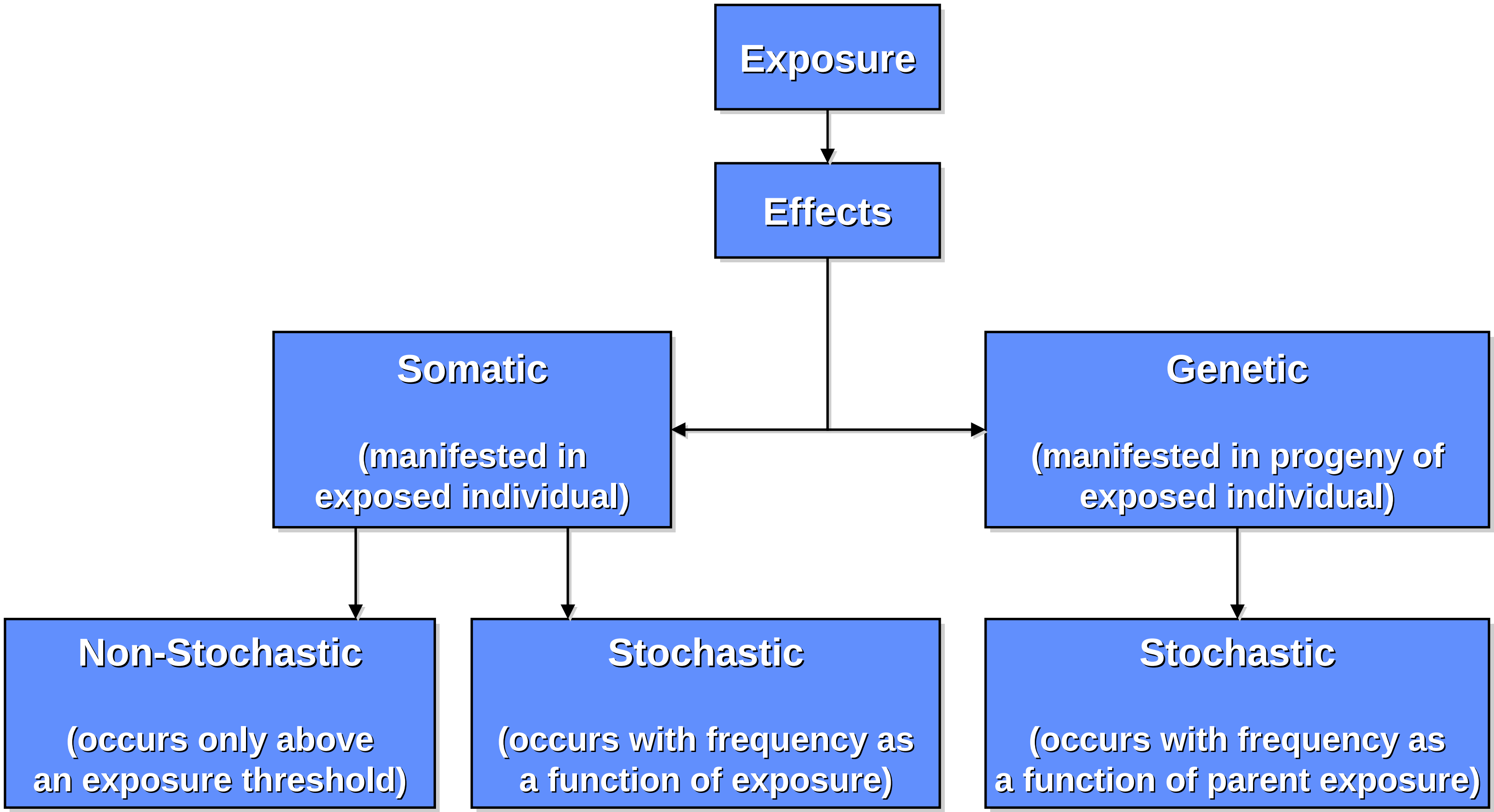


Surface Roughness

- **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 overexposure 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 in linear manner with dose**
    - **Classified as "latent" effects**
  - **Non-stochastic effects**
    - **Thresholds appear at various levels 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**

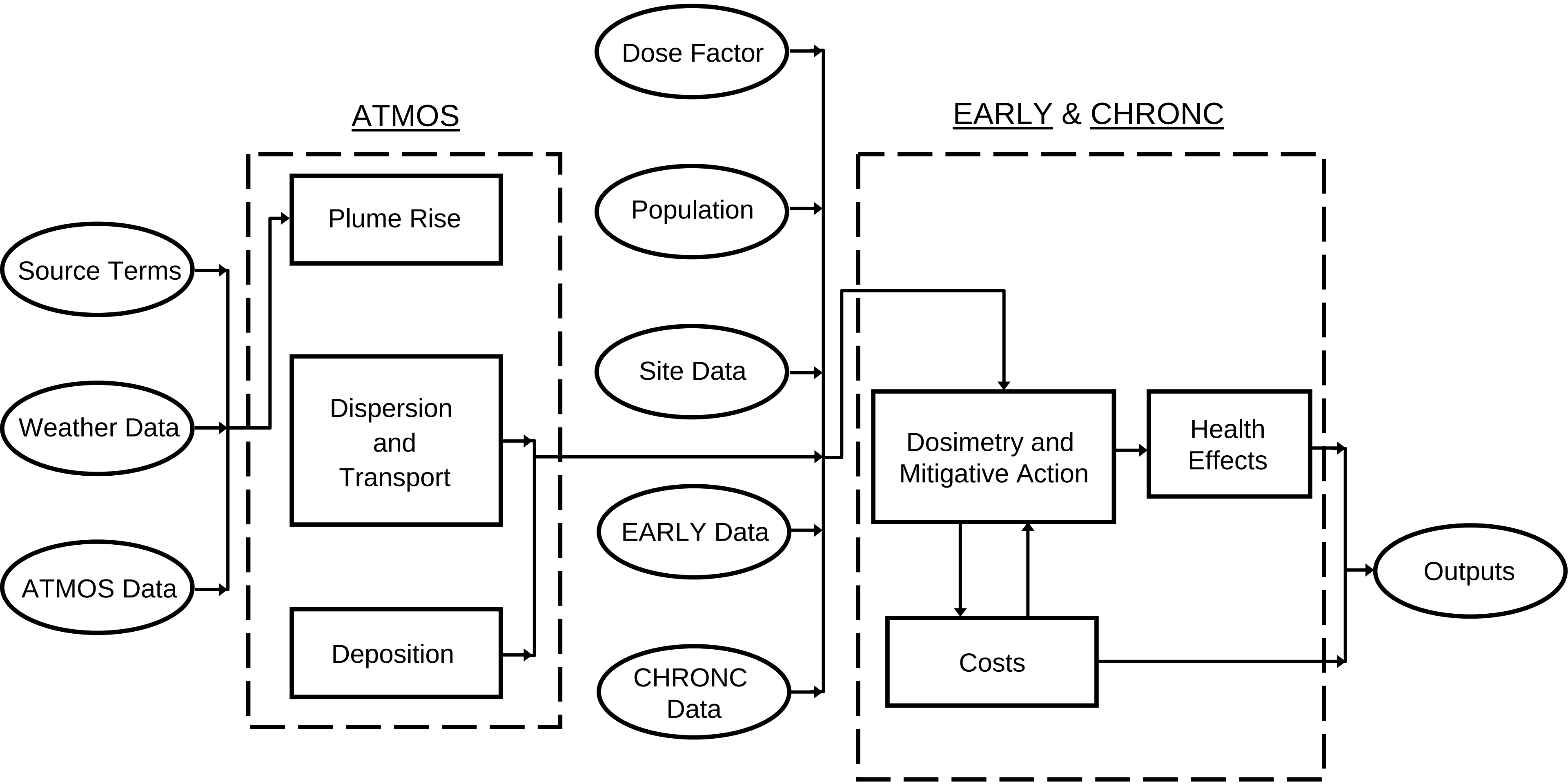
Summary of Cost Categories

- 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 of property

Summary of Protective Measures

- **Mitigative actions are protective measures designed to reduce**
  - **Radiation exposures**
  - **Public health effects**
- **Mitigative measures in MACCS2 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**

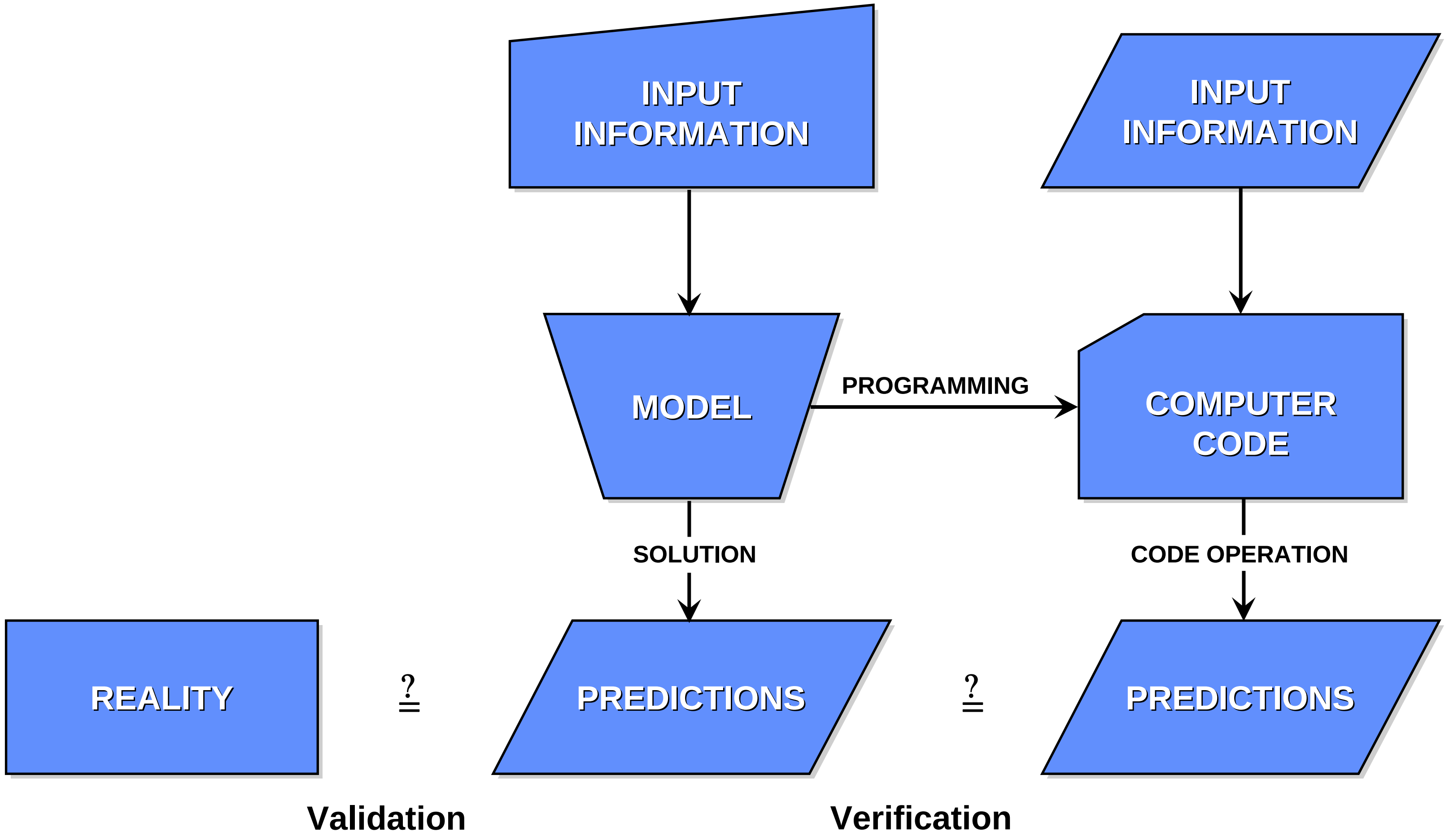
MACCS Modeling Diagram



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 parameters with greatest impact on results**
    - **Uncertainty analysis – determine probability distribution for predicted results corresponding to input uncertainties**

Code Verification / Model Validation Relationship



ORNL-DWG 82-14028

Solution for Workshop Exercise 1 (Part 1)

For a two hour ground level release in the morning of 10 curies of Iodine-132 (half-life = 2.3 hours) containing one-half million Btu 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 which 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 ^oC) higher than that at the 30-meter sensor.

1. Calculate Stability Class (slide 5-18)
   $\Delta T/\Delta z = -.33^oC / (30m - 10m) = -1.65^oC / 100m$ = Stability Class C (slightly unstable)

2. Calculate Thermal Energy of Plume
   Q = 500,000 Btu / 2hr = 250,000 Btu/hr
   Q = (250,000 Btu/hr)(1 watt / 3.4 Btu/hr) = 73,750 watts

3. See if plume is trapped in building wake (worst case for inhalation - no plume rise) (slide 5-30)
   $F = (8.79x10^{-6}\ m^4/s^3)(73,750\ watts) = 0.646$
   Is $u > [(9.09)(F) / H_b]^{1/3}$?
   $[(9.09)(0.646) / 38.3\ m]^{1/3} = 0.54$ which is < 4 m/s

   Yes, the plume is trapped in building wake - no need to calculate plume rise.

4. Calculate standard deviations of plume using the building wake formulas (slide 5-14)
   Assume f = 10% of centerline concentration
   $\sigma_{y,0} = (.23)(W_b) = (.23)(56.5m) = 13m$
   $\sigma_{z,0} = (.47)(H_b) = (.47)(38.3m) = 18m$

5. Use the meander & roughness formulas to develop scaling relationships for P-G curves (slides 5-20, 5-31)
   $\sigma_{y,m} = \sigma_y (\Delta t/\Delta t_{ref})^m = \sigma_y (120min / 10min)^{0.25} = 1.86\sigma_y$ (since Δt > 1hr, m = 0.25)
   $\sigma_{z,z0} = \sigma_z (z_0/3cm)^{0.2} = \sigma_z (1\ cm / 3cm)^{0.2} = 0.8\sigma_z$ (z_0 = 1cm for a plowed field)

6. Calculate standard deviations in y,z directions @ a distance of 9100 m downwind (slides 5-9, 5-10)
   $X_{0,y}$ = 100 m (Remember: C-stability curve and $\sigma_{y,0}$ = 13m - initial point on curve ~ 100m)
   $X_{0,z}$ = 200 m (Remember: C-stability curve and $\sigma_{z,0}$ = 18m)

   Now find σ_y @ (9100m + $X_{0,y}$ = 9200m) = 800 m
   Now use $\sigma_{y,m}$ meander relationship to scale σ_y appropriately.
   $\sigma_{y,m} = 1.86\sigma_y$ = 1488m

   Now find σ_z @ (9100m + $X_{0,z}$ = 9300m) = 400 m
   Now use $\sigma_{z,z0}$ roughness relationship to scale σ_z appropriately.
   $\sigma_{z,z0} = 0.8\sigma_z$ = 320m

7. Determine the mixing height for adding in reflection terms. (slide 5-24)
   h = 500m

8. Calculate "z term" for use in the reflection formula (slide 5-27)

$$\sum_{n=-\infty}^{\infty} e^{\left[-\frac{1}{2}\left(\frac{2nh-H-z}{\sigma_z}\right)^2\right]} + e^{\left[-\frac{1}{2}\left(\frac{2nh+H-z}{\sigma_z}\right)^2\right]} =$$

Assume z = 2m (approximate height of farmer)
H = 0m (no plume rise)
h = 500m

calculating in above formula out until the terms are negligible (n=0,±1) gives
z term = 0.99998 + 0.00743 + 0.00773 + 0.99998 + 0.00773 + 0.00743
z term = 2.03

9. Calculate concentration (slide 5-27)
C = (Q) exp(-y2/2σy2) (z term) / (2π)($\sigma_{y,m}$)($\sigma_{z,z0}$)(u)
C = (10Ci / 7200 s) (1) (2.03) / (2)(π)(1488m)(320m)(4m/s) = 2.36×10^{-10} Ci/m^3

10. Calculate the decayed concentration
$C_d = C\, e^{-\lambda t}$ (where $\lambda = \ln 2 / t_{.5}$)
C_d = (2.36×10^{-10})e{[-ln 2 / (2.3 hr)(3600s/hr)]*x*[(9100 m / 4m/s)]} = **1.95×10^{-10} Ci/m^3**

Solution for Workshop Exercise 1 (Part 2)

What concentration would the farmer see if the PBL were moderately stable?

1. Stability Class F (in problem description) (slide 5-18)

2. Calculate Thermal Energy of Plume
   $Q = 500{,}000$ Btu / 2hr = 250,000 Btu/hr
   $Q = (250{,}000$ Btu/hr)(1 watt / 3.4 Btu/hr) = 73,750 watts

3. See if plume is trapped in building wake (worst case for inhalation - no plume rise) (slide 5-30)
   $F = (8.79\text{x}10^{-6}\ m^4/s^3)(73{,}750 \text{ watts}) = 0.646$
   Is $u > [(9.09)(F) / H_b]^{1/3}$?
   $[(9.09)(0.646) / 38.3 \text{ m}]^{1/3} = 0.54$ which is < 4 m/s

   Yes, the plume is trapped in building wake - no need to calculate plume rise.

4. Calculate standard deviations of plume using the building wake formulas (slide 5-14)
   Assume f = 10% of centerline concentration
   $\sigma_{y,0} = (.23)(W_b) = (.23)(56.5m) = 13m$
   $\sigma_{z,0} = (.47)(W_b) = (.47)(38.3m) = 18m$

5. Use the meander & roughness formulas to develop scaling relationships for P-G curves
   (slides 5-20, 5-31)
   $\sigma_{y,m} = \sigma_y (\Delta t/\Delta t_{ref})^m = \sigma_y (120min / 10min)^{0.25} = 1.86\sigma_y$ (since Δt > 1hr, m = 0.25)
   $\sigma_{z,z0} = \sigma_z (z_0/3cm)^{0.2} = \sigma_z (1 \text{ cm} / 3cm)^{0.2} = 0.8\sigma_z$ (z_0 = 1cm for a plowed field)

6. Calculate standard deviations in y,z directions @ a distance of 9100 m downwind (slides 5-9, 5-10)
   $X_{0,y}$ = 350 m (Remember: F-stability curve and $\sigma_{y,0}$ = 13m - initial point on curve ~ 100m)
   $X_{0,z}$ = 1500 m (Remember: F-stability curve and $\sigma_{z,0}$ = 18m)

   Now find σ_y @ (9100m + $X_{0,y}$ = 9450m) = 290 m
   Now use $\sigma_{y,m}$ meander relationship to scale σ_y appropriately.
   $\sigma_{y,m} = 1.86\sigma_y = 539m$

   Now find σ_z @ (9100m + $X_{0,z}$ = 10600m) = 49 m
   Now use $\sigma_{z,z0}$ roughness relationship to scale σ_z appropriately.
   $\sigma_{z,z0} = 0.8\sigma_z = 39.2m$

7. Determine the mixing height for adding in reflection terms. (slide 5-24)
   h = 500m

8. Calculate "z term" for use in the reflection formula (slide 5-27)

$$\sum_{n=-\infty}^{\infty} e^{\left[-\frac{1}{2}\left(\frac{2nh-H-z}{\sigma_z}\right)^2\right]} + e^{\left[-\frac{1}{2}\left(\frac{2nh+H-z}{\sigma_z}\right)^2\right]} =$$

Assume z = 2m (approximate height of farmer)
H = 0m (no plume rise)
h = 500m

calculating in above formula out until the terms are negligible (n=0) gives
z term = 0.99870 + 0.99870
z term = 2.0

9. Calculate concentration (slide 5-27)
C = (Q) exp(-y2/2σy2) (z term) / (2π)($\sigma_{y,m}$)($\sigma_{z,z0}$)(u)
C = (10Ci / 7200 s) (1) (2.0) / (2)(π)(539m)(39.2m)(4m/s) = 5.23×10^{-9}

10. Calculate the decayed concentration
$C_d = C\, e^{-\lambda t}$ (where $\lambda = \ln 2 / t_{.5}$)
C_d = (5.23×10^{-9})e{[-ln 2 / (2.3 hr)(3600s/hr)]*x*[(9100 m / 4m/s)]} = **4.33×10^{-9} Ci/m^3**

Solution for Workshop Exercise 1 (Part 3)

What concentration would the farmer see if the PBL were moderately stable and the windspeed was 1 m/s?

1. Stability Class F (in problem description) (slide 5-18)

2. Calculate Thermal Energy of Plume
   Q = 500,000 Btu / 2hr = 250,000 Btu/hr
   Q = (250,000 Btu/hr)(1 watt / 3.4 Btu/hr) = 73,750 watts

3. See if plume is still trapped in building wake since the wind speed is smaller (slide 5-30)
   (worst case for inhalation - no plume rise)
   $F = (8.79\times10^{-6}\ m^4/s^3)(73{,}750\ watts) = 0.646$
   Is $u > [(9.09)(F) / H_b]^{1/3}$?
   $[(9.09)(0.646) / 38.3\ m]^{1/3} = 0.54$ which is < 1 m/s

   Yes, the plume is ***still*** trapped in building wake - no need to calculate plume rise.

4. Calculate standard deviations of plume using the building wake formulas (slide 5-14)
   Assume f = 10% of centerline concentration
   $\sigma_{y,0} = (.23)(W_b) = (.23)(56.5m) = 13m$
   $\sigma_{z,0} = (.47)(W_b) = (.47)(38.3m) = 18m$

5. Use the meander & roughness formulas to develop scaling relationships for P-G curves (slides 5-20, 5-31)
   $\sigma_{y,m} = \sigma_y (\Delta t/\Delta t_{ref})^m = \sigma_y (120min / 10min)^{0.25} = 1.86\sigma_y$ (since Δt > 1hr, m = 0.25)
   $\sigma_{z,z0} = \sigma_z (z_0/3cm)^{0.2} = \sigma_z (1\ cm / 3cm)^{0.2} = 0.8\sigma_z$ (z_0 = 1cm for a plowed field)

6. Calculate standard deviations in y,z directions @ a distance of 9100 m downwind (slides 5-9, 5-10)
   $X_{0,y}$ = 350 m (Remember: F-stability curve and $\sigma_{y,0}$ = 13m - initial point on curve ~ 100m)
   $X_{0,z}$ = 1500 m (Remember: F-stability curve and $\sigma_{z,0}$ = 18m)

   Now find σ_y @ (9100m + $X_{0,y}$ = 9450m) = 290 m
   Now use $\sigma_{y,m}$ meander relationship to scale σ_y appropriately.
   $\sigma_{y,m} = 1.86\sigma_y = 539m$

   Now find σ_z @ (9100m + $X_{0,z}$ = 10600m) = 49 m
   Now use $\sigma_{z,z0}$ roughness relationship to scale σ_z appropriately.
   $\sigma_{z,z0} = 0.8\sigma_z = 39.2m$

7. Determine the mixing height for adding in reflection terms. (slide 5-24)
   h = 500m

8. Calculate "z term" for use in the reflection formula (slide 5-27)

$$\sum_{n=-\infty}^{\infty} e^{\left[-\frac{1}{2}\left(\frac{2nh-H-z}{\sigma_z}\right)^2\right]} + e^{\left[-\frac{1}{2}\left(\frac{2nh+H-z}{\sigma_z}\right)^2\right]} =$$

Assume z = 2m (approximate height of farmer)
H = 0m (no plume rise)
h = 500m

calculating in above formula out until the terms are negligible (n=0) gives
z term = 0.99870 + 0.99870
z term = 2.0

9. Calculate concentration (slide 5-27)
C = (Q) exp(-y2/2σy2) (z term) / (2π)($\sigma_{y,m}$)($\sigma_{z,z0}$)(u)
C = (10Ci / 7200 s) (1) (2.0) / (2)(π)(539m)(39.2m)(1m/s) = $2.09\text{x}10^{-8}$ Ci/m^3

10. Calculate the decayed concentration
C_d = C $e^{-\lambda t}$ (where λ = ln 2 / $t_{.5}$)
C_d = ($2.09\text{x}10^{-8}$)e{[-ln 2 / (2.3 hr)(3600s/hr)]*x*[(9100 m / 1m/s)]} = **$9.76\text{x}10^{-9}$ Ci/m^3**

Solution for Workshop Exercise 2 (Part 1)

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

1. Calculate the effective plume height (slide 5-41)

   σ_z exponential terms = 2 (from slide 5-34)

   $z = \sigma_z [(\pi/2)]^{.5} / (\sigma_z \text{ exponential terms}) = [\pi/4]^{.5} = 0.627\ \sigma_z$

   $\sigma_{z,800}$ = 42 (from slide 5-35 for 800m)

   $\sigma_{z,13000}$ = 106 (from slide 5-35 for 13000m)

   $\therefore\ z_{800} = (0.627)(42) = 26.33$ m

   $z_{13000} = (0.627)(106) = 66.46$ m

2. Calculate the fraction of release that has been deposited at 800m and at 13,000m (slide 5-41)

   $Q/Q_o = e^{-\{[(.01\ m/s)][(800m)/(1m/s)]/26.33m\}} = 0.74$ (for 800m)

   $Q/Q_o = e^{-\{[(.01\ m/s)][(13000m)/(1m/s)]/66.46m\}} = 0.14$ (for 13000m)

3. Now calculate the deposition itself (slide 5-41)

   $D_{800} = (8.9\text{x}10^{-8}\ Ci/m^3)(1800s)(.01\ m/s)(0.74)$

   D_{800} = **$1.19\text{x}10^{-6}\ Ci/m^2$**

   $D_{13000} = (3.4\text{x}10^{-9}\ Ci/m^3)(1800s)(.01\ m/s)(0.14)$

   D_{13000} = **$8.57\text{x}10^{-9}\ Ci/m^2$**

Solution for Workshop Exercise 2 (Part 2)

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 in/hr?

1. Calculate the washout coefficient (slide 5-43)

   $\Lambda = (9.5\text{x}10^{-5})(I)^{0.8} = (9.5\text{x}10^{-5})[(1\text{in/hr})(25.4\text{mm/in})]^{0.8}$

   $= \boxed{1.26\text{x}10^{-3}}$

2. Calculate the fraction of plume deposition (slide 5-43)

   $Q/Q_o = e^{-\Lambda t}$

   $= e^{-[1.26\text{x}10\text{-}3][(800\text{m})/(1\text{m/s})]} = \boxed{0.365}$ (this is the fraction left to be deposited)

   $\therefore$ Fraction deposited prior to 800m = 1 - 0.365 = **0.635**

   $= e^{-[1.26\text{x}10\text{-}3][(13000\text{m})/(1\text{m/s})]} = 7.7\text{x}10^{-8}$ (this is the fraction left to be deposited)

   $\therefore$ Fraction deposited prior to the mall ~ 1 (compete depletion)

Solution for Workshop Exercise 3

Continuing the workshop example, what is the dose to an individual located on the mall who is present at the time the plume is passing?

1. Calculate the air concentration (slides 5-38, Exercise 2)

   $Conc_{air} = (3.4\times10^{-9})(.14) = \boxed{4.76\times10^{-10}\ Ci/m^3}$

2. Calculate the inhalation dose (slide 5-46)

   $Dose_{rate} = (\text{Usage Rate})(\text{Air Concentration})(\text{DCF})$

   $= (20m^3/day)(4.76\times10^{-10}Ci/m^3)(3.2\times10^{-2}rem/\mu Ci)(10^6\ \mu Ci/Ci)$

   $= 0.000305\ rem/day$

   $\therefore$ Total $Dose_{air} = (0.00305\ rem/day)(1\ day / 1440\ min)(30\ min) = \boxed{6.35\times10^{-6}\ rem}$

Solution for Workshop Exercise 4

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? (Note: Half-life of ^{137}Cs is 30 years)

1. Calculate the decay

$$C/C_o = e^{-[(\ln 2)(t)/t_{.5}]} = e^{-[(\ln 2)(1\ \mathrm{yr})/30\mathrm{yrs}]} = \boxed{0.98}$$

2. Calculate the weathering coefficient (slide 5-50)

$$\mathrm{Coeff} = (10^{-5})(e^{-[(\ln 2)(1\ \mathrm{yr})/.5\mathrm{yrs}]}) + (10^{-7})(e^{-[(\ln 2)(1\ \mathrm{yr})/5\mathrm{yrs}]}) + (10^{-9})(e^{-[(\ln 2)(1\ \mathrm{yr})/50\mathrm{yrs}]})$$

$$= \boxed{2.6\mathrm{x}10^{-6}\ \mathrm{m}^{-1}}$$

3. Calculate the concentration (slide 5-50, Exercise 2)

$$C_{air} = (\text{Weathering coefficient})(\text{Deposition})$$

$$= (2.6\mathrm{x}10^{-6}\ \mathrm{m}^{-1})(8.57\mathrm{x}10^{-9}\ \mathrm{Ci/m}^2)(.98) = \boxed{\mathbf{2.18x10^{-14}\ Ci/m^3}}$$