Level 2/3 PRA: Beyond Core Damage

Lecture 6-4

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Key Topics

- Accident Mitigation and Emergency Response
- Level 2 PRA
- Level 3 PRA

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Resources

- American Nuclear Society and the Institute of Electrical and Electronics Engineers, “PRA Procedures Guide,” *NUREG/CR-2300*, January 1983.
- F.E. Haskin, A.L. Camp, S.A. Hodge, and D.A. Powers, “Perspectives on Reactor Safety,” *NUREG/CR-6042*, Revision 2, March 2002.
- U.S. Nuclear Regulatory Commission, “Severe Accident Risks: An Assessment for Five U.S. Nuclear Power Plants,” *NUREG-1150*, December 1990.

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Other References

- D. Helton, “Scoping Study on Advanced Modeling Techniques for Level 2/3 PRA,” U.S. Nuclear Regulatory Commission, May 2009. (ADAMS ML091320447)
- N. Bixler, et al., “MACCS Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project,” *NUREG/CR-7009*, August 2014.
- Environmental Protection Agency, “PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents, *EPA-400/R-16/001*, November 2016.
- R. Draxler, “An Overview of the HYSPLIT Modeling System for Trajectory and Dispersion Applications,” National Oceanic and Atmospheric Administration, April 7, 2018. (Available from: https://www3.epa.gov/scram001/9thmodconf/draxler.pdf)
- U.S. Nuclear Regulatory Commission, “Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants,” *NUREG-1738*, February 2001.
- D. Algama, et al., “Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor,” draft report, U.S. Nuclear Regulatory Commission, June 2013. (ADAMS ML13133A132)

Terminology

- Level 2 commonly used in two different ways
  - Analysis starting with initiating event and ending with radiological release
  - Analysis starting with plant damage (Level 1) and ending with radiological release
- Similarly, for Level 3
  - Analysis starting with initiating event and ending with offsite consequences
  - Analysis starting with radiological release and ending with offsite consequences
- This lecture uses latter, narrower definitions

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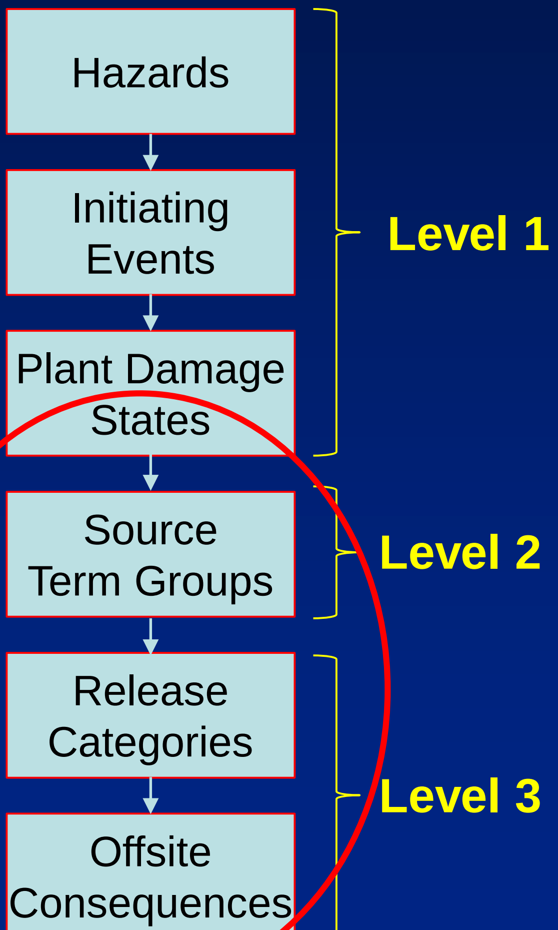
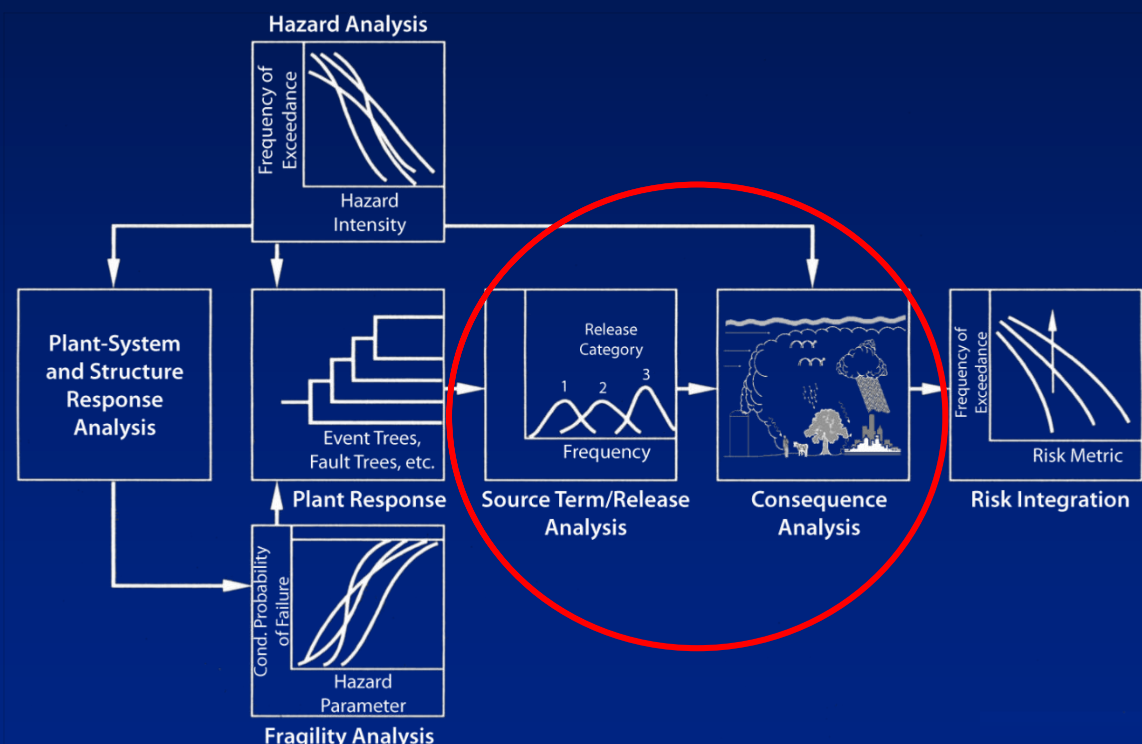
Level 2 and Level 3 PRA





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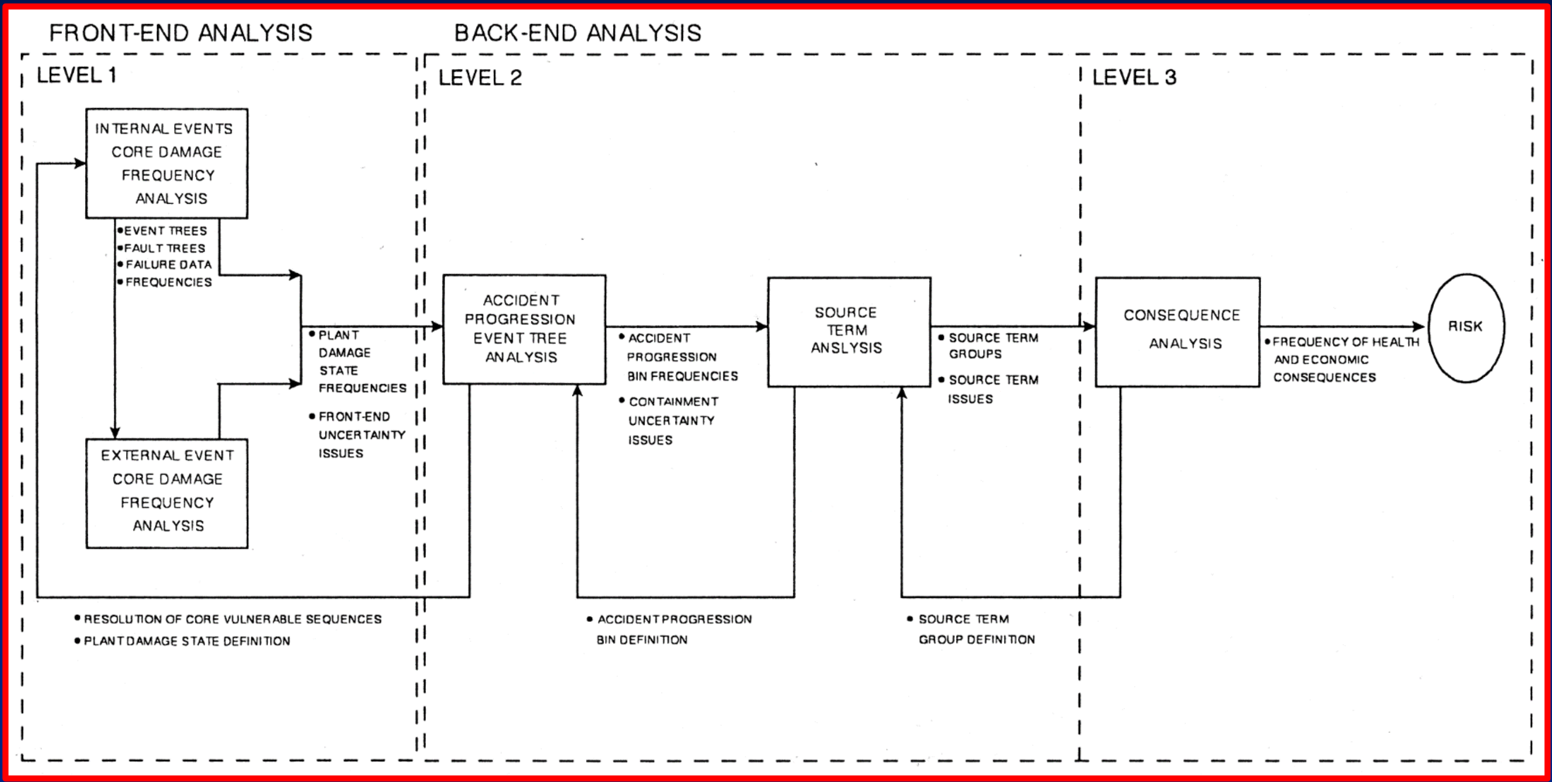
A More Detailed, Historical View



NUREG-1150

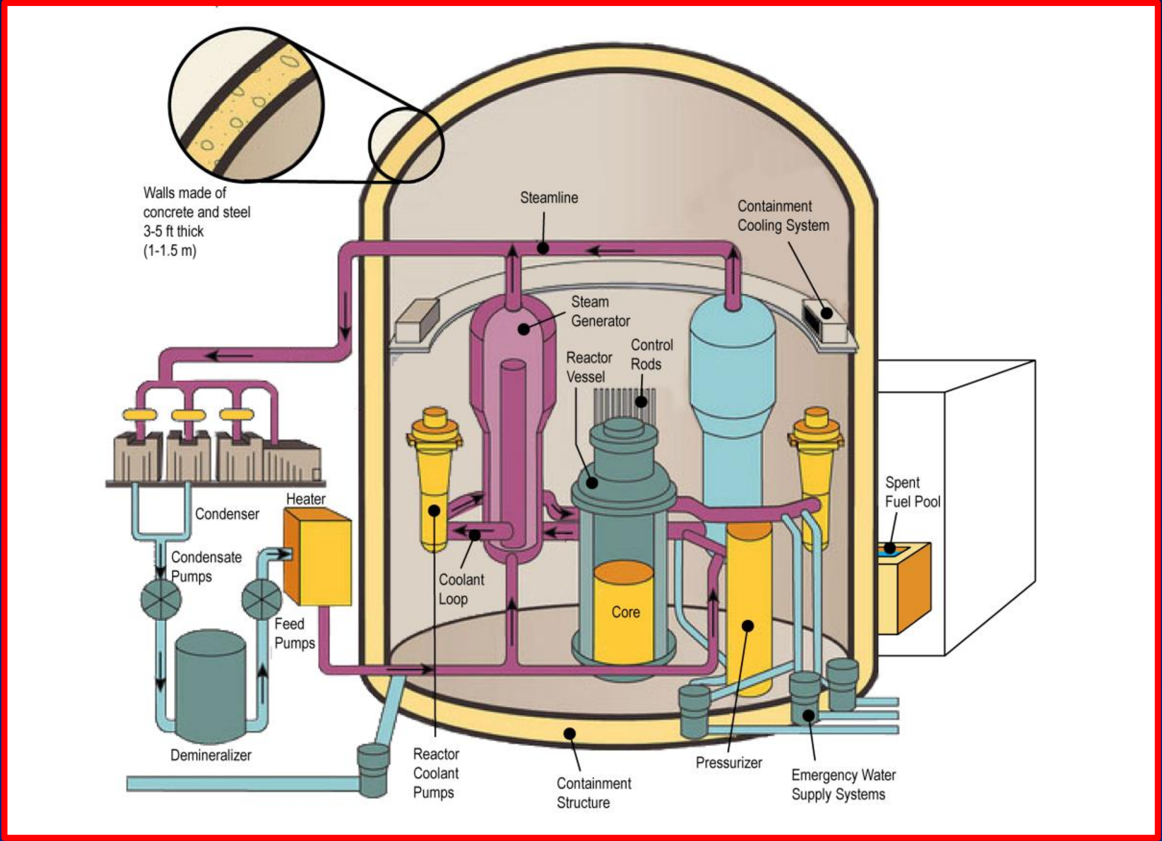
Overview: Accident Mitigation

Mitigation Aims

- Arrest core damage (cooling)
- Reduce source term (scrubbing, deposition, filtration)
- Prevent/delay release (isolation, venting)

Active and Passive Systems/Features

- Injection/recirculation, containment sump
- Spray, fan coolers
- Isolation, vent
- Containment and other buildings



Adapted from: https://www.nrc.gov/reactors/pwrs.html

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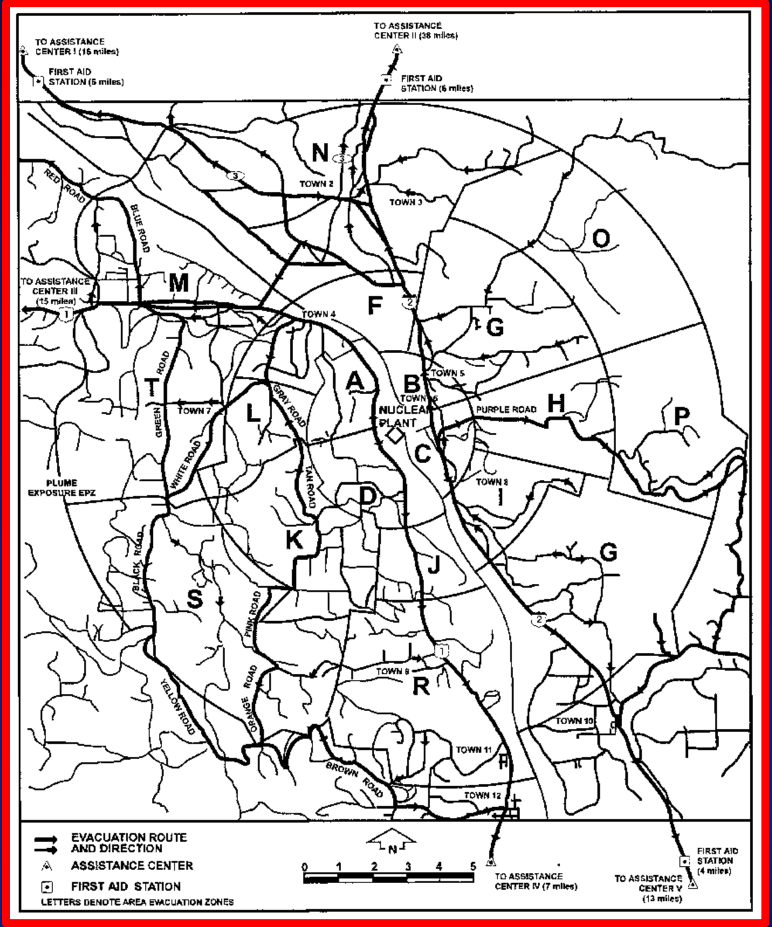
Overview: Emergency Preparedness and Response

- Emergency Planning Zone (EPZ)
  - Plume exposure pathway (~10 mile radius)
  - Ingestion pathway (~50 mile radius)
- Emergency Classifications
  - Notification of Unusual Event
  - Alert
  - Site Area Emergency
  - General Emergency
- Protective Actions
  - Sheltering
  - Evacuation
  - Potassium iodide
  - Interdiction
  - Relocation



EPA Protective Action Guides (PAGs)

PAG = "projected dose to an individual from a release of radioactive material at which a specific protective action to reduce or avoid that dose is recommended"

Phase	Protective Action Recommendation	PAG, Guideline, or Planning Guidance
Early Phase	Sheltering-in-place or evacuation of the public[b]	**PAG**: 1 to 5 rem (10 to 50 mSv) projected dose over four days[c]
	Supplementary administration of prophylactic drugs – KI[d]	**PAG**: 5 rem (50 mSv) projected child thyroid dose[e] from exposure to radioactive iodine
	Limit emergency worker exposure (total dose incurred over entire response)	**Guideline**: 5 rem (50 mSv)/year (or greater under exceptional circumstances)[f]
Intermediate Phase	Relocation of the public	**PAG**: $\geq$ 2 rem (20 mSv) projected dose[c] in the first year, 0.5 rem (5 mSv)/year projected dose in the second and subsequent years
	Apply simple dose reduction techniques	**Guideline**: < 2 rem (20 mSv) projected dose[c] in the first year
	Food interdiction[g]	**PAG**: 0.5 rem (5 mSv)/year projected whole body dose, or 5 rem (50 mSv)/year to any individual organ or tissue, whichever is limiting
	Alternative drinking water	**PAG**: pending finalization of proposal
	Limit emergency worker exposure (total dose incurred over entire response)	**Guideline**: 5 rem (50 mSv)/year
	Reentry	**Guideline**: Operational Guidelines[h] (stay times and concentrations) for specific reentry activities (see Section 4.6)

Environmental Protection Agency, "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents, *EPA-400/R-16/001*, November 2016

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Level 2 PRA

- Interfaces
  - Level 1: plant damage states include information beyond core damage, e.g., status of RCS (temperature, pressure, integrity) and support systems
  - Level 3: Source terms and other characteristics (e.g., release location, energy) relevant to consequence analysis
- Key processes
  - Mitigating system response
  - Severe accident progression
  - Containment response
  - Human and organizational response

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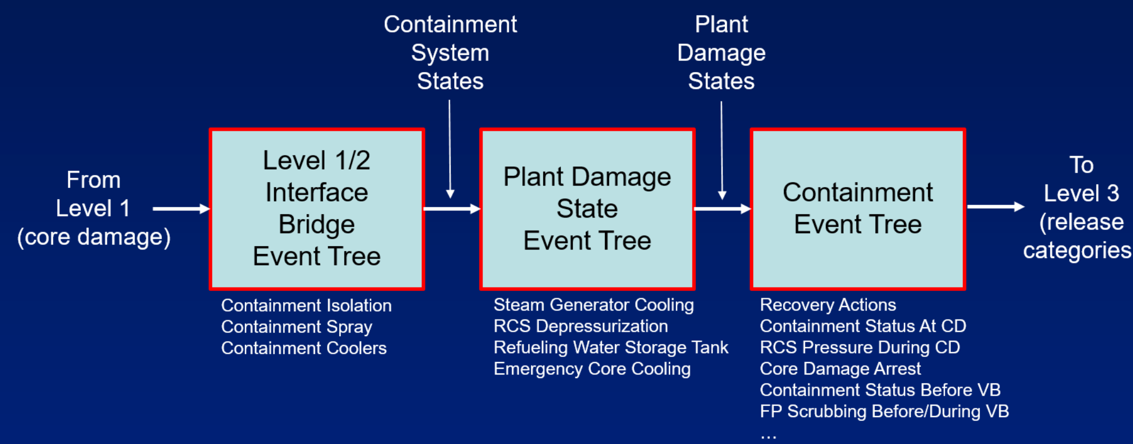
Mitigating Systems

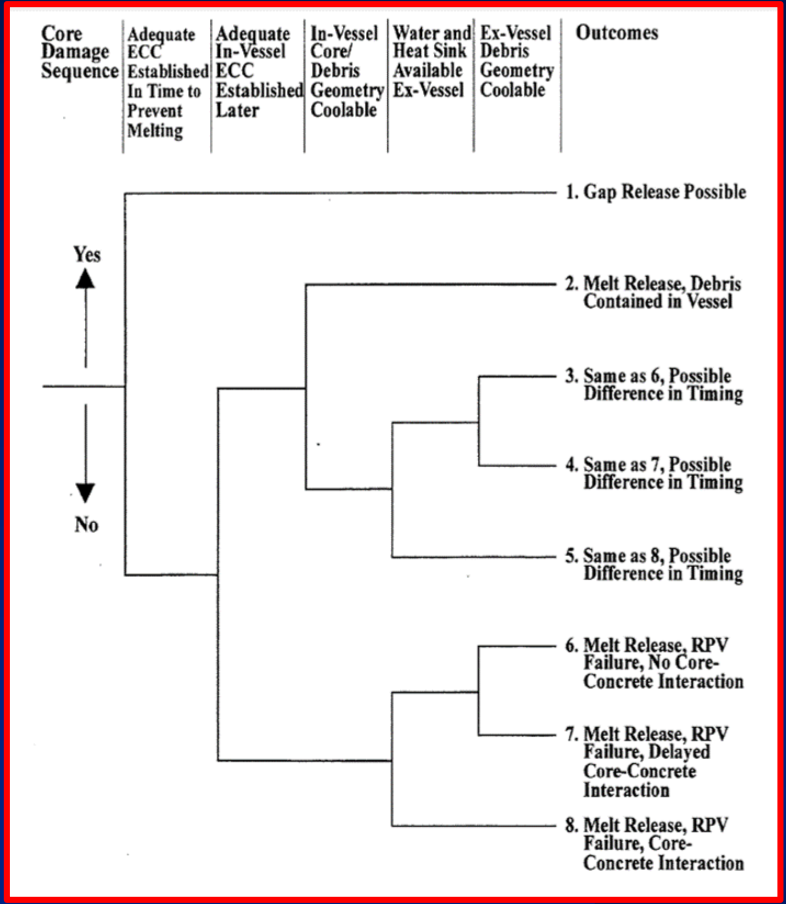
- Active Systems
  - Containment spray
  - Fan coolers
  - Hydrogen igniters
  - Isolation
  - Vents



- Analogous to Level 1 models
  - Bridge trees
  - Consider support, environmental conditions

Severe Accident Progression

- Stages
  - Core uncovery and heatup
  - Cladding oxidation
  - Fuel liquefaction and holdup
  - Core slumping/relocation
  - Lower head failure
  - Core-coolant and core-concrete interactions
- PRA Challenges
  - Selection of representative scenarios for system codes (e.g., MELCOR, MAAP)
  - Selection of simulation end time
  - Treatment of uncertainties (model and parameter)



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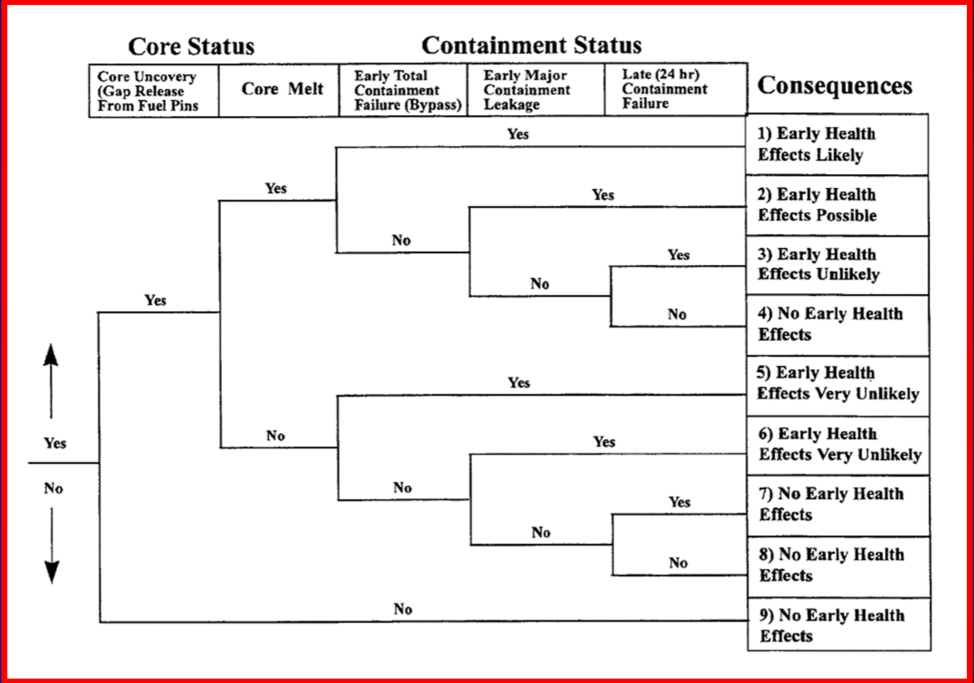
Containment Response

- Severe-accident failure mechanisms
  - Direct containment heating
  - Fuel-coolant interactions
  - Liner meltthrough
  - Hydrogen explosion
  - Long-term overpressure
- Other mechanisms
  - External missiles
  - Isolation failure
  - Bypass



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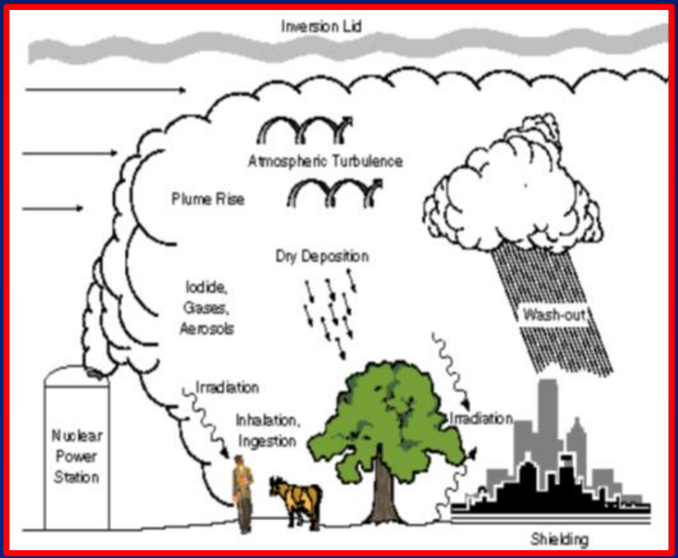
Human Reliability Analysis

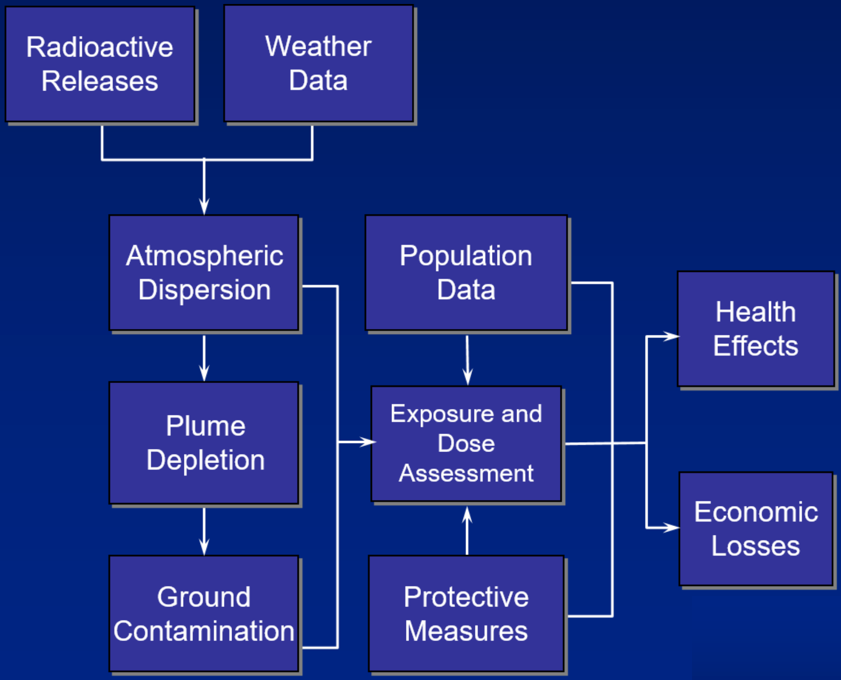
- Complications for an already difficult analysis
  - Performance for an extreme scenario that overwhelmed protection systems and caused core damage
  - Guidance rather than procedures – adherence to prioritization or selection of lower-priority options?
  - Uncertain information; don't necessarily know what PRA scenario is occurring
  - Need for field actions; potential effect from severe accident progression
  - Increased challenges from multi-unit events
  - Ex-control room organizations (Technical Support Center, offsite emergency response)
- No established standard approach; important to interview emergency response staff, observe exercises

TEPCO photo from "The Yoshida Testimony," Asahi Shinbun, 2014.

Level 3 PRA (aka Probabilistic Consequence Assessment)

Interface with Level 2 – map source term groups to release categories



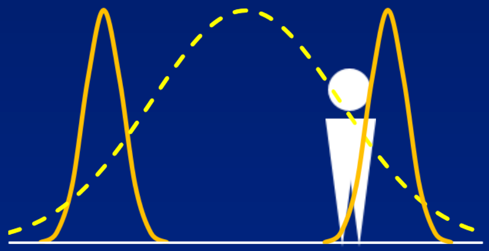


Severe Accident Consequence Analysis Codes

Code	Origin	Currently Supported	Gaussian Plume	Trajectory	Lagrangian	Met. Sampling	Exposure /Dose	Counter-measures	Early Health Effects	Latent Health Effects	Economic Impacts
CRAC/ CRAC2	USA		X			X	X	X	X	X	X
CRACIT	USA			X		X	X	X	X	X	X
ARANO	Finland		X			X	X	X	X	X	X
CONDOR	UK		X			X	X	X	X	X	X
COSYMA	EU		X	X		X	X	X	X	X	X
LENA	Sweden		X			X	X	X		X	
MACCS	USA	X	X			X	X	X	X	X	X
OSCAAR	Japan	X		X		X	X	X	X	X	
PACE	UK	X	X		X	X	X	X	?	X	X

Atmospheric Transport

- Gaussian plume model based on averaging process
- More accurate modeling might make a difference for threshold phenomena (acute fatalities, EPA PAGs)
- HYSPLIT: Gaussian "puff"
- Other considerations
  - Weather sampling
  - Correlation with plant conditions for Level 1 and 2 analyses



MACCS Transport Illustration (Video)

- Plume segments move with wind shifting from northwest to northeast
- Segment width depends on dispersion that has occurred due to varying weather conditions
- Segment length depends on wind speed

MACCS Video

Other Considerations

- Protective Actions
  - Timing
  - Compliance
  - Vulnerable cohorts
  - Correlation with initiator
  - Disruptive events
  - Non-radiological impacts
  - Long-term effects
- Dose and Effects
  - LNT
  - Compliance

What can go wrong?

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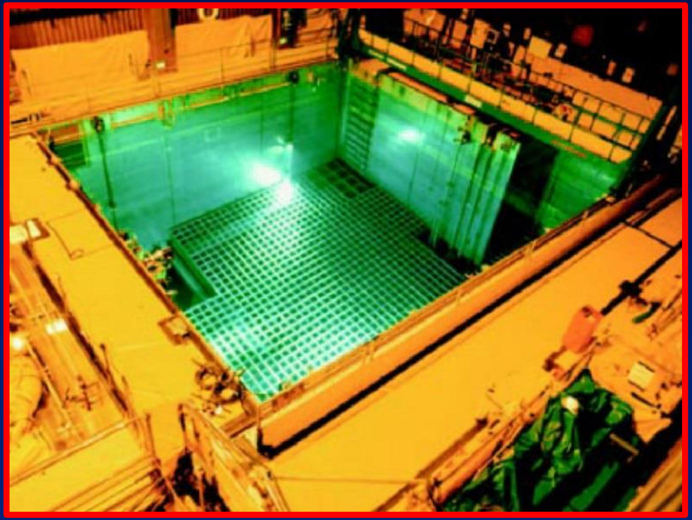
Spent Fuel Pools



- Features
  - Low decay heat levels, large water inventories
  - Strong structures
- Concerns
  - Outside containment
  - Zirconium oxidation (“fires”)
  - Combined core + SFP accident
  - Hazardous environment prior to fuel damage
- Initiators
  - Loss of inventory
  - Loss of SFP cooling
- Level 1 metric: “fuel damage frequency”
- U.S. studies include:
  - NUREG-1738 (2001)
  - Algama et al. (2013)
- International interest

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Comments

- Changing view on the nature of accidents
  - Past emphasis
    - Large, early releases => acute fatalities
    - Large, late releases => cancer fatalities, other health effects
  - Improved analyses + empirical experience
    - Low likelihood of large early doses, avoidability of late doses
    - Increased importance of: a) non-radiological effects, and b) land contamination and associated effects (psycho-social, economic)
    - Increased importance of non-atmospheric pathways
- Current Level 3 analyses are inductive; deductive approaches might be needed to confirm the above

Thought Exercise

Following the 2011 earthquake and tsunami in Japan, the Grand Duchy of Fenwick decides to hold an earthquake/flooding emergency preparedness exercise. This an expensive and disruptive undertaking and so will be done only one time. The Exercise Coordinator says she will design the scenario to ensure that all parts of the Duchy's Emergency Plan are exercised, and will develop the specific scenario elements by asking the heads of key departments (police, fire, building & safety, etc.) what they think might happen. Do you have any suggestions for her?