

Quantifying the Risk of Nuclear Fuel Recycling Facilities

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Statement of Purpose

To discuss the safety analysis of nuclear fuel recycling plants and in particular to consider how quantitative risk assessment (QRA) might be applied to assess the radiological risk of the operation of such plants

Fundamentals of QRA

- **Step 1. Define the system in terms of what constitutes normal operation**
- **Step 2. Identify and characterize the sources of danger, that is, the hazards**
- **Step 3. Develop “what can go wrong” scenarios and “damage states”**

Fundamentals of QRA (cont'd)

- **Step 4. Quantify the likelihoods of the different scenarios and damage states**
- **Step 5. Assemble the scenarios into appropriate measures of risk**
- **Step 6. Interpret the results to guide the risk management process**

Basic Principles

- **Triplet definition of risk**
- **Scenarios linking threats to consequences**
- **Quantification of uncertainties**
- **“Credibility” definition of probability**
- **Bayesian inferential reasoning**

Our Meaning of Risk

Asking the question, “what is the risk of something” requires answers to the following questions:

- What can go wrong?**
- If something goes wrong, how likely is it?**
- What are the consequences?**

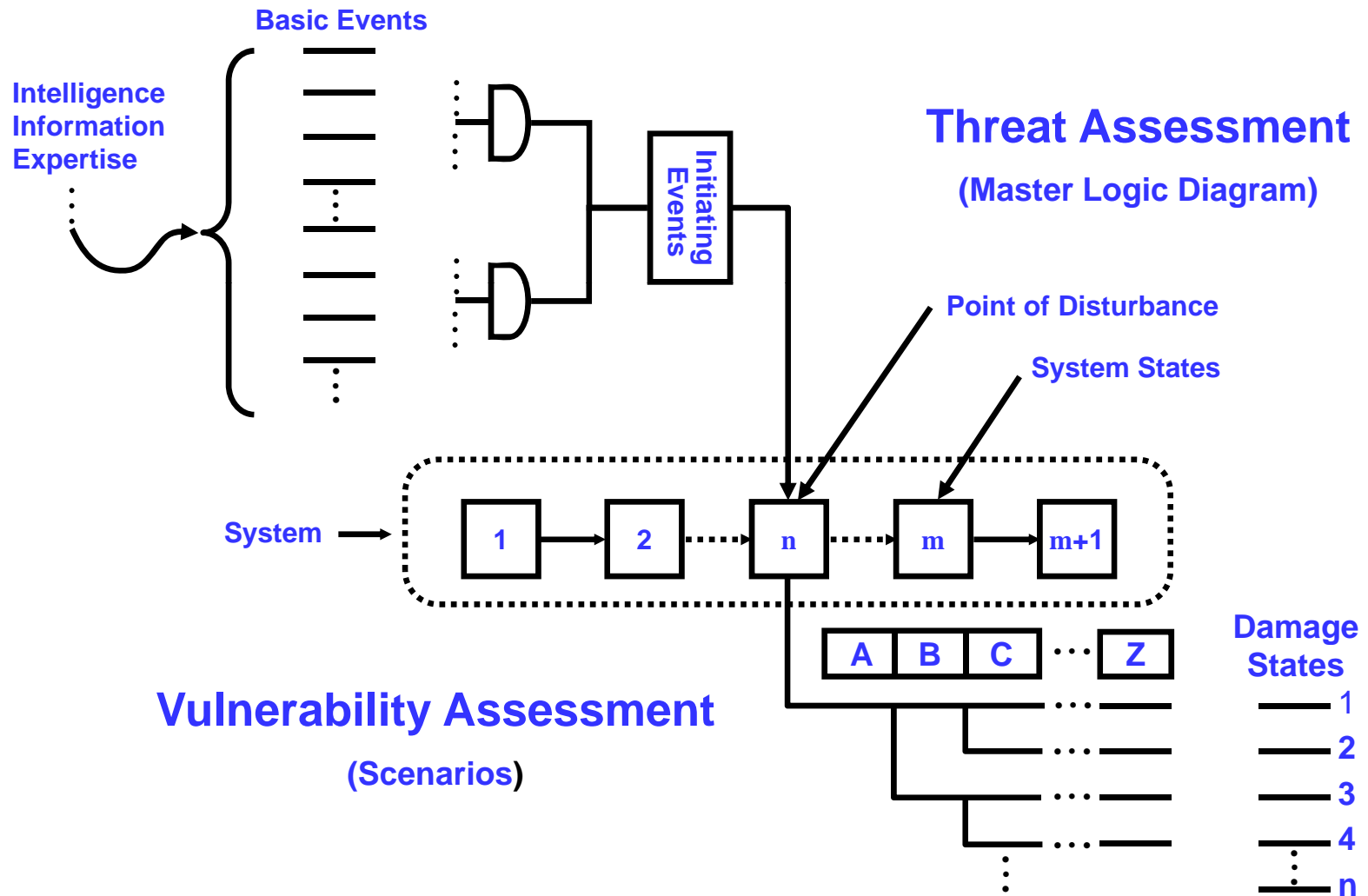
Set of Triplets Definition of Risk

$$R = \{ \langle \mathbf{s}_i, \mathbf{L}_i, \mathbf{x}_i \rangle \}_c$$

Structuring the Scenarios

- **System analysis (success scenario)**
- **Threat analysis (initiating events)**
- **Vulnerability analysis (consequences)**

Linking of Threats and Consequences



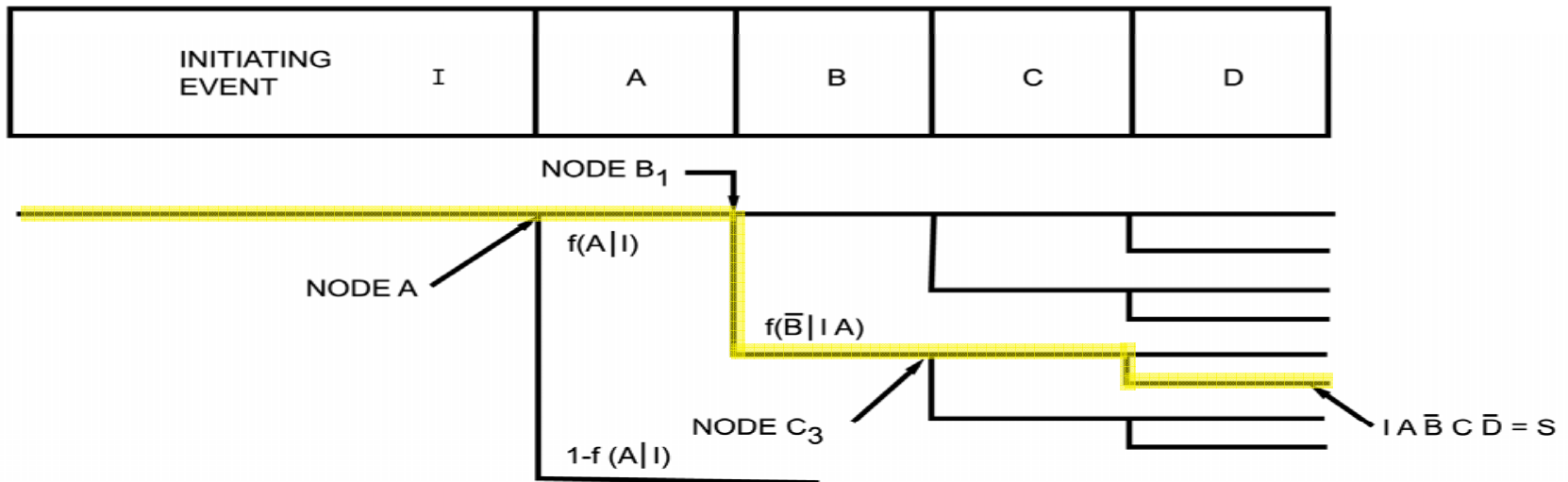
Threat Types

- **Internal:** Fires, explosions, equipment failure, operator error, instrument malfunction, criticality events, process malfunctions, power disruptions, structural failures, deliberate human acts, failure to follow procedures or believe the instruments
- **External:** Fires, loss of external power supplies, loss of other utilities, severe storms, sitewide pipeline and utility accidents, seismic events, hurricanes, tornadoes, nearby facility accidents, site intrusions, toxic gas releases, transportation accidents, volcanoes, surface geology, lightning, flooding events

Threat Categories

- **Disruptive Events:** Events that cause an immediate change to the facility. They are typically characterized by an event occurrence frequency and by directly measurable immediate consequences. Examples are severe storms, tornadoes, earthquakes, fires, and airplane crashes.
- **Nominal Events and Processes:** Expected events and natural processes that evolve continuously over the life of the facility. They are typically characterized by a rate, which may be constant or changing over time. The potential consequences from these processes depend on the duration of the exposure period. An example is the aging of engineered and natural systems.

Scenarios



$$S = I A \bar{B} C \bar{D}$$

$$\phi(S) = \phi(I) f(A|I) f(\bar{B}|IA) f(C|I A \bar{B}) f(\bar{D}|I A \bar{B} C)$$

Quantification

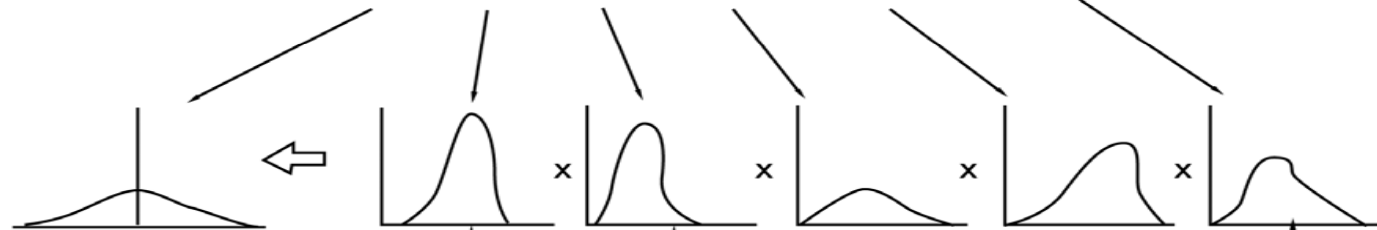
SCENARIO
BOOLEAN
EQUATION

$$S = I\bar{A}\bar{B}\bar{C}\bar{D}$$

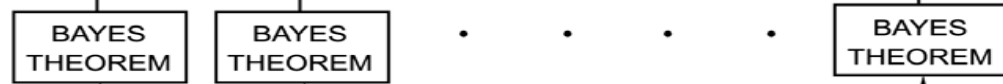
FREQUENCY
EQUATION

$$\phi(S) = \phi(I) f(A/I) f(\bar{B}/IA) f(C/I\bar{A}\bar{B}) f(\bar{D}/IABC)$$

UNCERTAINTY
PROPAGATION



BAYESIAN
INFERENCE



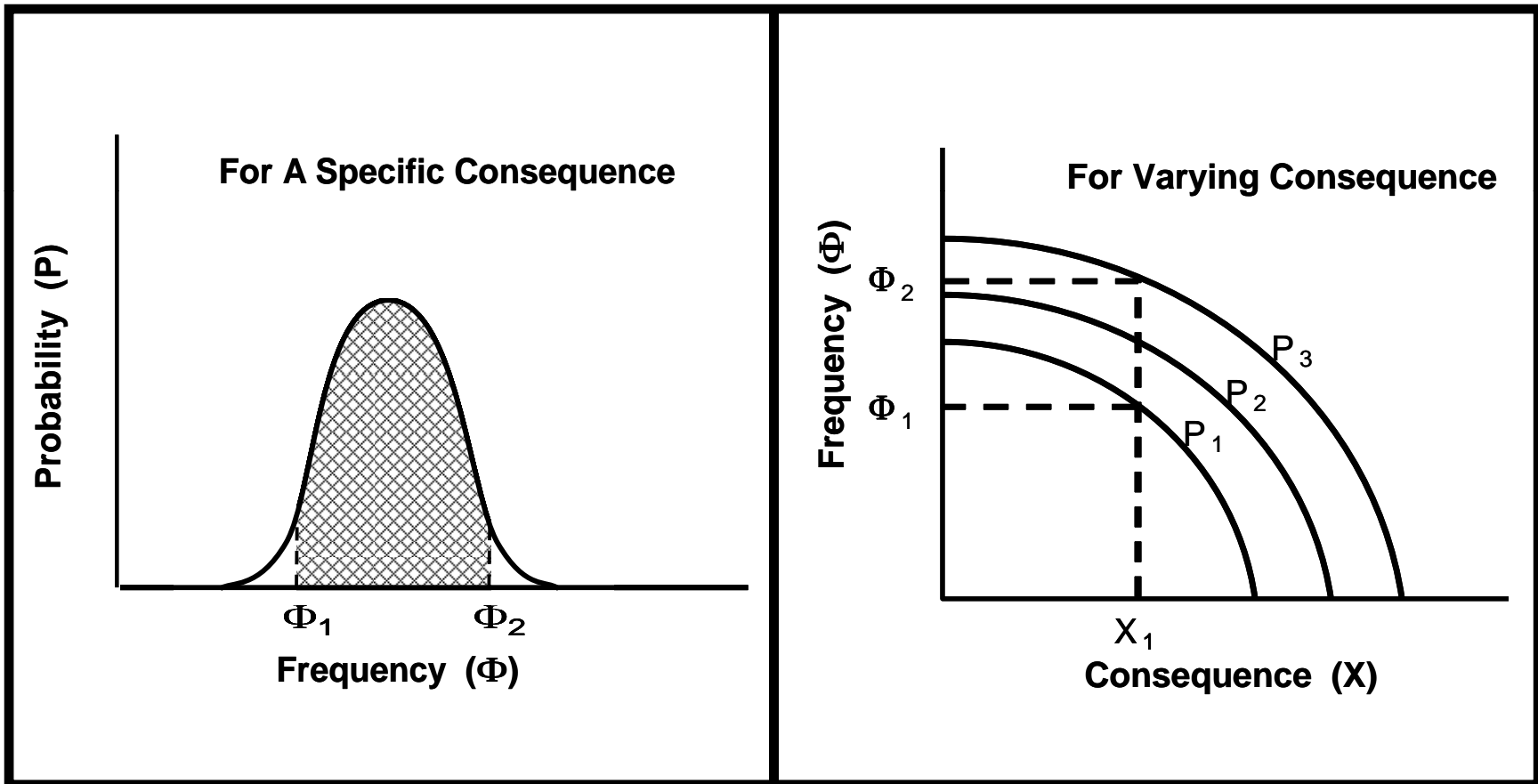
EVIDENCE
SETS



Probability and Bayes Theorem

- **Probability is the “credibility” of a hypothesis based on all the available evidence and is a positive number ranging from 0 to 1 that obeys Bayes theorem**
- **Bayes theorem answers the question, how does the probability of a given hypothesis change with new information**

Form of the Results



Safety Experience of Nuclear Fuel Recycling Plants

- **No operating plants in U.S.**
- **Plants in France, United Kingdom, Japan, and Russia**

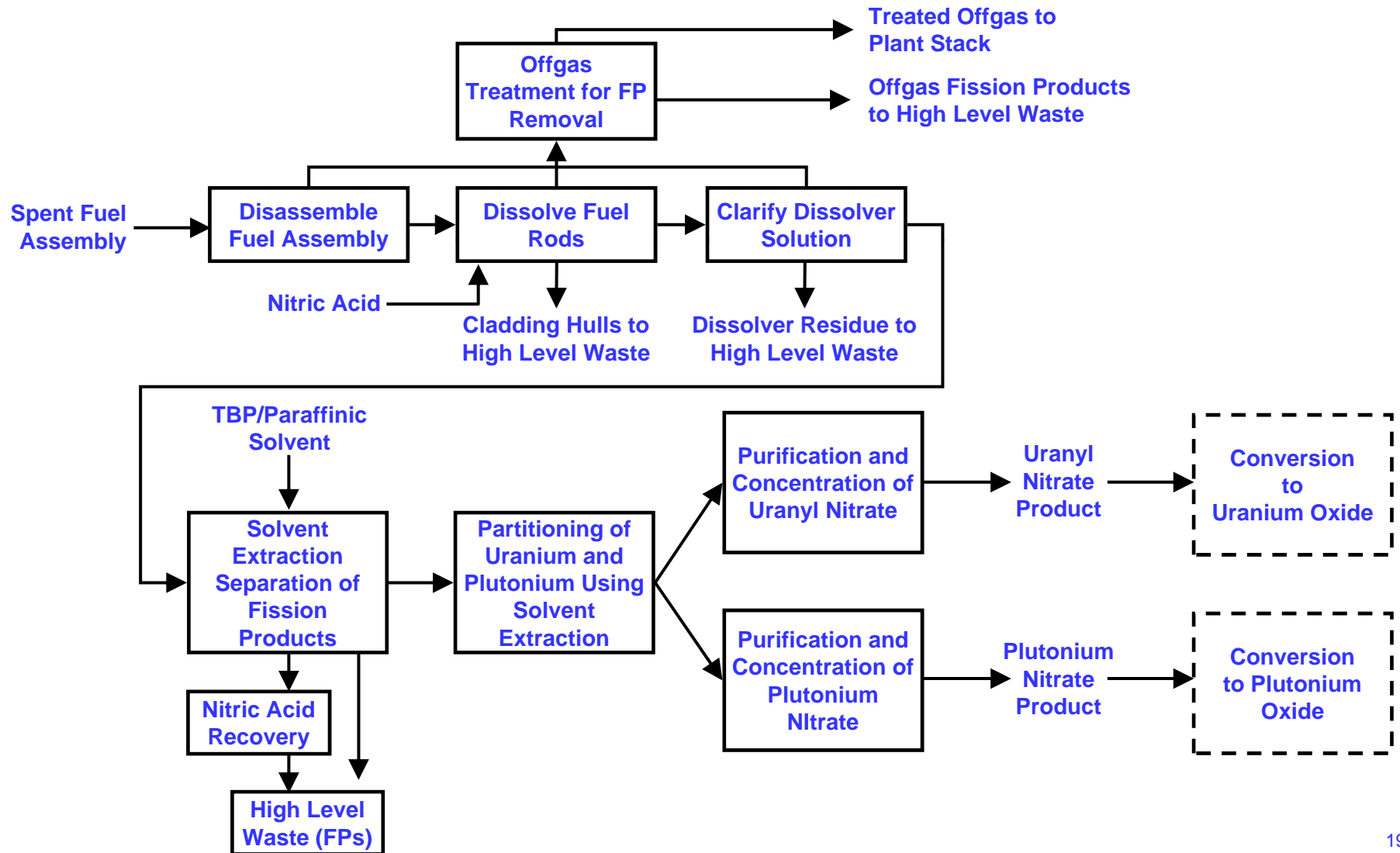
Past U.S. Experience

- **Government plants in Savannah River, Hanford, and Idaho**
- **West Valley, New York**

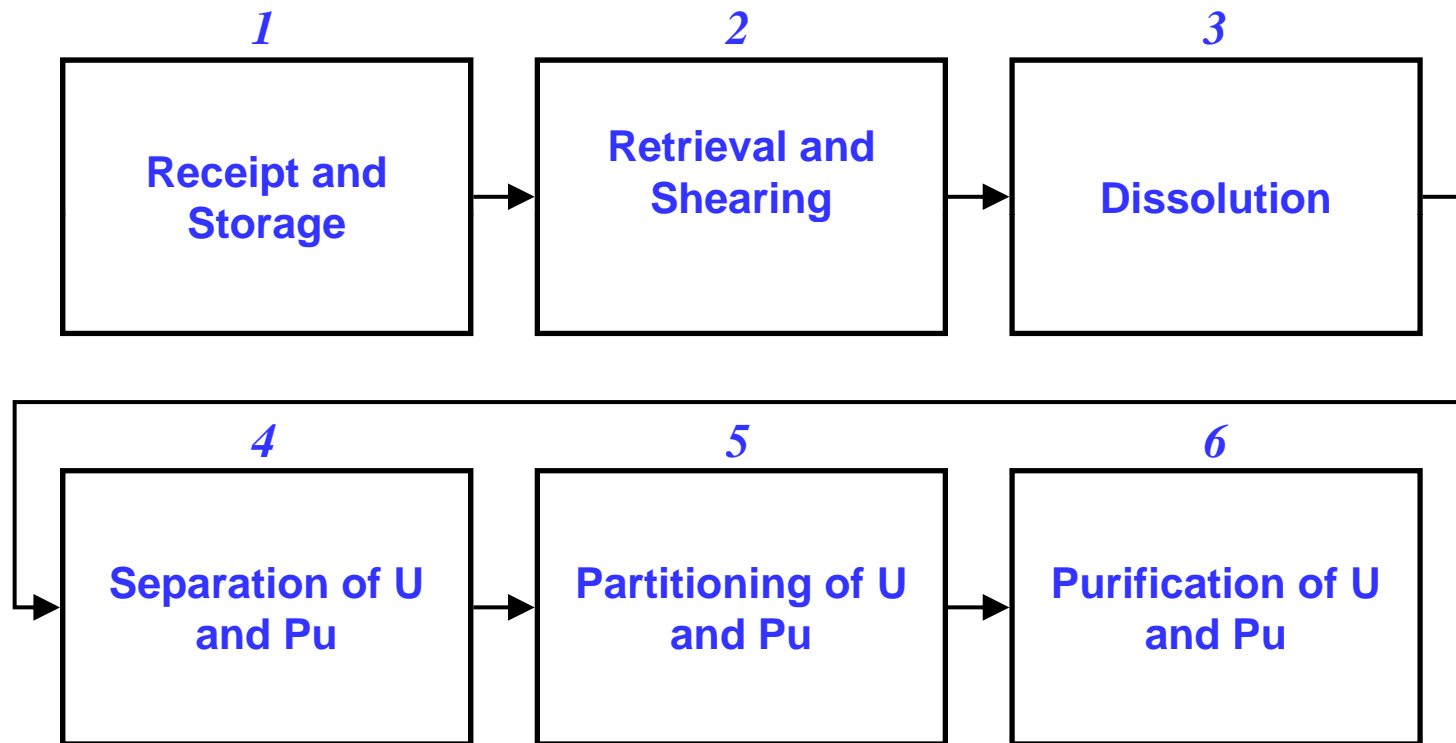
Recycling Plant Incidents

- **Red oil incidents: Hanford 1953, Savannah River 1953 and 1957, Oak Ridge 1959, Canada 1980, and Russia 1993**
- **Criticality: Russia 1968 and Japan 1999**
- **Leaks, spills, and releases: All, including West Valley**
- **Waste tank explosion: Russia 1957**

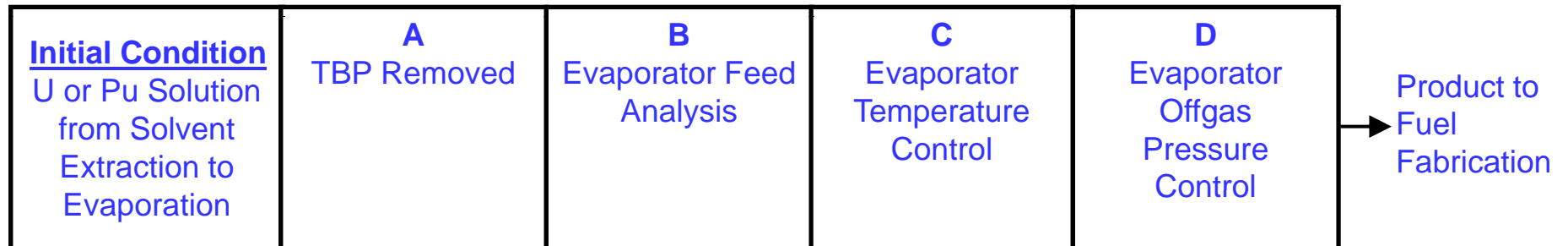
Simplified PUREX Process Flow Chart



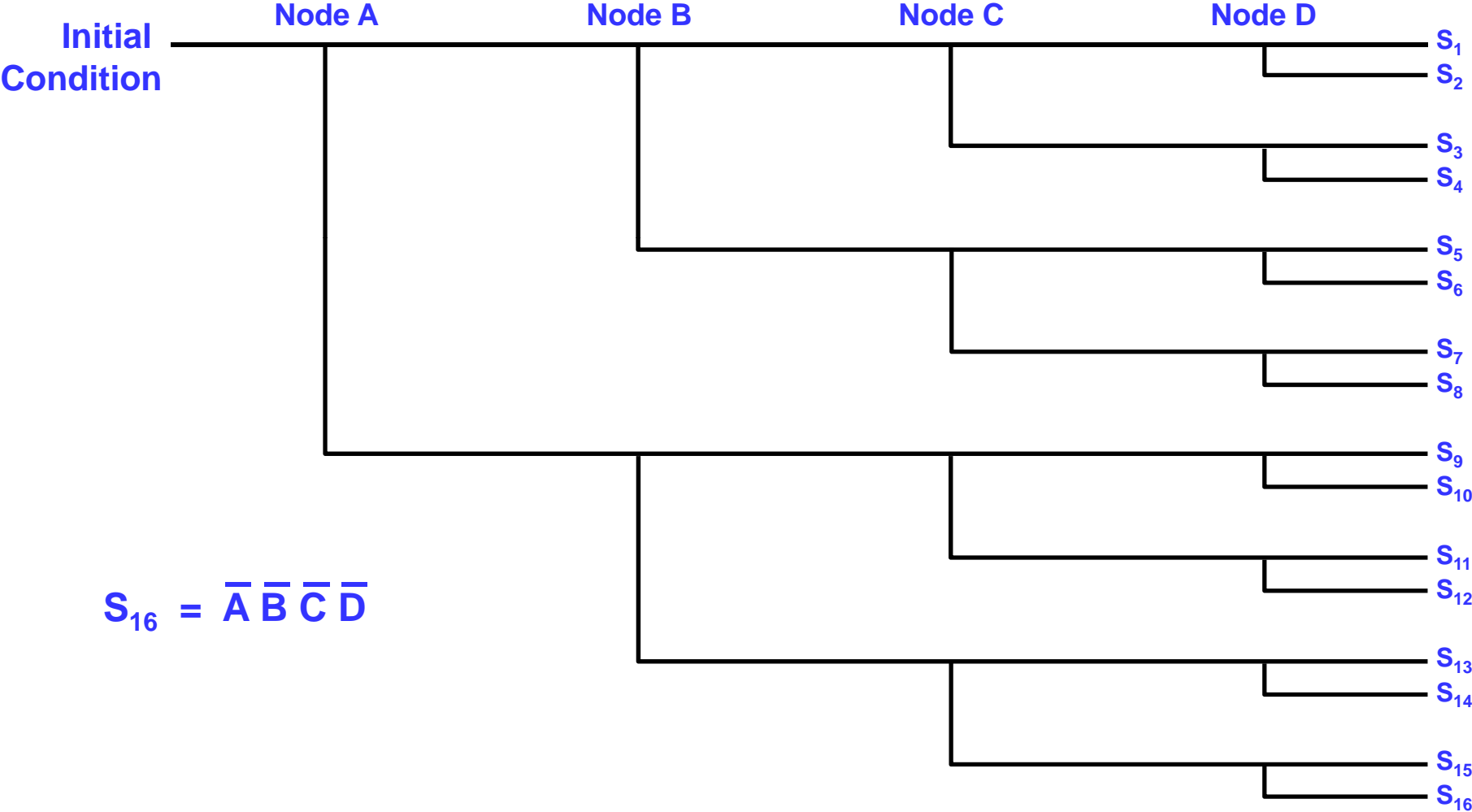
System Success Diagram



Concentration and Purification of U and Pu Nitrates



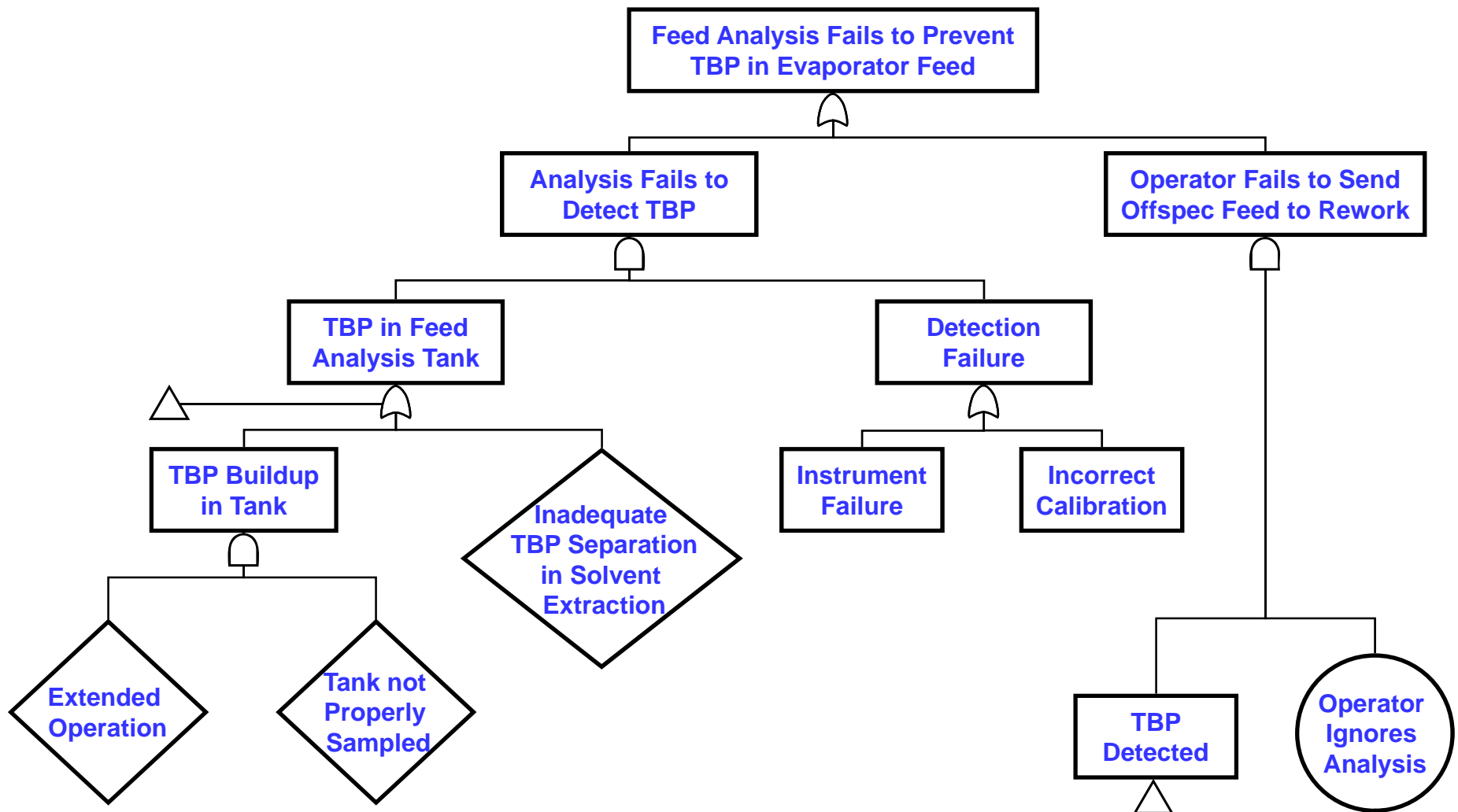
Event Tree for Red Oil Explosion Risk



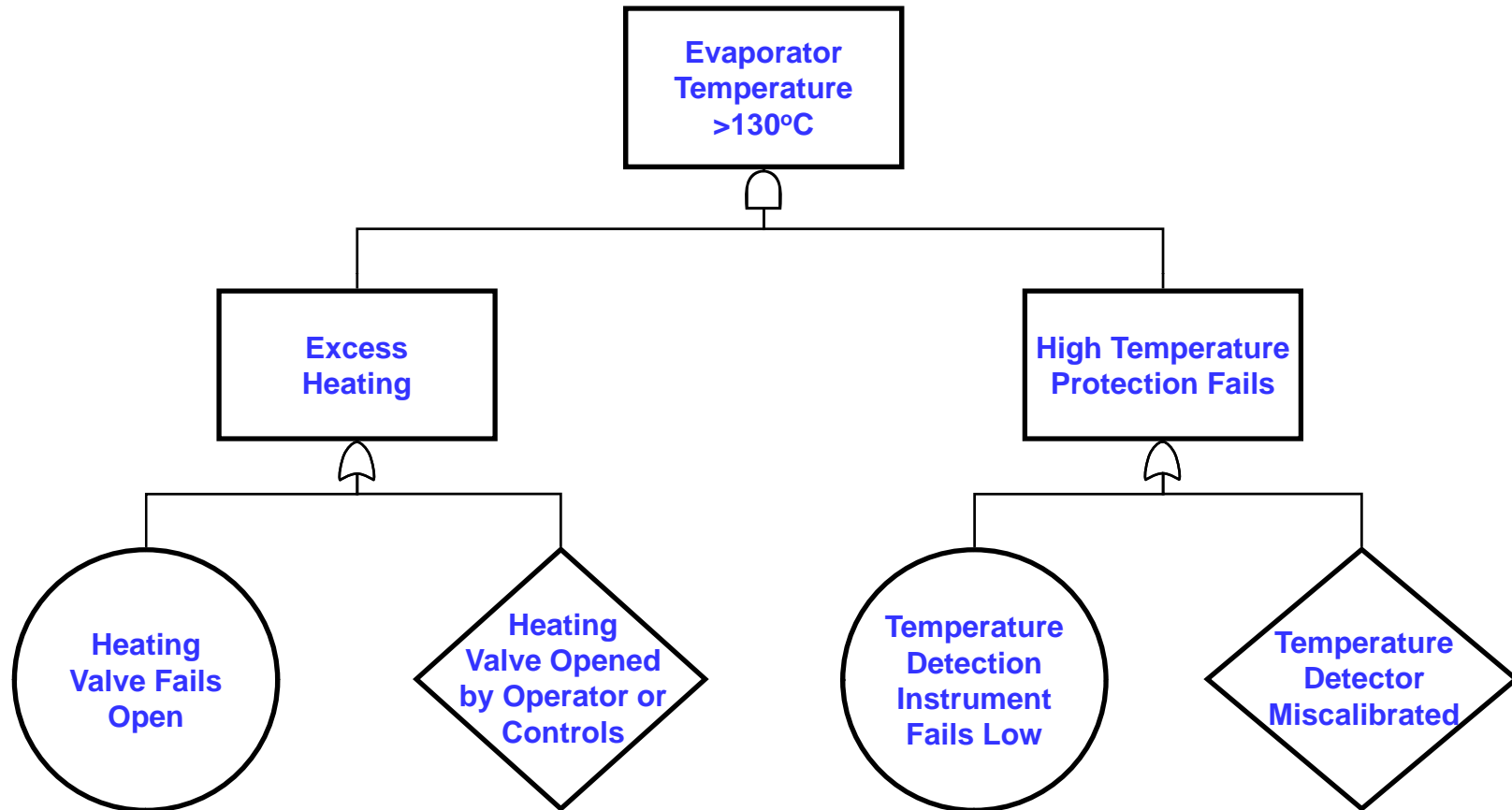
Summary of Scenarios and Consequences

Scenario	Description	Consequence or Outcome
S ₁	Evaporator systems operate as designed.	Product conforming to specification.
S ₂	All systems work except offgas system pressure fails high or low.	Off spec product.
S ₃	Evaporator temperature control fails high increasing heat input to evaporator; pressure control compensates for increased heat input.	Off spec product.
S ₄	Temperature control fails high; pressure control does not compensate.	Off spec product; possible nitrate precipitation in evaporate and shut down for repair.
S ₅	Evaporator feed analysis fails. All other systems function.	Possible off spec product.
S ₆	Evaporator feed analysis fails; evaporator pressure control fails.	Off spec product.
S ₇	Evaporator feed analysis fails; temperature control fails high; pressure control works.	Off spec product.
S ₈	Evaporator feed analysis fails; evaporator temperature control fails high; evaporator pressure control fails.	Off spec product; possible nitrate precipitation in evaporate and shut down for repair.
S ₉	Excess TBP in feed tank; feed analysis detects TBP.	Rework of evaporator feed required.
S ₁₀	Excess TBP in feed tank; feed analysis detects TBP; temperature control works; pressure control fails high or low.	Rework of evaporator feed required.
S ₁₁	Excess TBP in feed tank; feed analysis detects TBP; temperature control fails high; pressure control works.	Rework of evaporator feed required.
S ₁₂	Excess TBP in feed tank; feed analysis detects TBP; temperature control works; pressure control fails high or low.	Rework of evaporator feed required.
S ₁₃	Excess TBP in feed tank; feed analysis fails to detect TBP; temperature control works; pressure control works.	Off spec product; possible fire in fuel fabrication denitrator from TBP in product.
S ₁₄	Excess TBP in feed tank; feed analysis fails to detect TBP; temperature control works; pressure control fails high or low.	Off spec product; possible fire in fuel fabrication denitrator from TBP in product.
S ₁₅	Excess TBP in feed tank; feed analysis fails to detect TBP; temperature control fails; pressure control works.	Off spec product; possible fire in fuel fabrication denitrator from TBP in product.
S ₁₆	Excess TBP in feed tank; feed analysis fails to detect TBP; temperature control fails; pressure control fails high.	Red oil formation and possible overpressure or red oil explosion.

Fault Tree: Evaporator Feed



Fault Tree: Evaporator Temperature Control



Quantification of Scenarios and Total Risk

- **Develop event probability distribution functions**
- **Convolute event PDFs into scenario PDFs**
- **Assemble scenarios into frequency of exceedance curves**

Use of QRA During Design Nuclear Power Plant Example

System(s) or Operator Action	Percent Reduction in Core Damage Frequency if the Individual System (or Operator Action) Failure Frequency Could Be Reduced to Zero			
	First Iteration	Second Iteration	Third Iteration	Fourth Iteration
1. Electric Power	11	65	43	52
2. Auxiliary Feedwater	9	11	11	31
3. Two Trains of Electric Power Recovered				21
4. Low Pressure Injection / Decay Heat Removal	4	3	8	19
5. Failure to Reclose PORV / PSVs		5	20	17
6. ESFAS / ECCAS			14	15
7. High Pressure Injection Systems	3	9	15	14
8. Operator Recovery of Electric Power During Station Blackout		50	14	14
9. Sump Recirculation Water Source				11
10. Component Cooling Water			3	8
11. Throttle HPI Flow (Operator Action)			1	4
12. Failure of Main Steam Safety Valve to Reclose			1	4
13. Service Water	32	<1	10	4
14. Safeguards Chilled Water	20	8	13	1
15. BWST Suction Valve				1
16. Containment Isolation			1	
Relative Core Melt Frequency	1.00	0.30	0.10	0.06

Summary and Conclusion

- **Provided a framework for quantitative risk assessment**
- **Highlighted applicability to nuclear fuel recycling facilities**
- **QRA has advanced to a high level of maturity**
- **QRA enhances risk management of any system**