NSE
Nuclear Science and Engineering
science : systems : society

POTENTIAL USE OF RISK INFORMATION IN THE FUKUSHIMA DAIICHI NUCLEAR POWER PLANT DECOMMISSIONING

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BIOGRAPHICAL SKETCH

DR. MICHAEL W. GOLAY is a professor of nuclear science and engineering at the Massachusetts Institute of Technology, where he has worked since 1971. He is director of the Reactor Technology Course for Utility Executives and the Nuclear Operational Risk Management Course, both cosponsored by MIT and the National Academy for Nuclear Training. He has focused his work upon improving nuclear power performance both in the United States and internationally, particularly through use of probabilistic and dynamic methods of analysis. Recent activities include low carbon energy strategies, risk-informing nuclear enterprises and projects, and service on the National Academy of Sciences Fukushima Study Committee. He has also been an active advisor to governmental and industrial organizations, particularly concerning risk-informed regulation and decision-making under uncertainty. Professor Golay received his Ph.D. in nuclear engineering from Cornell University, and performed post-doctoral research at Rennselaer Polytechnic Institute. He was also a visiting researcher at Electricité de France. He has served on the INPO Advisory Council, the NRC's Research Review Committee, the DOE's TOPS Committee (on non-proliferation), and national laboratory and nuclear power plant oversight committees. He is a Fellow of the American Association for the Advancement of Science and of the American Nuclear Society.

PRESENTATION OUTLINE SAFETY IN FUKUSHIMA DECOMMISSIONING

- Creation of High Quality Systems and Processes – Uses Classical Method
  - High design standards
  - Deterministic performance requirements
- Risk Information – Uses Complementary Probabilistic Method for System Refinement
  - System failures and end-states
  - Deterministic and probabilistic risk analyses
  - Bayesian treatments of uncertain knowledge

CONTEXT FOR USING RISK INFORMATION

- 1. Deterministic Design, Maintenance and Processes of High Quality Systems
  - Reflecting high design standards
  - Governed by conservative, deterministic performance requirements
- 2. Use of Best-Estimate Risk Information for Improvement and Failure Prevention for These Systems
  - Identification of system failure events and outcome possibilities
  - Deterministic and probabilistic risk analyses for system performance evaluation and requirements
  - Treatments of uncertain knowledge
    - Influence and sensitivities of uncertainties
    - Bases for belief in alternative explanations

USES OF RISK ASSESSMENT RESULTS

- Quantification of Risks of Alternative Activities*
- For a Particular Activity, Identification of Most Important:
  - Risk Contributors
  - Risks Most Sensitive to Event Uncertainties
  - System Vulnerabilities (Unacceptable End-States)
  - Uncertainties in System Performance
- For a Particular Activity, Identification of Most Effective Means of Reducing:
  - System Vulnerabilities
  - System Risks

*Least valuable use of results

STRUCTURE OF RISK ASSESSMENT

- What Can Happen
- How Likely is the Event
- What are the Consequences of the Event

Risk = Expected Consequences of an Activity*

$$= \sum_{\text{Events}} \left(\text{Prob.}_{\text{Event}} \cdot \text{Consequence}_{\text{Event}} \right)$$

*e.g., Transfer of all radioactive material from Fukushima site to interim repository site

DEFINITION OF RISK

Event Risk ∫ Expected Consequences From an Event

$R_i = \langle C_i \rangle$ = (Probability of Event, i) * (Consequences of Event, i)

= [(Frequency of Event, i) * (Time Interval of Interest)] * (Consequences of Event, i)

CORE DAMAGE RISK DUE TO N DIFFERENT CORE DAMAGE EVENTS

$$R_{total} = \sum_{i=1}^{N} R_i = \sum_{i=1}^{N} p_i \begin{bmatrix} \text{Consequence}_{1,\,i} \\ \Downarrow \\ \text{Consequence}_{M,\,i} \end{bmatrix}$$

EXAMPLE OF CORE-DAMAGE ACCIDENT CONSEQUENCES

$$\begin{bmatrix}\text{Consequences of} \\ \text{Core Damage,} \\ \text{Due to Core} \\ \text{Damage Event, i}\end{bmatrix} = \begin{bmatrix}\bullet\ \text{Consequence}_{1,i} \\ \bullet\ \text{Consequence}_{2,i} \\ \Downarrow \\ \bullet\ \text{Consequence}_{M,i}\end{bmatrix} \text{e.g.,} = \begin{bmatrix}\bullet\ \text{Core Damage}_i \\ \bullet\ \text{ECCS Damage}_i \\ \bullet\ \text{Control Room Contamination}_i \\ \Downarrow \\ \bullet\ \text{Containment Damage}_i\end{bmatrix}$$

e.g., Event i Could Be a Loss-of-Coolant-Accident (LOCA)

$$R_i = \begin{bmatrix}\text{Risks Due to} \\ \text{Core Damage,} \\ \text{Event, i}\end{bmatrix} = p_i \cdot \begin{bmatrix}\bullet\ \text{Consequence}_{1,i} \\ \bullet\ \text{Consequence}_{2,i} \\ \Downarrow \\ \bullet\ \text{Consequence}_{M,i}\end{bmatrix}$$

RISK VECTOR CALCULATION

$$\overrightarrow{\text{Risk}} = \sum_{\substack{\text{All Event}\\\text{Sequences}}} \vec{C}_i \, p_i = \langle \vec{C} \rangle = \begin{bmatrix} \langle C_1 \rangle \\ \langle C_2 \rangle \\ \downarrow \\ \langle C_n \rangle \end{bmatrix}$$

$\vec{C}_i$ = Vector of consequences associated with the i^{th} event sequence

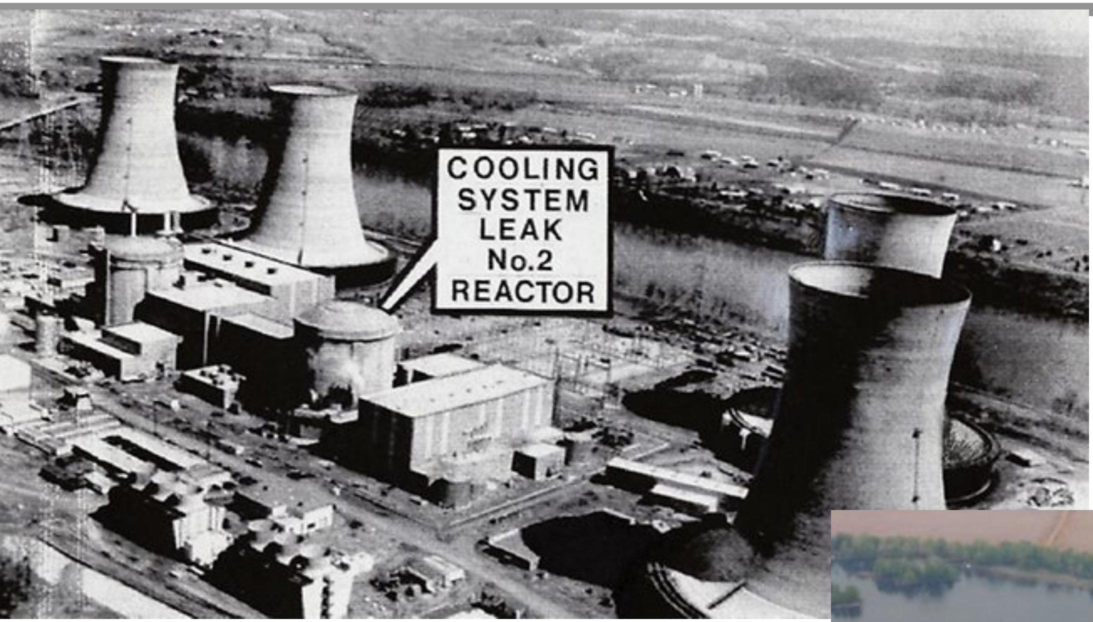
p_i = Probability of the i^{th} event sequence

$\langle \vec{C} \rangle$ = Mean, or expected, consequence vector

EXAMPLE

$$\vec{C}_i = \begin{bmatrix} \text{Offsite acute fatalities due to event i} \\ \text{Offsite latent fatalities due to event i} \\ \text{Onsite acute fatalities due to event i} \\ \text{Onsite latent fatalities due to event i} \\ \text{Offsite property loss due to event i} \\ \text{Onsite property loss due to event i} \\ \text{Costs to other NPPs due to event i} \end{bmatrix}$$

THREE MILE ISLAND (TMI)

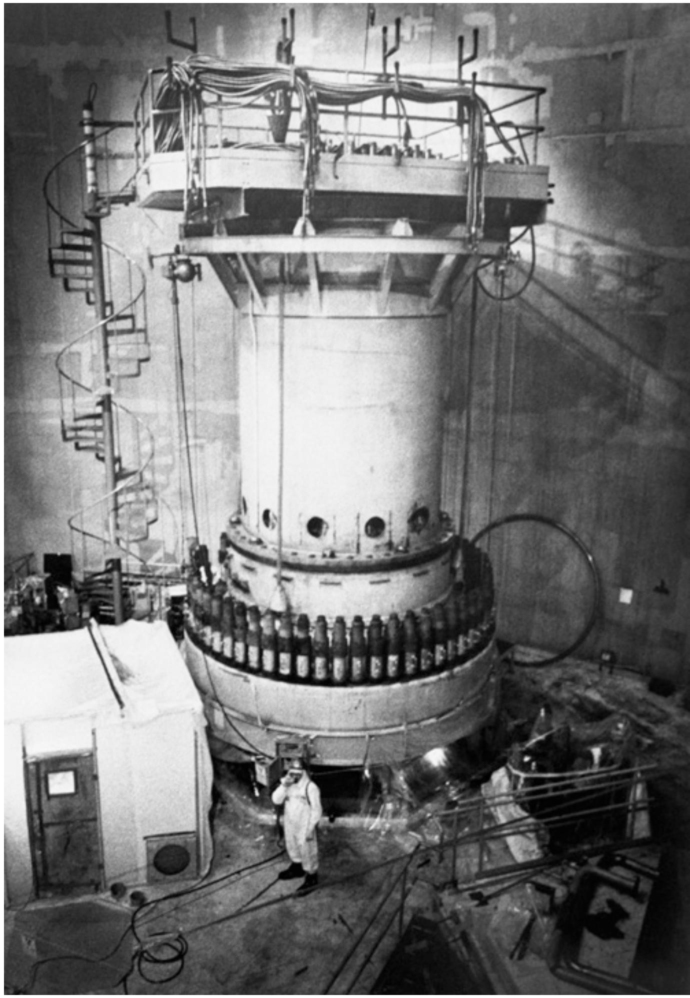


1970

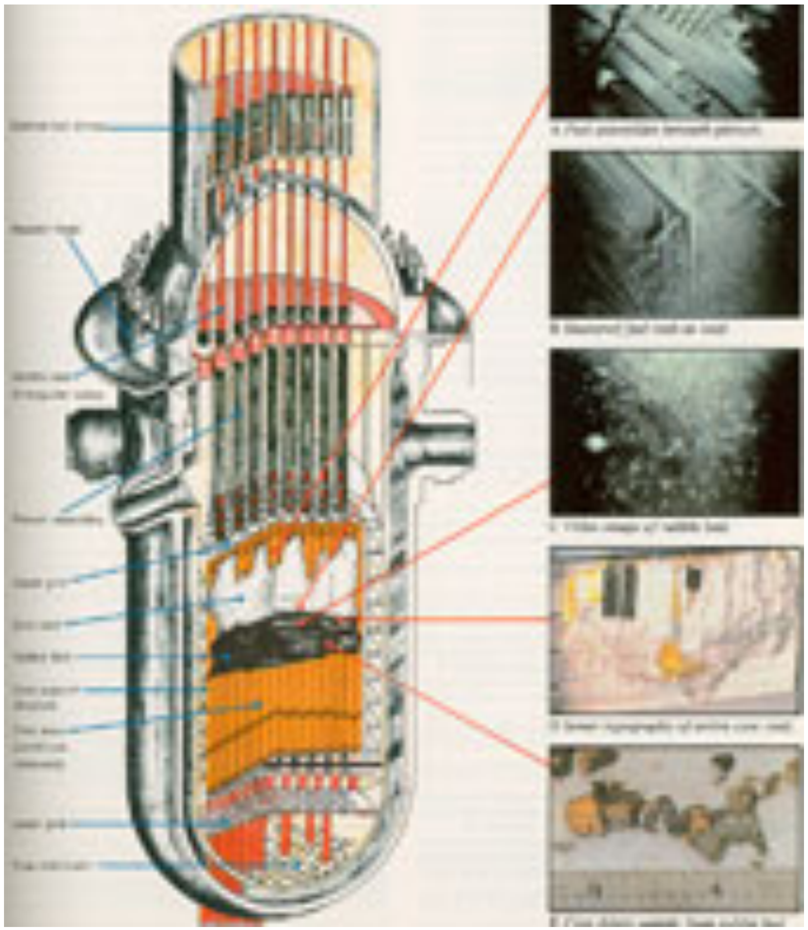
2015

INSIDE TMI

The vessel head sitting in its support stand alongside of the reactor. The head was removed to gain access to the damaged reactor

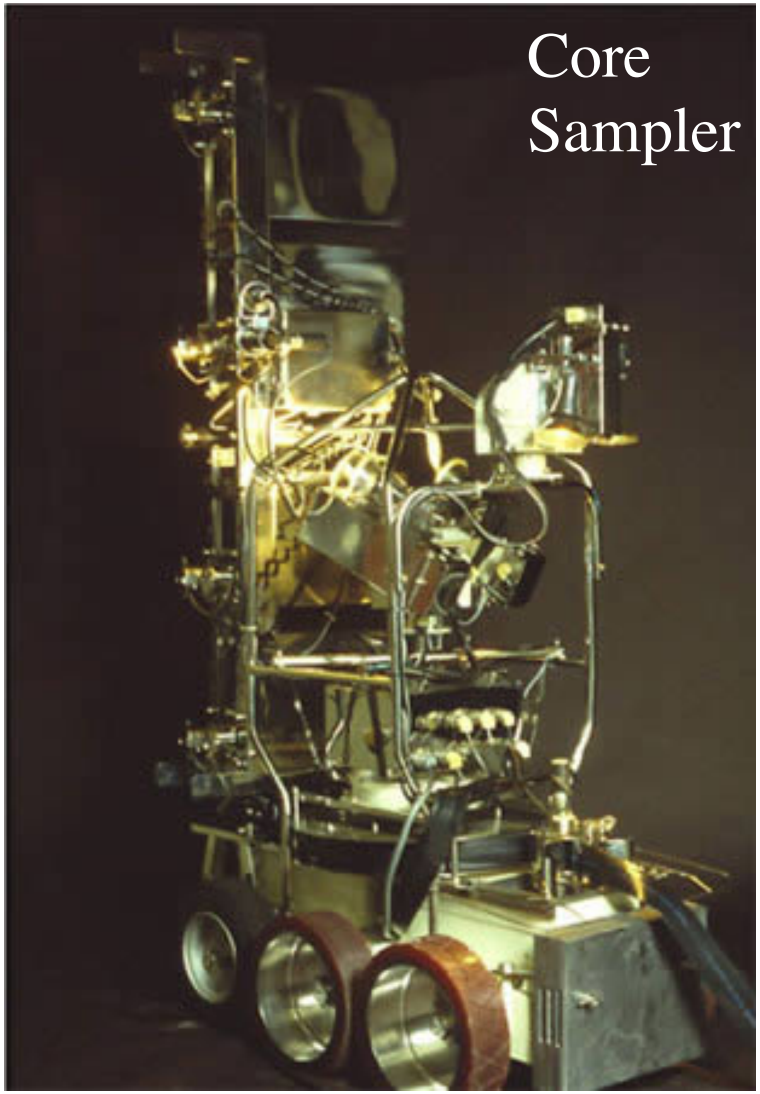


http://americanhistory.si.edu/tmi/index.htm



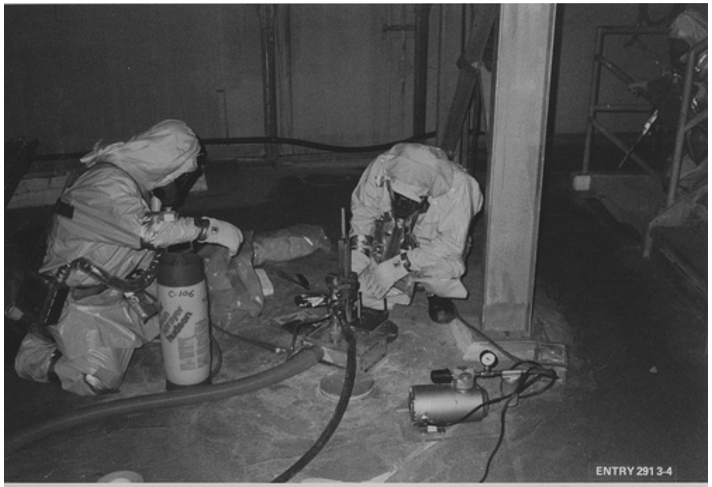
THE MACHINES THAT CLEANED UP TMI

Rover



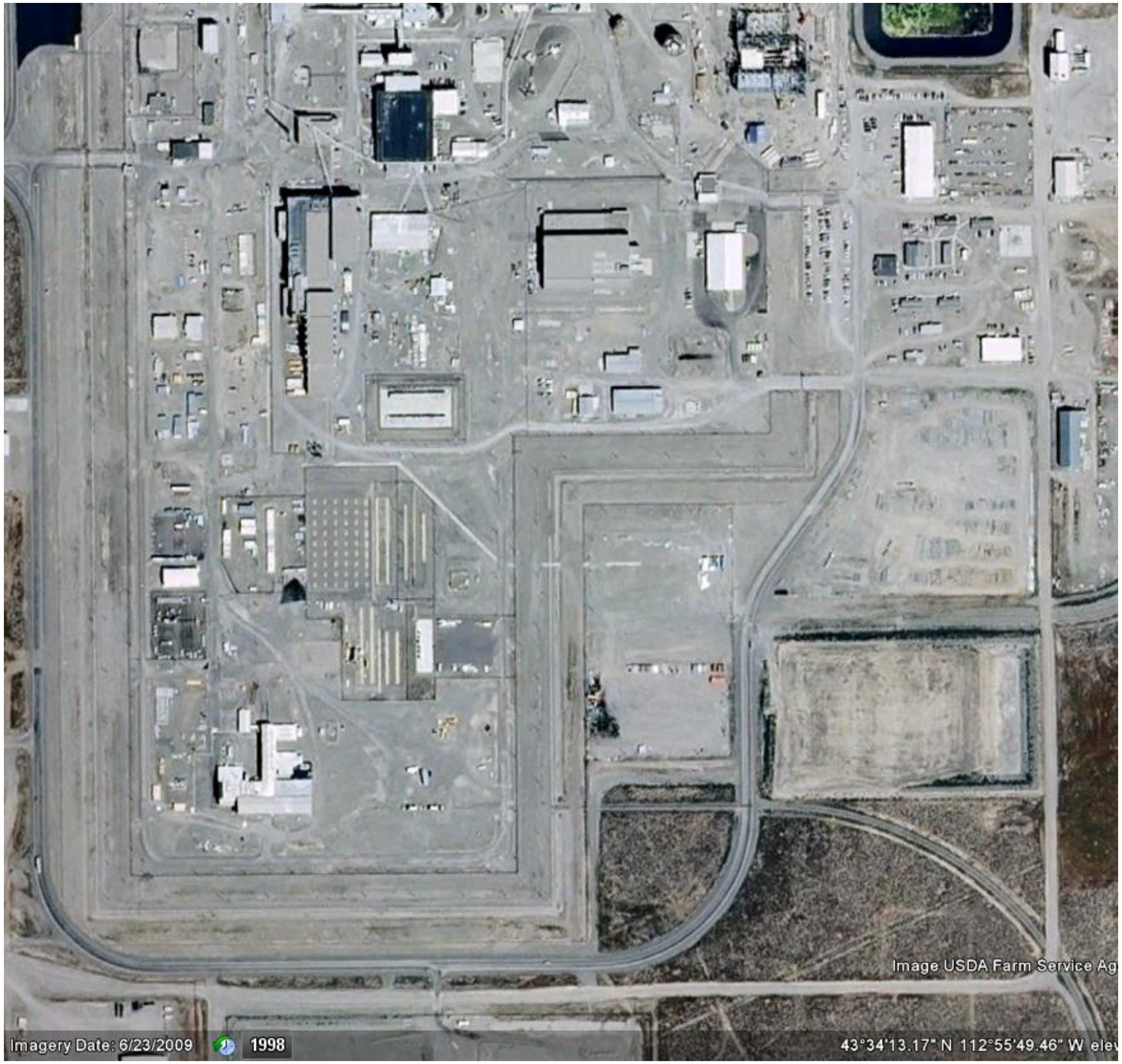
Core Sampler

TMI CLEANUP



INDEPENDENT SPENT FUEL STORAGE INSTALLATION (ISFSI) AT SHUTDOWN CONNECTICUT YANKEE SITE

IDAHO SPENT FUEL FACILITY AND THREE MILE ISLAND PLANT DEBRIS



POTENTIAL CONSEQUENCES OF CLEANUP FAILURE EVENT

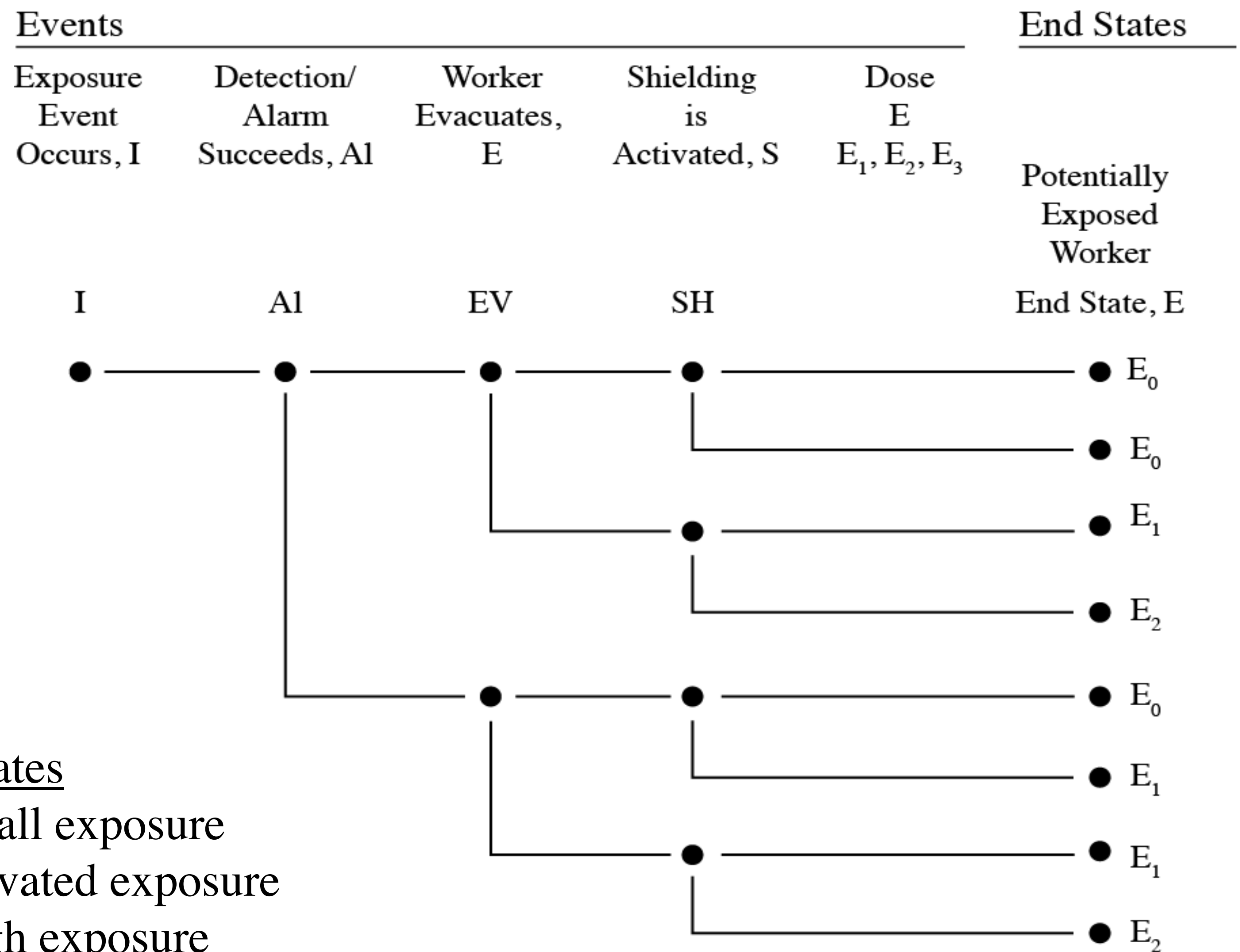
- Pollution
  - Sea
  - Ground and surface waters
  - Air
- Radiation Exposure Classes
  - Occupational
  - Public

FUKUSHIMA CLEANUP TASKS

- Outside Power Plant
  - Identification of radiation-polluted spaces
  - Collection and sequestering of contaminated materials
  - Interruption of means of radiation spreading:
    - Air/water based
- Within Power Plant
  - Identification of radiation-contaminated spaces
  - Identification and remediation of transport pathways for radioactive material
  - Pathway preparation for removal of radioactive materials
  - **Removal, packaging and transport away of radioactive materials***
  - Removal and sequestration of surface-contaminated materials
  - Removal of civil works and power conversion system materials
  - Restoration to "brown-field" power plant site conditions
  - Long-term surveillance of radioactive materials, as sequestered

*Example subject for risk-informed design and regulatory treatments

WORKER RADIATION EXPOSURE EVENT TREE



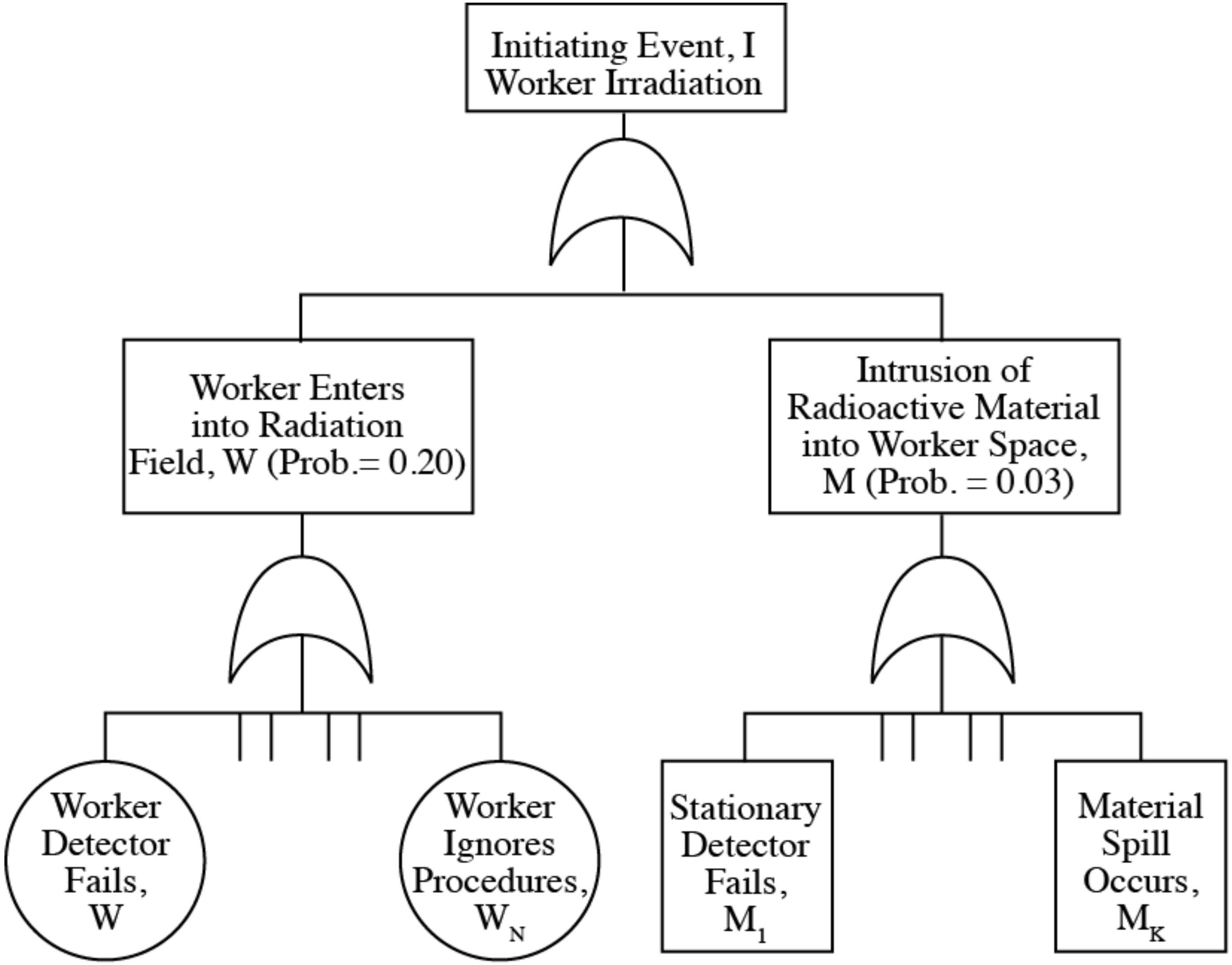
<u>End States</u>

E_0: Small exposure

E_1: Elevated exposure

E_2: High exposure

INTIATING EVENT FAULT TREE



EVENT, W, WORKER ENTERING INTO RADIATION FIELD

Probability	Event
0.20	Incorrect Worker Choices
0.1	• Worker does not follow procedure
0.1	• Worker chooses to enter radiation field
0.051	Incorrect Worker Information
0.05	• Erroneous communication
0.001	• Erroneous procedure
0.0001	• Detector failure
0.01	Negligent Worker Behavior
0.01	Shielding Error
0.27	

BOSTON USA, MBTA OPERATOR TIED OFF THROTTLE, DIDN'T SET BRAKE ON RUNAWAY TRAIN, 12/10/15

The lever used to regulate speed on a 01500 series subway car

Driverless train sped through four stations and more than 8 km with about 50 passengers on board

EVENT, M, RADIOACTIVE MATERIAL TRANSFER INTO WORKER SPACE

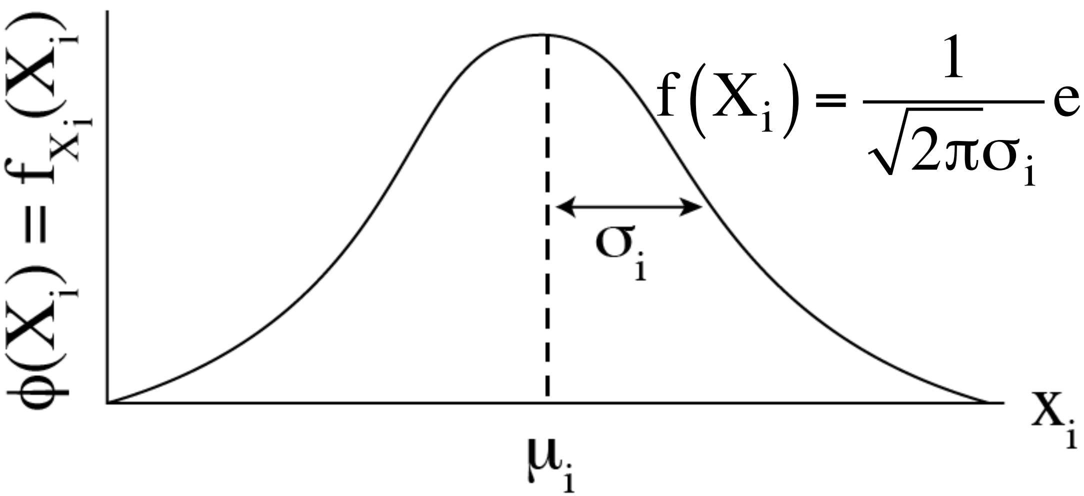
Probability	Event
0.02	Material Transfer Error
0.01	• Transfer operator error
0.001	• Transfer machine error
0.001	– Mechanical error
0.0001	– Control system error
0.01	Detector Error
0.001	Robotic Communications Error
0.0012	Cask Failures
0.001	• Cask drop and rupture
0.0001	• Cask closure failure
0.0001	• Cask fire
0.00001	• Cask random rupture
0.00001	Material Spill
0.032	

EXAMPLE PROBABILITY DENSITY DISTRIBUTION

Normal Distribution, $\phi(X_i)$,

Alternative Independent Variables, X_i:

- Distribution of radiation consequences, C; given marginal accident radiation exposure, D_A
- Event probability value; probability of spill of radioactive material of mass, M



$$f(X_i) = \frac{1}{\sqrt{2\pi}\sigma_i} e^{1/2\left(\frac{X_i - \mu_i}{\sigma_i}\right)^2}$$

X = random variable

μ_i = mean value of X_i

σ_i = standard deviation of X_i

ALTERNATIVE SYSTEM PERFORMANCE REQUIREMENTS

- Deterministic requirements
  - Are limited to small set of specified situations (DBAs)
  - Can be definitive, clear, unambiguous
  - Uncertainties remain unstated – are treated via conservative assumptions, required redundancy

- Probabilistic requirements
  - Are formulated for all end-state situations of interest (event tree branch outcomes)
  - Can be elaborate, complex
  - Use best-estimate analyses
    - Event combinations
    - Probabilities
    - Event importance and sensitivity evaluations
  - Portray uncertainty estimates quantitatively

- Both apporoaches utilize models, data, expert judgments

EXAMPLE DESIGN BASIS ACCIDENT:
MATERIAL IS SPILLED FROM TRANSFER/STORAGE CONTAINER DURING TRANSPORT BY RAIL TO IFSCE AT ROKKASHIO

- Deterministic Treatment
  - All material in a cask, M, spills into environment at location $\vec{r}'$
  - Occurs at worst place, worst population, worst time
  - Occurs with worst weather
  - No protective or evasive population protection action is allowed
  - $$\text{Population dose} = \int_{\text{all space}} d\vec{r}\, MAg(F) \left[\sum_{\text{Species Released, } i} f_i \underbrace{J_i \vec{r}'(\vec{r}' \to \vec{r})}_{\text{Transport function}} \sum_{\text{Uptake Mechanisms, } j} K_{ij} \cdot \text{Effectiveness}_i \right]$$
  - $$\text{Cumulative Dose}_{\text{Consequence}}, C = \sum_{i\text{, species released}} (MAf_i) \int_{\text{All Space}} d\vec{r}\, g(\vec{r}) \cdot J_i(\vec{r}' \Rightarrow \vec{r}) \cdot E_i \sum_{j\text{, Uptake Pathway}} k_{ij}$$

FACTORS AFFECTING TOTAL RADIATION DOSE RECEIVED BY EXPOSED POPULATION

Quality	Definition
C	Consequences to individual of exposure to dose, D
A(t)	Activity of material released
f_i	Fraction of material released of type i (Source Term)
$g(\vec{r})$	Distribution of individuals susceptible to exposure
$J_i(\vec{r} \Rightarrow \vec{r})$	Transport function, i, for movement of a unit mass of material of type, i, from spill location, $\vec{r}$; to point, $\vec{r}$, subject to current conditions**
M	Mass of material released
E_i	Dose effectiveness of exposure of individual to unit mass of material, i
K_{ji}	Uptake function for accumulation via mechanism j by individual exposed to unit mass of material, i

** Weather, wind, turbulence, rain, material condition, injection momentum, etc.

EXAMPLE LIMITED SET OF BOUNDING DESIGN BASIS ACCIDENTS (DBAs), SPECIFIED AT A SET OF TIMES AND PLACES OF OCCURRENCE

- DBA Case 1
  - All waste material in transfer container is released spontaneously in fine form
  - Weather is highly turbulent wind, at high velocity, directed toward greatest population
  - Released material is neutrally buoyant
  - Sustained rain occurs over greatest population center
- DBA Case 2
  - All waste material in transfer container is released spontaneously in fine form
  - Weather is calm, with stable stratification
  - Released material is neutrally buoyant
  - Sustained rain occurs over greatest population center
- DBA Case 3
  - All waste material in transfer container is released spontaneously in fine form
  - Weather is highly turbulent, at high velocity, directed toward great population
  - Released material is neutrally buoyant
  - No precipitation occurs over greatest population center

EXAMPLE LIMITED SET OF BOUNDING DESIGN BASIS ACCIDENTS (DBAs), SPECIFIED AT A SET OF TIMES AND PLACES OF OCCURRENCE, cont'

- DBA Case 4
  - All waste material in transfer container is released spontaneously in fine form
  - Weather is calm, with stable stratification
  - Released material is neutrally buoyant
  - No precipitation occurs over greatest population center
- DBA Case 5
  - Transfer container is exposed to sustained kerosene fire, causing material to be released in form of volatile vapors, and residual non-volatile species, escaping from transport container
  - Weather is high turbulent, at high velocity, directed toward greatest population
  - Released material is neutrally buoyant
  - Sustained rain occurs over greatest population center
- DBA Case 6
  - Transfer container is exposed to sustained kerosene fire, causing material to be released in form of volatile vapors, and residual non-volatile species, escaping from transport container
  - Weather is calm, with stable stratification
  - Released material is positively buoyant
  - Moisture precipitation does not occur

RISK-INFORMED TREATMENT OF RADIATION RELEASE EVENTS

Expected Consequence (Best Estimate-Based) of Radiation Release during Material Transfer from Fukushima to Interim Storage Site

$$\left\langle \text{Consequence} \right\rangle = \sum_{\substack{\text{Container} \\ \text{Travel} \\ \text{Segments} \\ \ell=1}}^{L} \left\langle C_\ell \right\rangle = \sum_{\ell=1}^{L} \left\langle C(D) \right\rangle_\ell = \sum_{\ell} \left\langle C(D) \right\rangle_m \sum_{n} \left(R_n \cdot J_n \right) \cdot \text{Prob}_n$$

n: released material magnitudes & types, transport + uptake categories

$$\text{Expected Consequence} = \sum_{\vec{r}} \text{People exposed at site } \vec{r} \text{ to dose, } D_{\text{Total}} \cdot \sum \text{Dose, } D_{\text{Total}}\text{, accumulated at site } \vec{r} \text{ due to release at site, } \vec{r}'\text{, and weather, J} \cdot \sum \text{Releases of type K at site } \vec{r}'$$

$$\cdot \text{Prob. (Release of type K at site } \vec{r}')$$

J reflects all sets of categories of transfer and radiation pathway mechanisms

K reflects all sets of categories of material types, magnitudes, forms released at site $\vec{r}'$

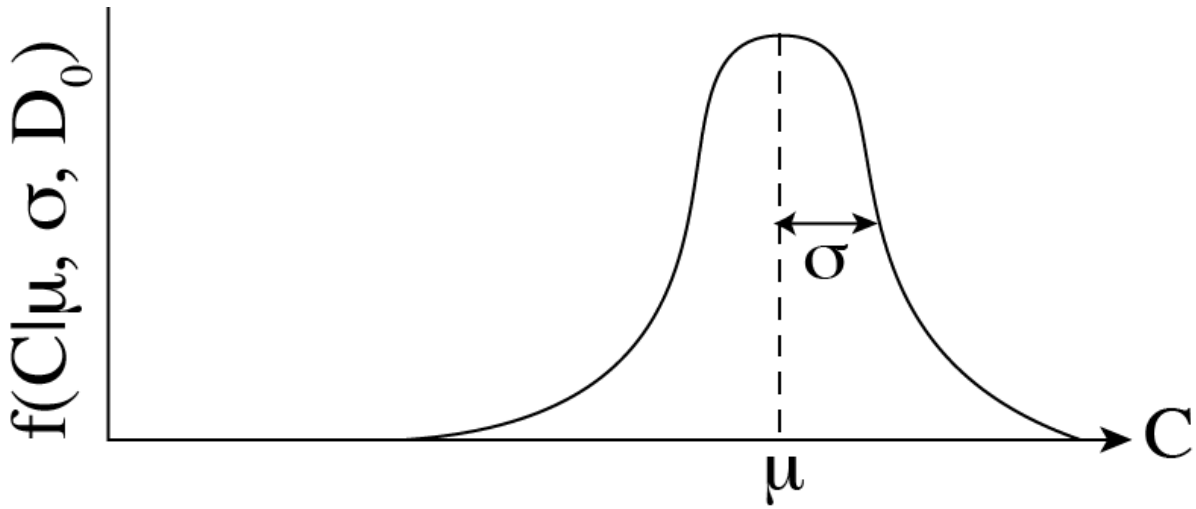
FACTORS IN RADIATION RELEASE ACCIDENT DURING RADIOACTIVE MATERIAL TRANSPORT

Symbol	Definition
C	Consequence (e.g., radiation-induced disease in an individual)
D	Radiation dose delivered to an individual at site, $\vec{r}$
ℓ	Segment of trajectory traveled by radioactive material being shipped from Fukushima to interim repository
$\vec{r}$	Site of exposure of individual
$\vec{r}'$	Site of release of radioactive material
$J_i(\vec{r}' \Rightarrow \vec{r})$	Transport function for unit material of type i released at site, $\vec{r}'$, and transported to site, $\vec{r}$
R	Release fraction of radioactive material of type i being transported by event of type n occurring at site $\vec{r}'$
M	Mass of radioactive material being transported
$Prob._n$	Probability of event of type n occurring at site $\vec{r}'$
i	ith category of radioactive material released in accident event, n, at site $\vec{r}'$

PROBABILISTIC MODELS PERMIT TREATMENTS OF VALIDITY BELIEFS OF ALTENATIVE HYPOTHESES

- Levels of belief by experts of alternative hypotheses can be stated probabilitisically
- Belief assessments can be propagated within probabilistic risk analyses to show implications for performance evaluations
- Levels of belief can be changed with logical consistency as new evidence becomes available (Bayesian updating)
- Such uses avoid the need to select among substantially uncertain hypotheses in assessing system performance, acceptability

DOSE-CONSEQUENCE MODEL

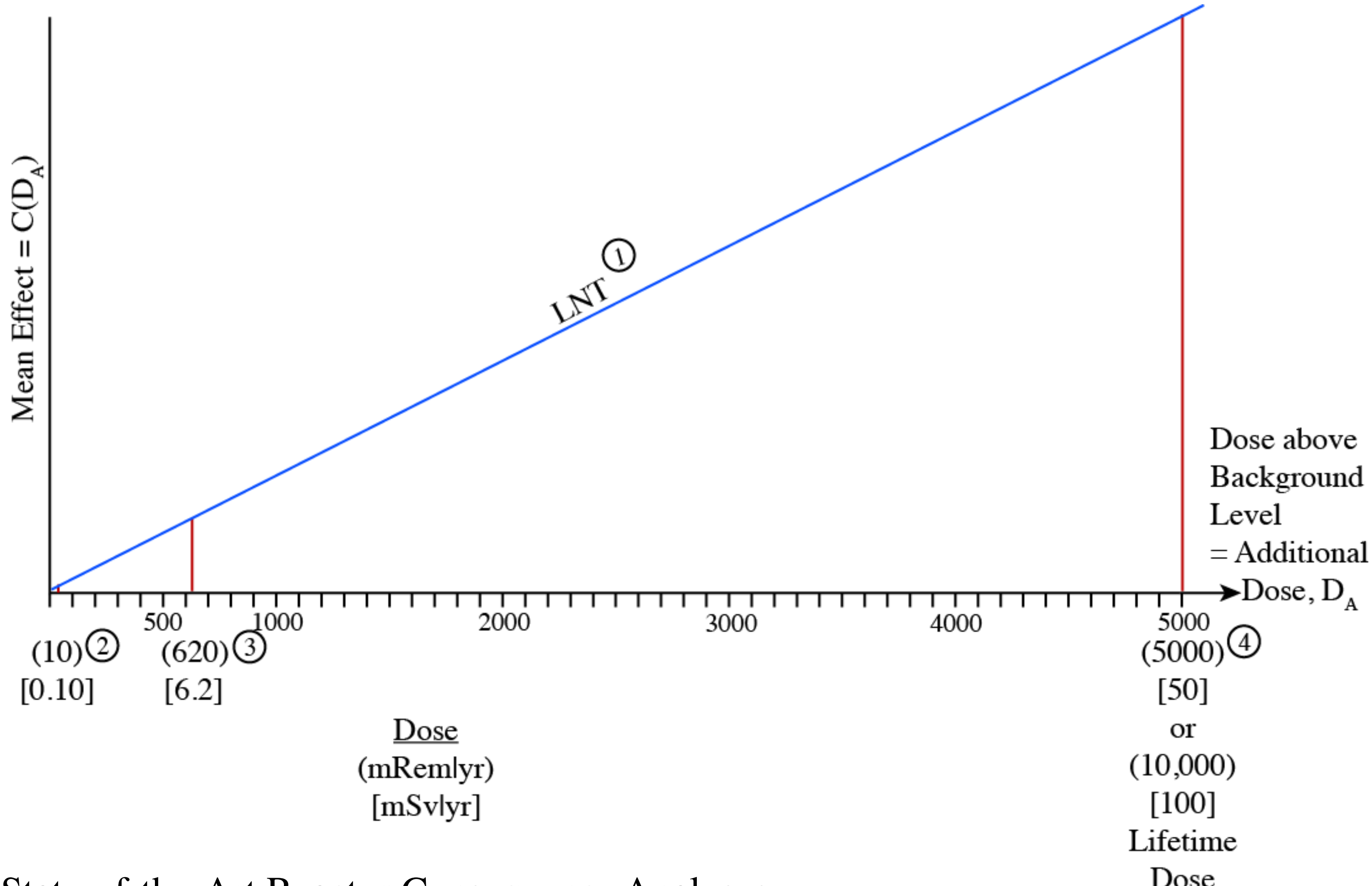


Consequences (D_0)

$D_0 = D_B + D_A$

Probability Density Function, $f(C|\mu, \sigma, D_0)$ Shows Relative Likelihood of Observing C, Given D_0

ALTERNATIVE INDIVIDUAL DOSE-EFFECT RELATIONSHIPS CONSIDERED BY NRC IN SOARCA* EXERCISE



*State-of-the-Art Reactor Consequence Analyses

LEGEND

Model Number	Model
1	Linear, No Threshold (LNT)
2	Threshold, D_T = 10 mRem/yr, 0.10 mSv/yr, LNT for $D > D_T$
3	Threshold, D_T = 620 mRem/yr, 6.20 mSv/yr, LNT for $D > D_T$
4	Threshold, D_T = 5,000 mRem/yr, 50.0 mSv/yr, or 10,000 mRem/yr, 100 mSv/yr, lifetime dose

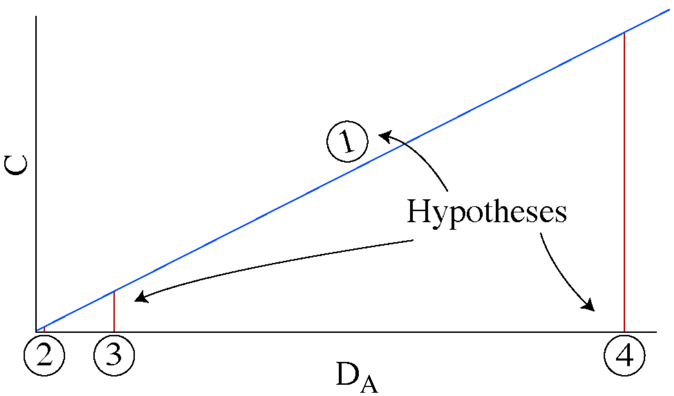
BAYESIAN EVIDENCE

Dose, D, $\Rightarrow$ Individual Consequence, C

$$P(j|E) = \frac{P(E|j)P(j)}{\sum_j P(E|j)P(j)}$$

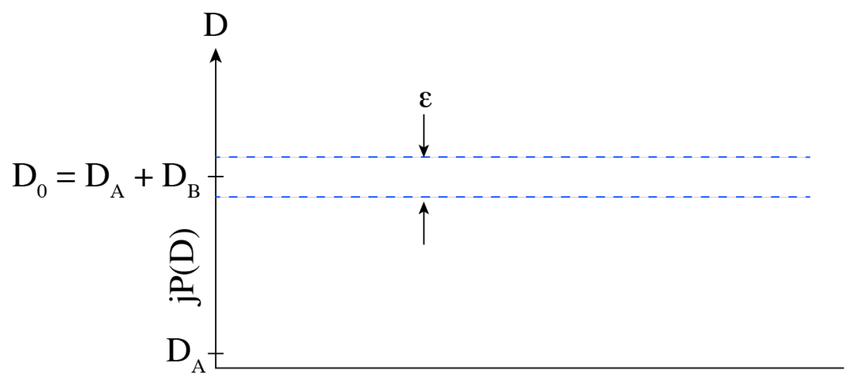
For j-th hypothesis
and Evidence, $E = C(D_0)$
D_0 = observed dose

$D_0 = D_B + D_A$
D_B = background dose exposure
D_A = additional dose exposure



Alternative Dose-Response Models Considered by NRC

$\Rightarrow$

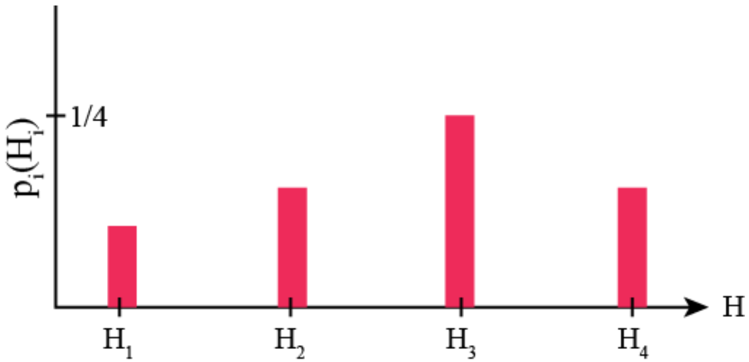


CON_{total} = Consequence due to dose exposure of accident =

$$\int_0^\infty dD_0 * H_{\text{Consequence Model*}}(C|D_0)\, g_{\text{Dose Dist}}(D_0)$$

$g_{DoseDist}$ = distribution of individuals receiving dose, D_0
$C = C(D)$ = Individual Consequence of Exposure, D_0

BAYESIAN UPDATING OF ALTERNARIVE EXPOSURE – CONSEQUENCE MODEL LIKELIHOODS



Normalization: $\sum_i p_i(H_i) = 1$

Illustrative prior hypothesis: probability distribution, $p_i(H_i)$ – describes probability that H_i is the true hypothesis

New Evidence: Exposure $D_{Observed}$ $\Rightarrow$ New Consequence: $C_{Observed}$

New Evidence: $E = C_{Observed}(D_{Observed})$

Posterior hypothesis probability distribution, $p_i'(H_i)$.

$$p_i'(H_i|E) = \frac{p(E|H_i)p_i(H_i)}{\sum_i p(E|H_i)p_i(H_i)},$$ describes revised probability that H_i is the true hypothesis, where

$p(E|H_i)$ is probability of observing evidence, E; given that H_i is the true hypothesis.

ALTERNATIVE INDIVIDUAL EXPOSURE – CONSEQUENCE MODELS

Evidence: $E = C_{Observed} = C(D_0)$; $D_{Observed} = D_{Background} + D_{Additional}$ or $D_0 = D_B + D_A$

1) Linear Model: $Prob_L\left(C \mid D_0\right) = \phi^*\left(C \mid [\mu, \sigma, D_0]\right), 0 \le C < \infty$

$$\mu = \alpha D_0, \quad \sigma = << \mu$$

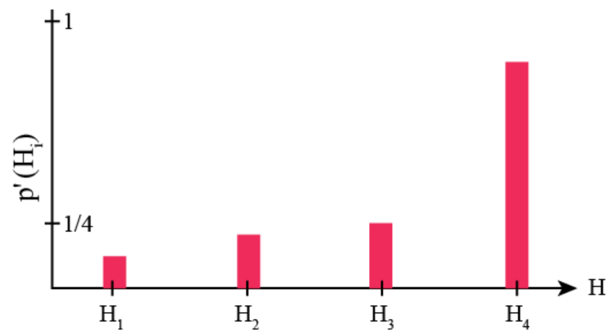
2) Threshold Model:

$$Prob_T\left(C \mid D\right) = \begin{cases} \phi\left(C \mid [\mu, \sigma, D_0]\right), \mu = \sigma D_0, \sigma << \mu, D_0 \ge D_T \\ 0, D_0 < D_T \end{cases}$$

Alternative Results:

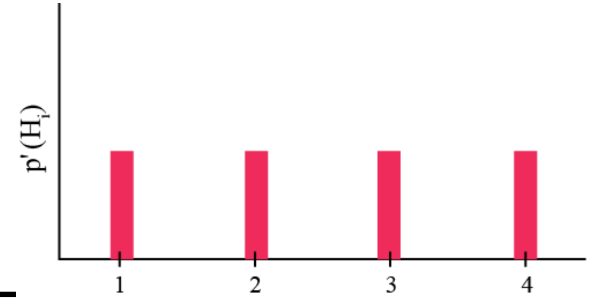
A) $C\left(D_0\right) \cong 0 << \alpha D_{0_{T_4}}$

$D_{T_3} < D_0 < D_{T_4}$ $\Rightarrow$



B) $C\left(D_0\right) \ge \alpha D_{0_{T_4}}, \; D_{T_4} >> D_{T_3} >> D_{T_2}$

$D_0 > D_{T_4}$ $\Rightarrow$



* Approximate relationship, ignore cases where $C < 0$, and re-normalize as needed over domain, $C > 0$

SUMMARY

- Risk information can be used for improvement of previously-created systems
- Risk analysis permits consideration of:
  - All system performance contributors, situations
  - Relative importance of individual system performance contributors
  - Effects of uncertainties
- PRA offers a complementary alternative to deterministic treatments of system performance – evaluations, requirements
- Bayesian analyses permit implications of alternative hypotheses to be accommodated in decision support

Backup Slides

DEFINITION OF RISK

Event Risk ∫ Expected Consequences From an Event

$R_i = \langle C_i \rangle$ = (Probability of Event, i) * (Consequences of Event, i)

= [(Frequency of Event, i) * (Time Interval of Interest)] * (Consequences of Event, i)

CORE DAMAGE RISK DUE TO N DIFFERENT CORE DAMAGE EVENTS

$$R_{total} = \sum_{i=1}^{N} R_i = \sum_{i=1}^{N} p_i \begin{bmatrix} \text{Consequence}_{1,\, i} \\ \Downarrow \\ \text{Consequence}_{M,\, i} \end{bmatrix}$$

EXAMPLE OF CORE-DAMAGE ACCIDENT CONSEQUENCES

$$\begin{bmatrix} \text{Consequences of} \\ \text{Core Damage,} \\ \text{Due to Core} \\ \text{Damage Event, i} \end{bmatrix} = \begin{bmatrix} \bullet\ \text{Consequence}_{1,i} \\ \bullet\ \text{Consequence}_{2,i} \\ \Downarrow \\ \bullet\ \text{Consequence}_{M,i} \end{bmatrix} \text{e.g.,} = \begin{bmatrix} \bullet\ \text{Core Damage}_i \\ \bullet\ \text{ECCS Damage}_i \\ \bullet\ \text{Control Room Contamination}_i \\ \Downarrow \\ \bullet\ \text{Containment Damage}_i \end{bmatrix}$$

e.g., Event i Could Be Core Damage, due to a Loss-of-Coolant-Accident (LOCA) Initiating Event

$$R_i = \begin{bmatrix} \text{Risks Due to} \\ \text{Core Damage,} \\ \text{Event, i} \end{bmatrix} = p_i \cdot \begin{bmatrix} \bullet\ \text{Consequence}_{1,i} \\ \bullet\ \text{Consequence}_{2,i} \\ \Downarrow \\ \bullet\ \text{Consequence}_{M,i} \end{bmatrix}$$

CUT SETS AND MINIMAL CUT SETS

CUT SET: A cut set is any set of failures of components and actions that will cause system failure.

MINIMAL CUT SET: A minimal cut set is one where failure of every set element is necessary to cause system failure. It does not contain another cut set.

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RISK IMPORTANCE MEASURES

$$\text{Risk} = R(q_1, q_2, \ldots, q_n),$$

where

r_i = reliability of the i^{th} plant component, action, or cut set

q_i = unreliability of the i^{th} component = 1 - r_i

$I_{\text{Fussell-Vesely}_i}$ = the fraction of total risk involving failure of element, i

$$I_{\text{Fussell-Vesely}_i} = \frac{R(q_i)}{R_{Nom}} = \frac{R\left(mcs_{i_1} + mcs_{i_2} + \cdots + mcs_{i_m}\right)}{R\left(mcs_1 + \cdots + mcs_n\right)}$$

where

$R(q_i)$ = risk arising from event sequences involving failure of component, action or cut set, i

R_{Nom} = nominal plant risk

m = number of minimal cut sets involving element (basic event) i

n = total number of minimal cut sets

RISK IMPORTANCE MEASURES

Risk Achievement Worth (RAW_i) Maximum relative possible increase in total risk due to failure of element, i; the element is assumed always to fail (failure event probability, $q_i = 1$).

$$RAW_i = \frac{R(q_i = 1)}{R_{Nom}}$$

where

RAW_i = the risk achievement worth of the i^{th} component, action or cut set

RISK IMPORTANCE MEASURES

Risk Reduction Worth (RRW_i) = Maximum possible relative reduction in risk due to perfection of event i reliability; the component is assumed always to succeed every time (failure event probability, q_i = 1).

$$RRW_i = \frac{R_{Nom}}{R(q_i = 0)}$$

where

RRW_i = the relative risk decrease importance of the i^{th} component, action or cut set

USES OF RISK IMPORTANCE MEASURES

- **Fussell-Vesely**
  - Measure a Component's or System's Participation in Risks
  - Can Be Used to Identify Which Components or Systems Contribute to Current Risks
- **Risk Achievement Worth**
  - Identifies Which Components or Systems Must Be Kept Reliable
- **Risk Reduction Worth**
  - Identifies Which Components or Systems Are Most Valuable for Improvement
  - Note

$$I_{Fussell-Vesely_i} = 1 - \frac{1}{RRW_i}$$

LECTURE OBJECTIVES

INTRODUCTION OF THE BASIC ELEMENTS OF PROBABILISTIC RISK (PRA) ANALYSES

- Risk
- PRA Structure
- PRA Results
- PRA Importance Measures

STRUCTURE OF RISK ASSESSMENT

- What Can Happen
- How Likely is the Event
- What are the Consequences of the Event

$$\text{Risk} = \text{Expected Consequences of an Activity*}$$

$$= \sum_{\text{Events}} \left(\text{Prob.}_{\text{Event}} \cdot \text{Consequence}_{\text{Event}}\right)$$

*e.g., Transfer of all radioactive material from Fukushima site to interim repository site

USES OF RISK ASSESSMENT RESULTS

- Quantification of Risks of Alternative Activities*
- Identification of Most Important Contributors to Risks of a Particular Activity
- Identifications of Contributors to Risks of a Particular Activity that are Most Sensitive to Uncertainties
- Identification of Most Important System Vulnerabilities
- Identification of Most Effective Means of Reducing System Vulnerabilities
- Identification of Most Effective Means of Reducing System Risks
- Identification of Most Important Uncertainties in System Performance
- Identification of Most Effective Means of Reducing Sensitivity of Risks to Uncertainties

*Least valuable use of results

IDAHO NATIONAL LABORATORY (INL) SPENT FUEL STORAGE FACILITY

The Department of Energy stores three metric tons of spent fuel in pools like this at the Idaho National Laboratory, and 277 metric tons stored in dry casks