PRA Methodology Overview

22.39 Elements of Reactor Design, Operations, and Safety

Lecture 9

Fall 2006

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PRA Synopsis

Figure removed due to copyright restrictions.
Futron Corp., International Space Station PRA, Dec. 2000

NPP End States

- Various states of degradation of the reactor core.
- Release of radioactivity from the containment.
- Individual risk.
- Numbers of early and latent deaths.
- Number of injuries.
- Land contamination.

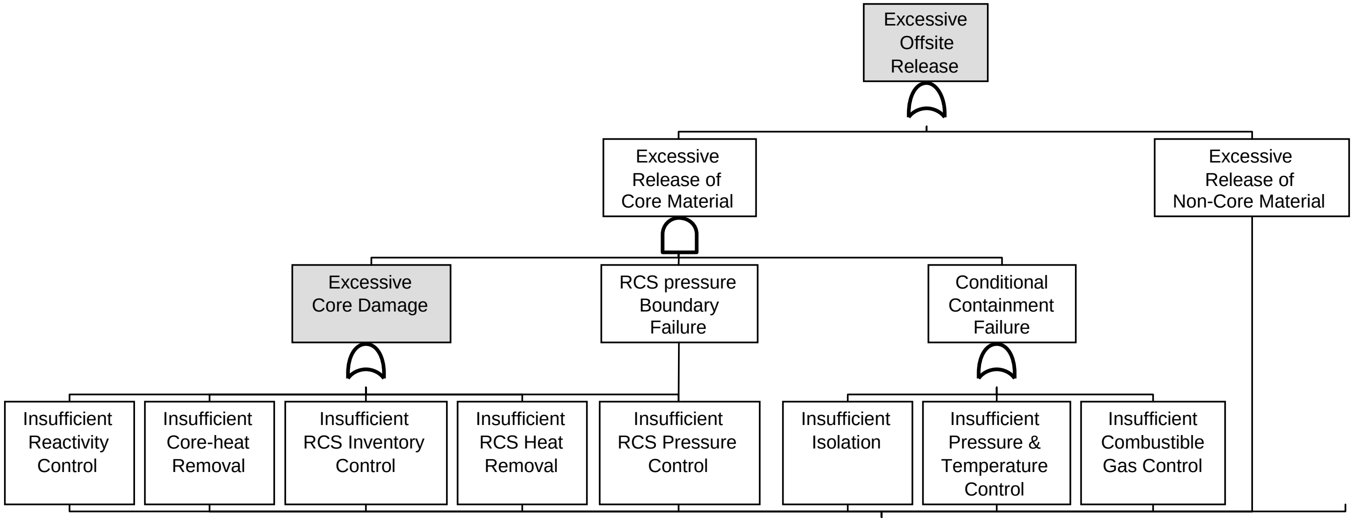
The Master Logic Diagram (MLD)

- **Developed to identify Initiating Events in a PRA.**
- **Hierarchical depiction of ways in which system perturbations can occur.**
- **Good check for completeness.**

MLD Development

- **Begin with a top event that is an end state.**
- **The top levels are typically functional.**
- **Develop into lower levels of subsystem and component failures.**
- **Stop when every level below the stopping level has the same consequence as the level above it.**

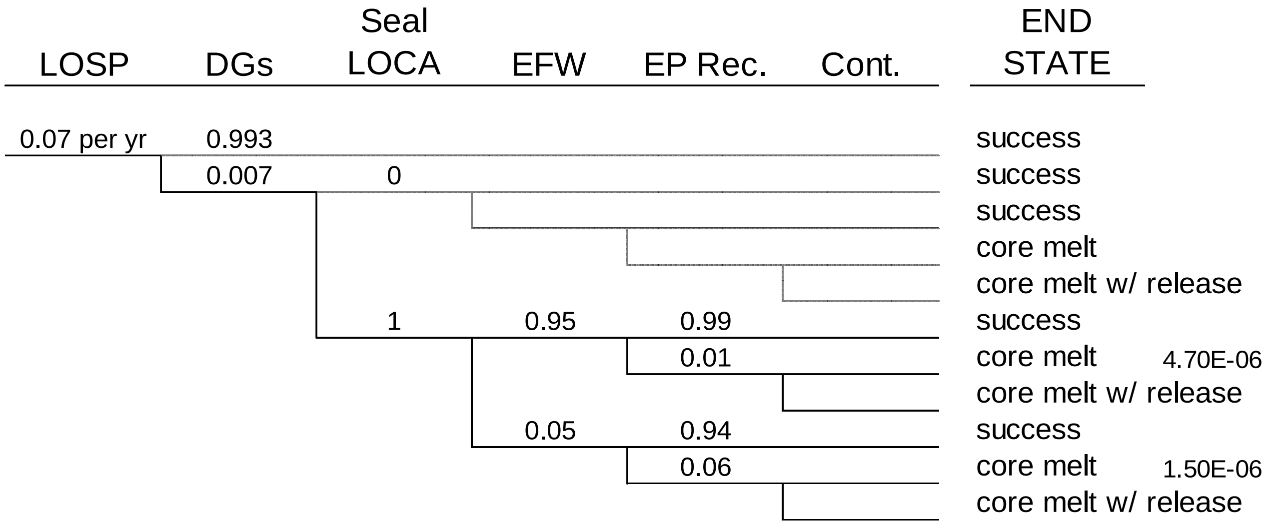
Nuclear Power Plant MLD



NPP: Initiating Events

- Transients
  - Loss of offsite power
  - Turbine trip
  - Others
- Loss-of-coolant accidents (LOCAs)
  - Small LOCA
  - Medium LOCA
  - Large LOCA

ILLUSTRATION EVENT TREE: Station Blackout Sequences



LOSP | DGs | Seal LOCA | EFW | EP Rec. | Cont. | END STATE

0.07 per yr
0.993 — success
0.007
0 — success
success
core melt
core melt w/ release
1
0.95
0.99 — success
0.01 — core melt 4.70E-06
core melt w/ release
0.05
0.94 — success
0.06 — core melt 1.50E-06
core melt w/ release

From: K. Kiper, MIT Lecture, 2006

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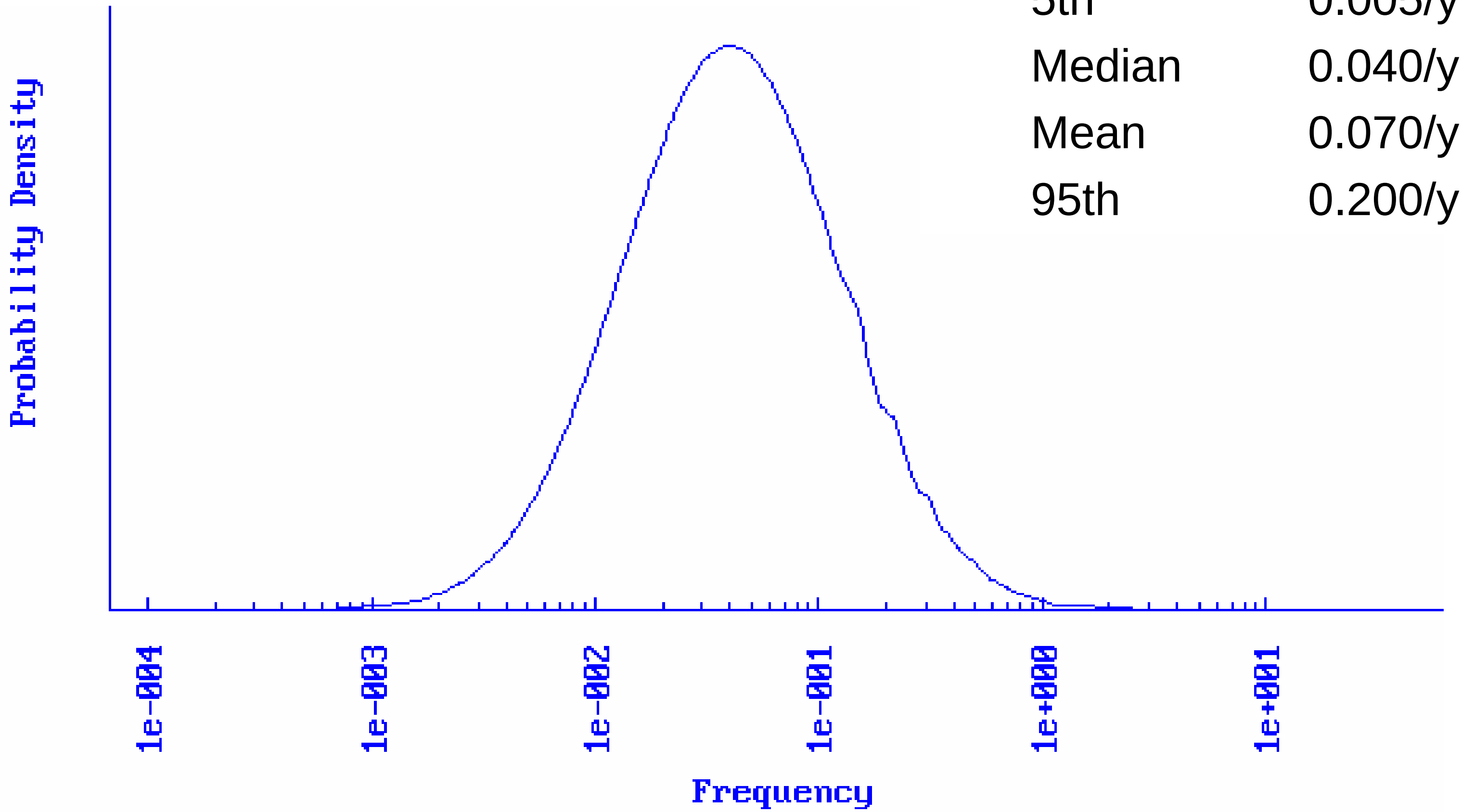
LOSP Distribution



Epistemic Uncertainties		
5th	0.005/yr	(200 yr)
Median	0.040/yr	(25 yr)
Mean	0.070/yr	(14 yr)
95th	0.200/yr	(5 yr)

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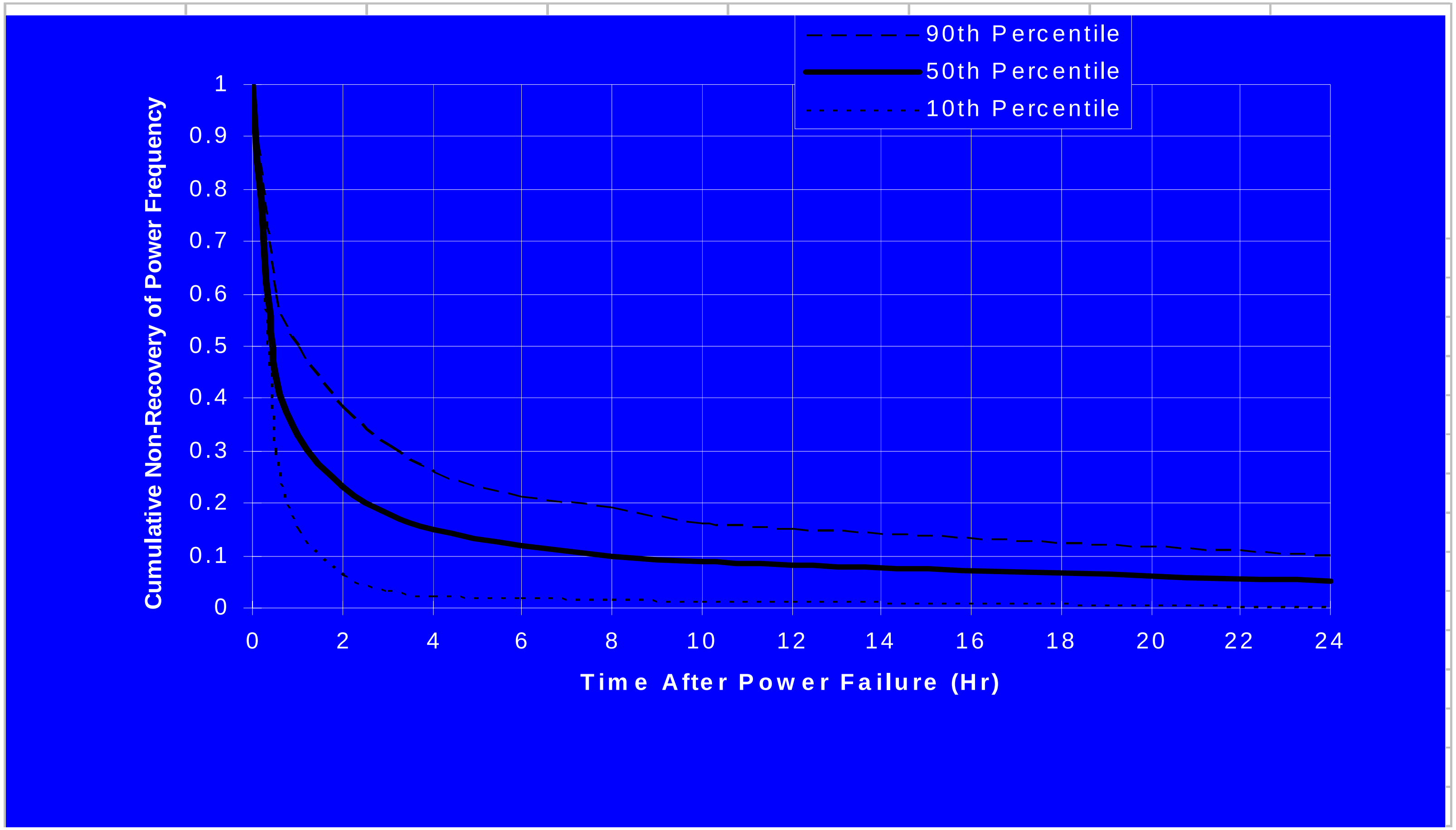
Offsite Power Recovery Curves



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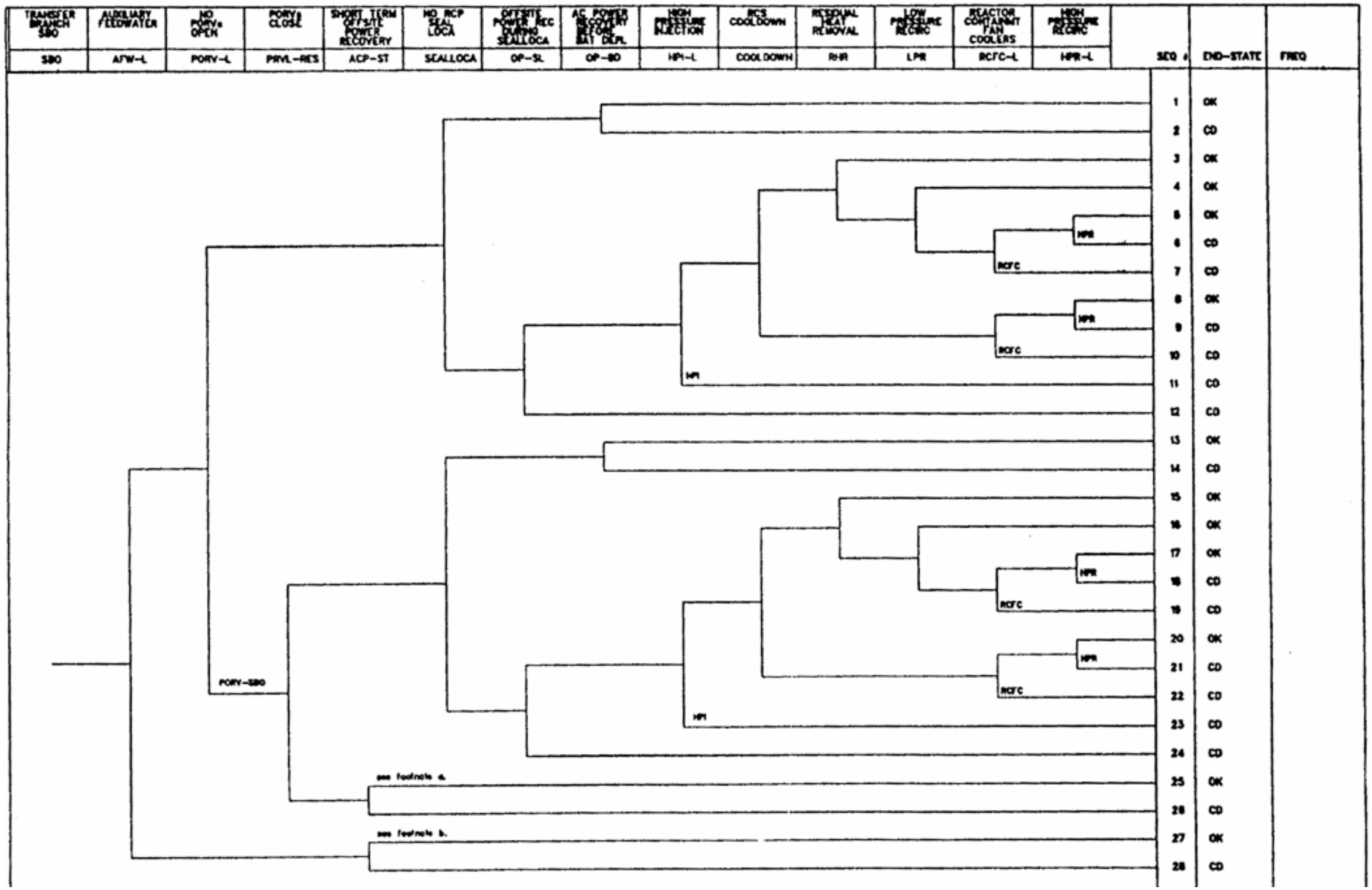
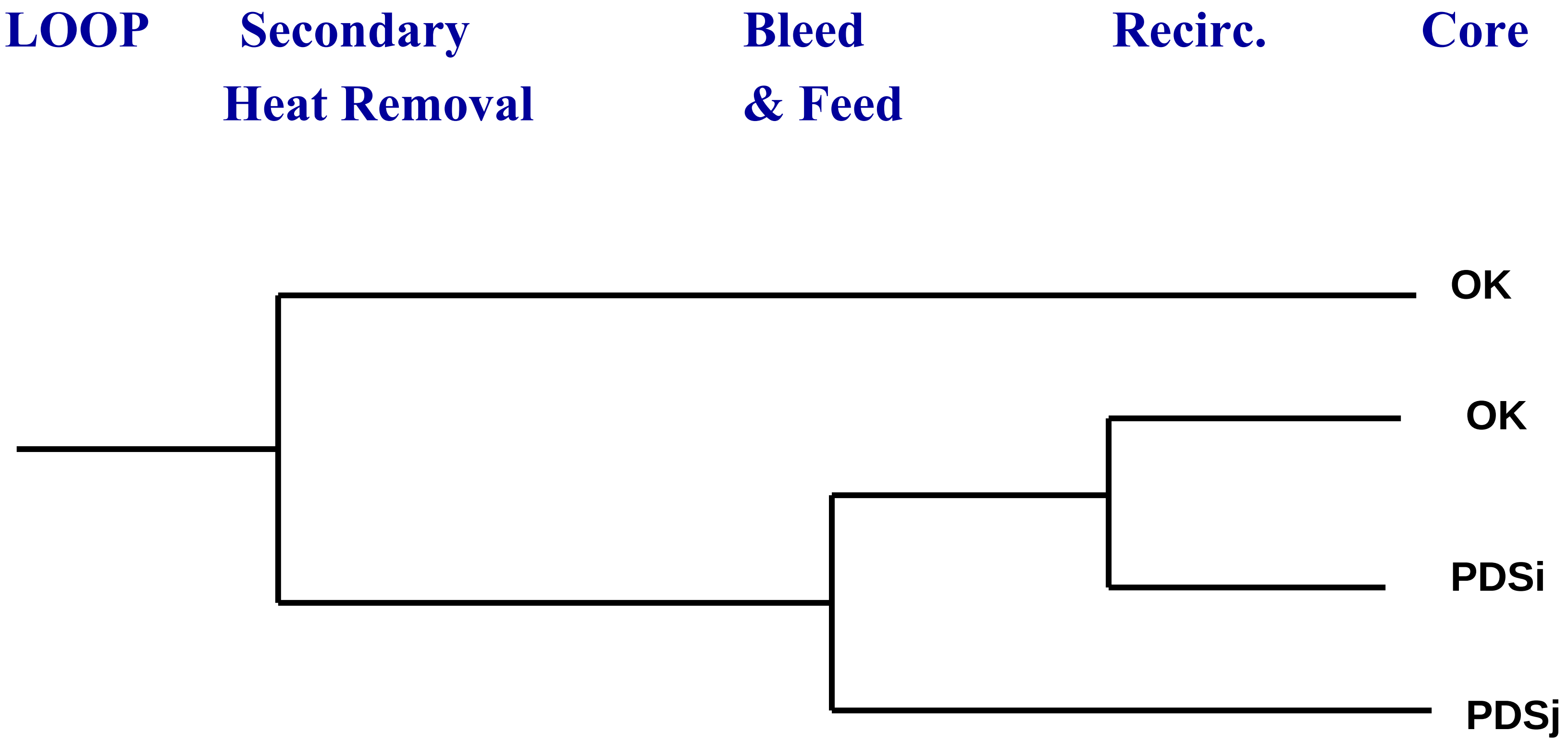
STATION BLACKOUT EVENT TREE



Courtesy of U.S. NRC.

NPP: Loss-of-offsite-power event tree



LOOP

Secondary Heat Removal

Bleed & Feed

Recirc.

Core

OK

OK

PDSi

PDSj

Human Performance

- **The operators must decide to perform feed & bleed.**
- **Water is "fed" into the reactor vessel by the high-pressure system and is "bled" out through relief valves into the containment. Very costly to clean up.**
- **Must be initiated within about 30 minutes of losing secondary cooling (a thermal-hydraulic calculation).**

J. Rasmussen’s Categories of Behavior

- *Skill-based behavior:* Performance during acts that, after a statement of intention, take place without conscious control as smooth, automated, and highly integrated patterns of behavior.
- *Rule-based behavior:* Performance is consciously controlled by a stored rule or procedure.
- *Knowledge-based behavior:* Performance during unfamiliar situations for which no rules for control are available.

Reason's Categories

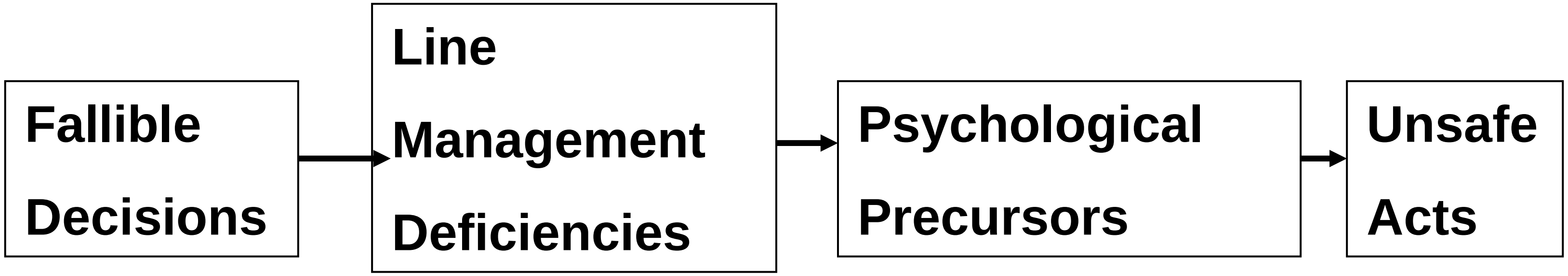
Unsafe acts

- Unintended action
  - Slip
  - Lapse
  - Mistake
- Intended violation

Latent conditions

- **Weaknesses that exist within a system that create *contexts* for human error beyond the scope of individual psychology.**
- **They have been found to be significant contributors to incidents.**
- **Incidents are usually a combination of hardware failures and human errors (latent and active).**

Reason's model



Line Management Deficiencies

Fallible Decisions

Psychological Precursors

Unsafe Acts

J. Reason, *Human Error*, Cambridge University Press, 1990

Pre-IE ("routine") actions

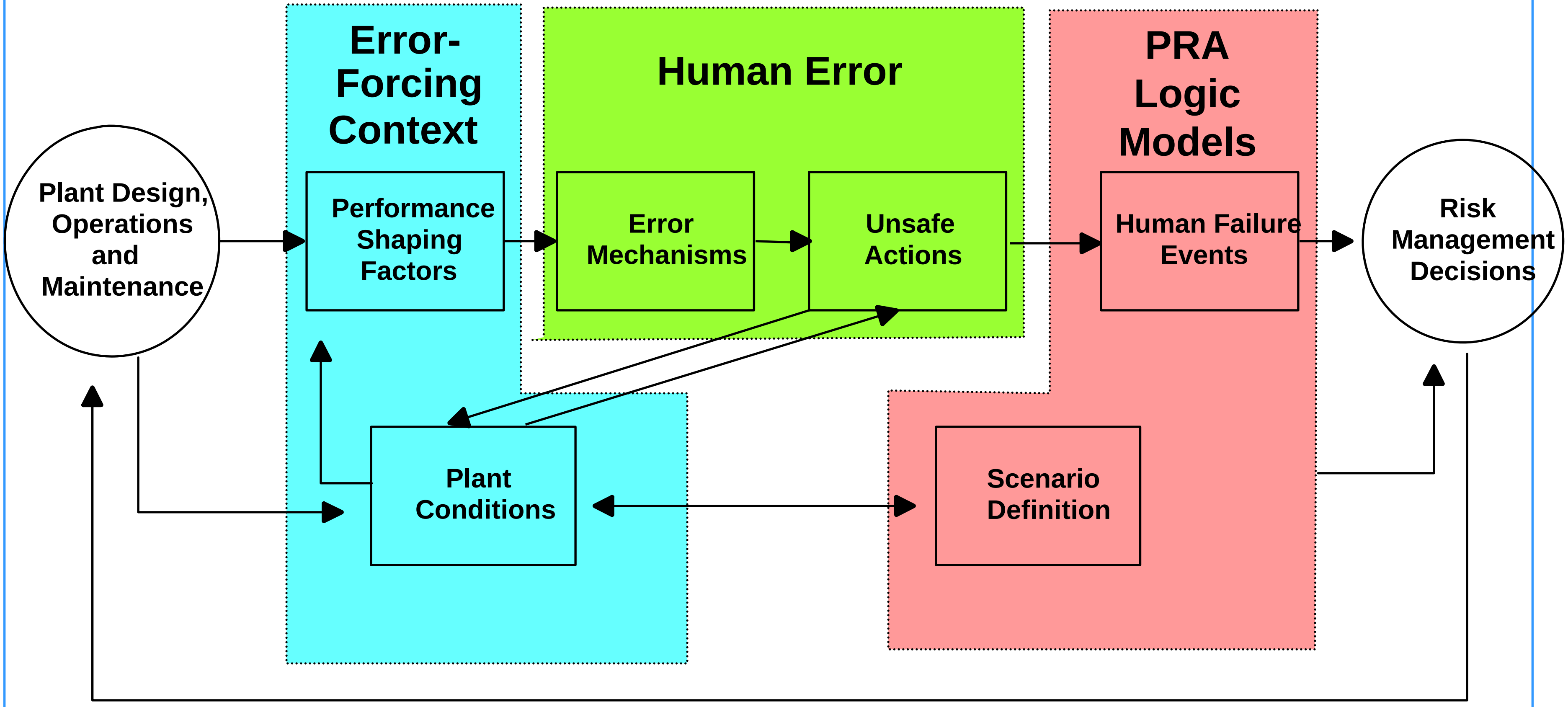
	Median	EF
Errors of commission	3×10^{-3}	3
Errors of omission	10^{-3}	5

A.D. Swain and H.E. Guttmann, *Handbook of Human Reliability Analysis with Emphasis on Nuclear Power Plant Applications*, Report NUREG/CR-1278, US Nuclear Regulatory Commission, 1983.

Post-IE errors

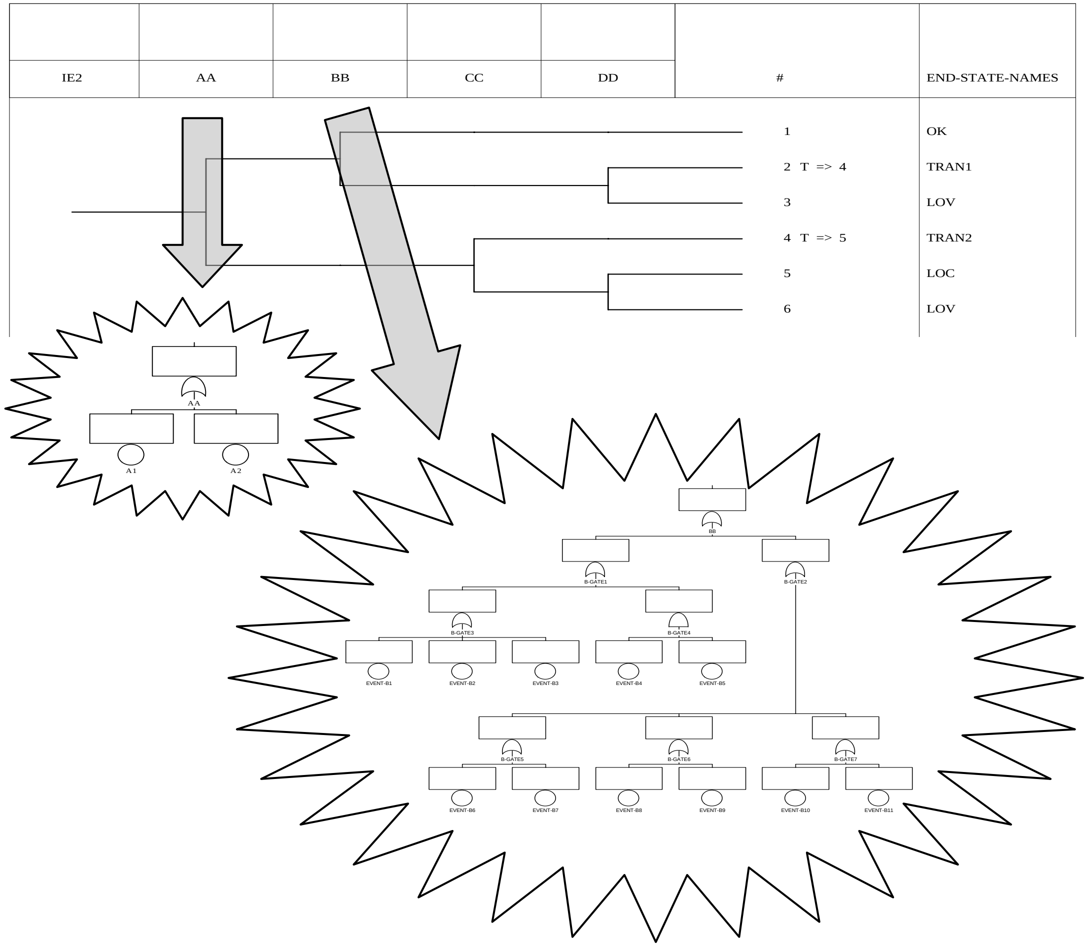
- Models still being developed.
- Typically, they include detailed task analyses, identification of performance shaping factors (PSFs), and the subjective assessment of probabilities.
- PSFs: System design, facility culture, organizational factors, stress level, others.

The ATHEANA Framework

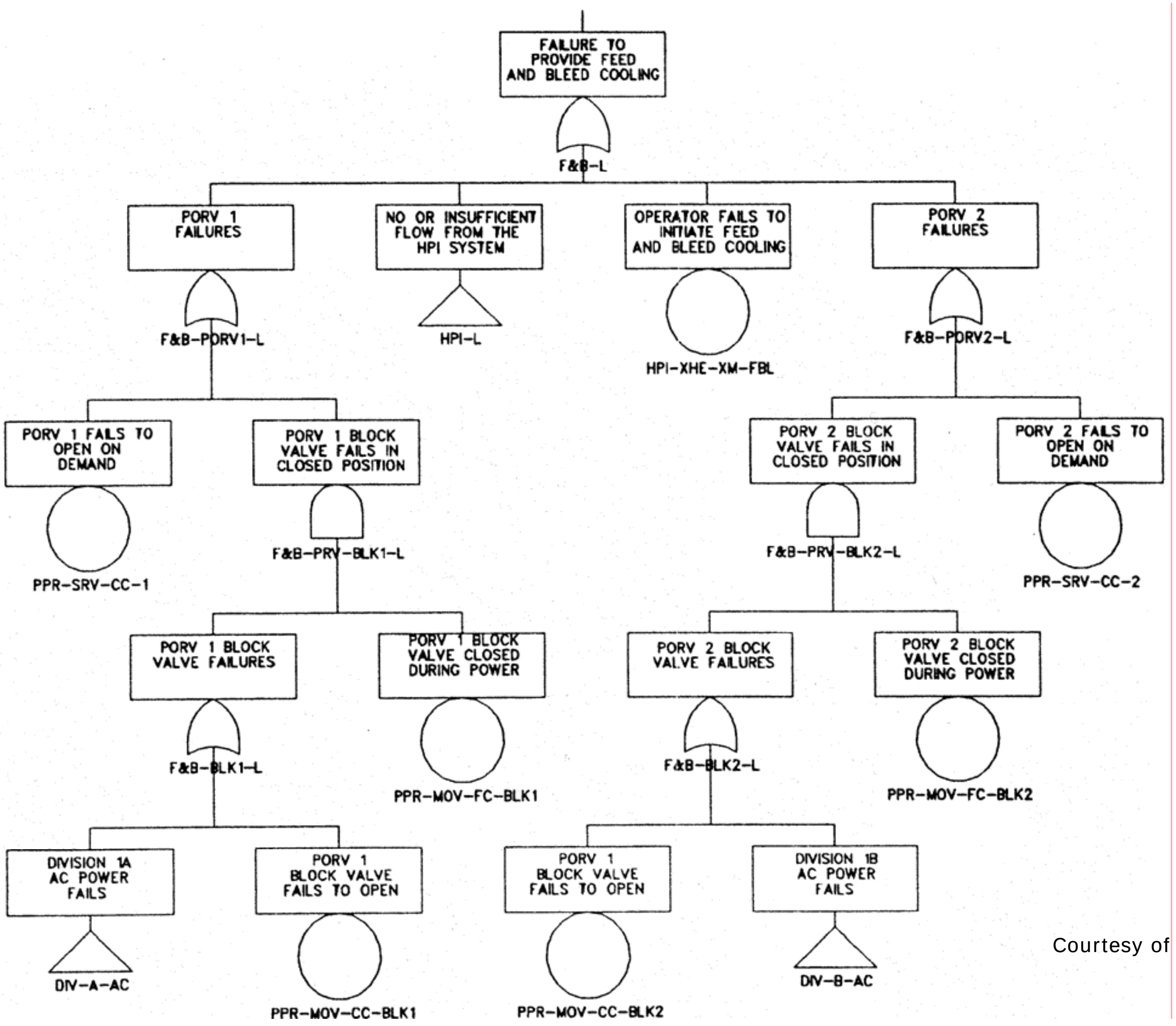


NUREG/CR-6350, May 1996.

Risk Models


IE2
AA
BB
CC
DD
#
END-STATE-NAMES
1
OK
2 T => 4
TRAN1
3
LOV
4 T => 5
TRAN2
5
LOC
6
LOV
AA
A1
A2
BB
B-GATE1
B-GATE2
B-GATE3
B-GATE4
EVENT-B1
EVENT-B2
EVENT-B3
EVENT-B4
EVENT-B5
B-GATE5
B-GATE6
B-GATE7
EVENT-B6
EVENT-B7
EVENT-B8
EVENT-B9
EVENT-B10
EVENT-B11

FEED & BLEED COOLING DURING LOOP 1-OF-3 SI TRAINS AND 2-OF-2 PORVS FOR SUCCESS



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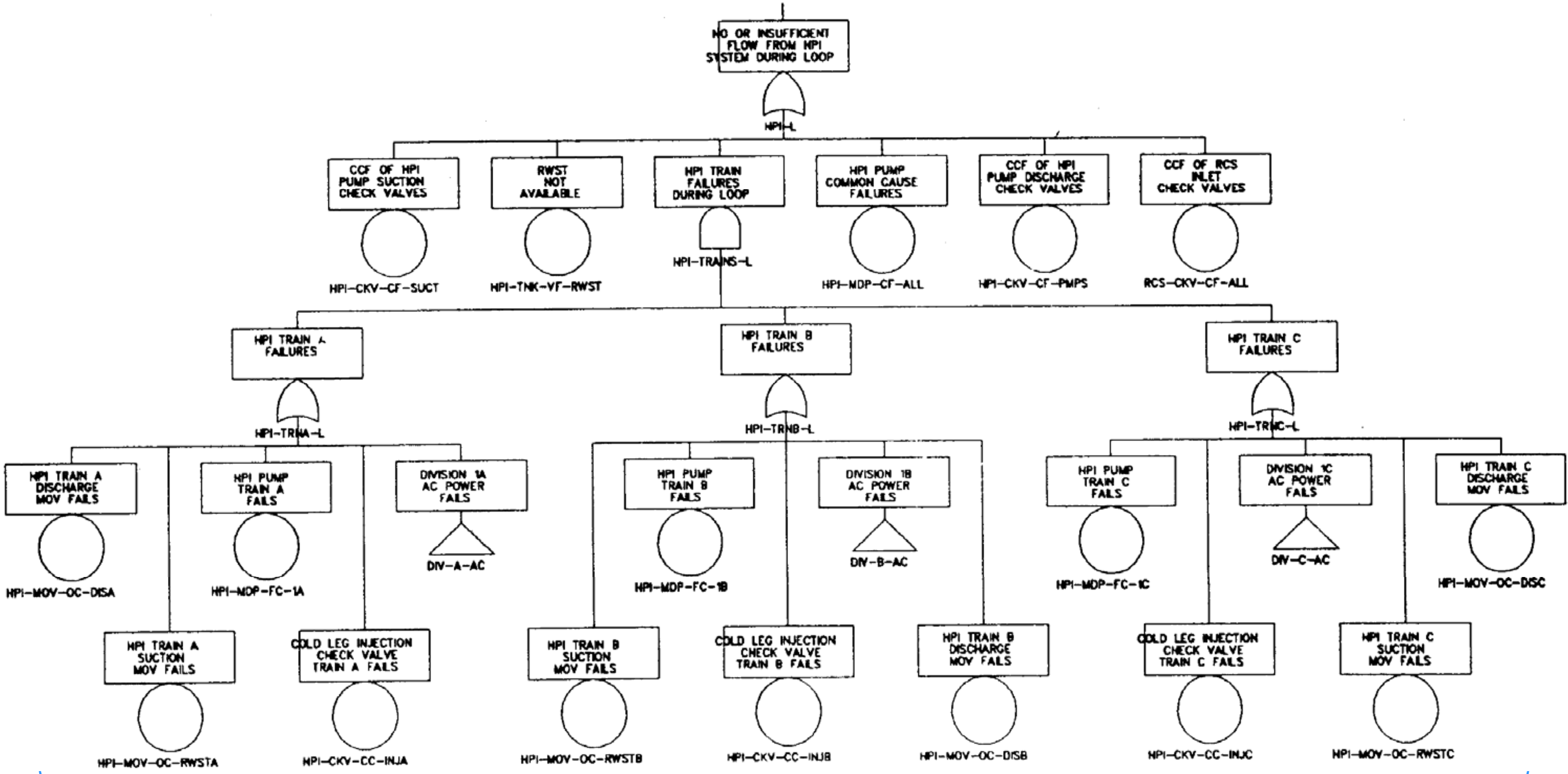
HIGH PRESSURE INJECTION DURING LOOP 1-0F-3 TRAINS FOR SUCCESS



Courtesy of U.S. NRC.

Cut sets and minimal cut sets

- ***CUT SET*:** **Any set of events (failures of components and human actions) that cause system failure.**

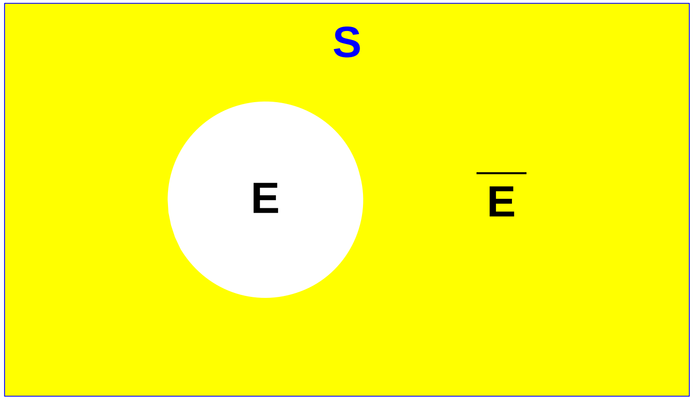
- ***MINIMAL CUT SET*:** **A cut set that does not contain another cut set as a subset.**

Indicator Variables

$$X_j = \begin{cases} 1, \text{ If } E_j \text{ is T} \\ 0, \text{ If } E_j \text{ is F} \end{cases}$$

Important Note: **$X^k = X$, k: 1, 2, …**

Venn Diagram



$$X_T = \phi(X_1, X_2, \ldots X_n) \equiv \phi(\underline{X})$$

$\phi(\underline{X})$ is the structure or switching function.

It maps an n-dimensional vector of 0s and 1s onto 0 or 1.

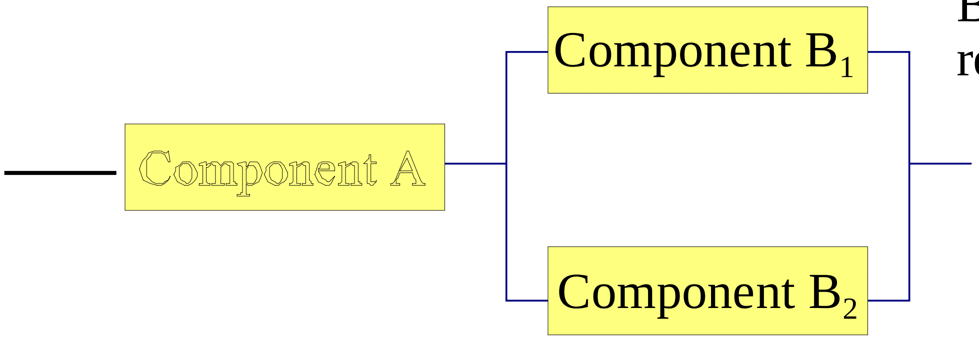
Disjunctive Normal Form:

$$\mathbf{X}_{\mathbf{T}} = 1 - \prod_{1}^{\mathbf{N}} (1 - \mathbf{M}_{\mathbf{i}}) \equiv \coprod_{1}^{\mathbf{N}} \mathbf{M}_{\mathbf{i}}$$

Sum-of-Products Form:

$$X_T = \sum_{i=1}^{N} M_i - \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} M_i M_j + \ldots + (-1)^{N+1} \prod_{i=1}^{N} M_i$$

Dependent Failures: An Example



B_1 and B_2 are identical redundant components

MCS: $M_1 = \{X_A\}$ $M2 = \{X_{B1}, X_{B2}\}$

System Logic	$X_S = 1 - (1 - X_A)(1 - X_{B1}X_{B2}) =$ $= X_A + X_{B1}X_{B2} - X_A X_{B1} X_{B2}$
Failure Probability	$P(\text{fail}) = P(X_A) + P(X_{B1} X_{B2}) - P(X_A X_{B1} X_{B2})$

Example (cont'd)

- In general, we cannot assume independent failures of B_1 and B_2. This means that

$$P(X_{B1}\,X_{B2}) \geq P(X_{B1})\,P(X_{B2})$$

- How do we evaluate these dependencies?

Dependencies

- **Some dependencies are modeled explicitly, e.g., fires, missiles, earthquakes.**
- **After the explicit modeling, there is a class of causes of failure that are treated as a group. They are called *common-cause failures.***

Special Issue on Dependent Failure Analysis, *Reliability Engineering and System Safety,* vol. 34, no. 3, 1991.

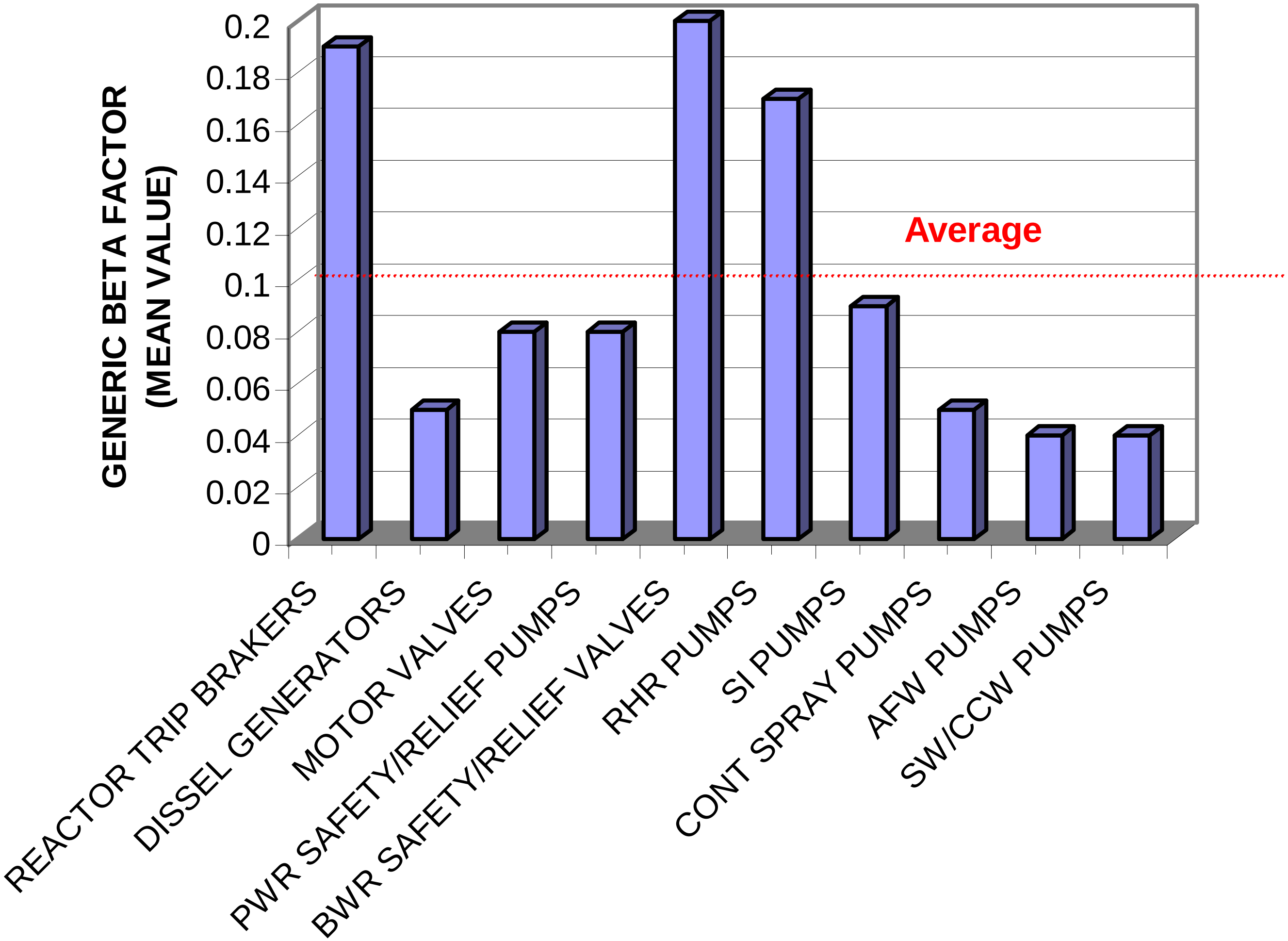
The Beta-Factor Model

- The β-factor model assumes that common-cause events always involve failure of all components of a common cause component group

- It further assumes that

$$\beta = \frac{\lambda_{\mathrm{CCF}}}{\lambda_{\mathrm{total}}}$$

Generic Beta Factors



Data Analysis

- **The process of collecting and analyzing information in order to estimate the parameters of the epistemic PRA models.**

- **Typical quantities of interest are:**
  - **Initiating Event Frequencies**
  - **Component Failure Frequencies**
  - **Component Test and Maintenance Unavailability**
  - **Common-Cause Failure Probabilities**
  - **Human Error Rates**

General Formulation

$$X_T = \varphi(X_1,\ldots X_n) \equiv \varphi(\underline{X})$$

$$\mathbf{X_T = 1 - \prod_{1}^{N} (1 - M_i) \equiv \coprod_{1}^{N} M_i}$$

$$X_T = \sum_{i=1}^{N} M_i - \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} M_i M_j + \ldots + (-1)^{N+1} \prod_{i=1}^{N} M_i$$

X_T : the TOP event indicator variable (e.g., core melt, system failure)

M_i : the ith minimal cut set (for systems) or accident sequence (for core melt, containment failure, et al)

TOP-event Probability

$$P(X_T) = \sum_1^N P(M_i) + \ldots + (-1)^{N+1} P\left(\prod_1^N M_i\right)$$

$$P(X_T) \cong \sum_1^N P(M_i)$$

Rare-event approximation

The question is how to calculate the probability of M_i

$$P(M_i) = P(X_k^i \ldots X_m^i)$$

RISK-SIGNIFICANT INITIATING EVENTS

Risk-Significant Initiating Event	Period	Number of Events	Mean Frequency	Trend
General Transients	1998 – 2004	2120	7.57E-1	⬇
BWR General Transients	1997 – 2004	699	8.56E-1	⬇
PWR General Transients	1998 – 2004	1421	7.10E-1	⬇
Loss of Feedwater	1993 – 2004	188	9.32E-2	⬇
Loss of Heat Sink	1995 – 2004	259	1.24E-1	⬇
BWR Loss of Heat Sink	1996 – 2004	154	1.88E-1	⬇
PWR Loss of Heat Sink	1991 – 2004	105	9.23E-2	⬇
Loss of Instrument Air (BWR)	1994 – 2004	19	7.60E-3	⬇
Loss of Instrument Air (PWR)	1990 – 2004	17	1.19E-2	⬇
Loss of Vital AC Bus	1988 – 2004	43	2.98E-2	⬌
Loss of Vital DC Bus	1988 – 2004	3	2.35E-3	⬌
Stuck Open SRV (BWR)	1993 – 2004	14	2.07E-2	⬌
Stuck Open SRV (PWR)	1988 – 2004	2	2.30E-3	⬌
Steam Generator Tube Rupture	1988 – 2004	3	3.48E-3	⬌
Very Small LOCA	1988 – 2004	5	3.92E-3	⬌

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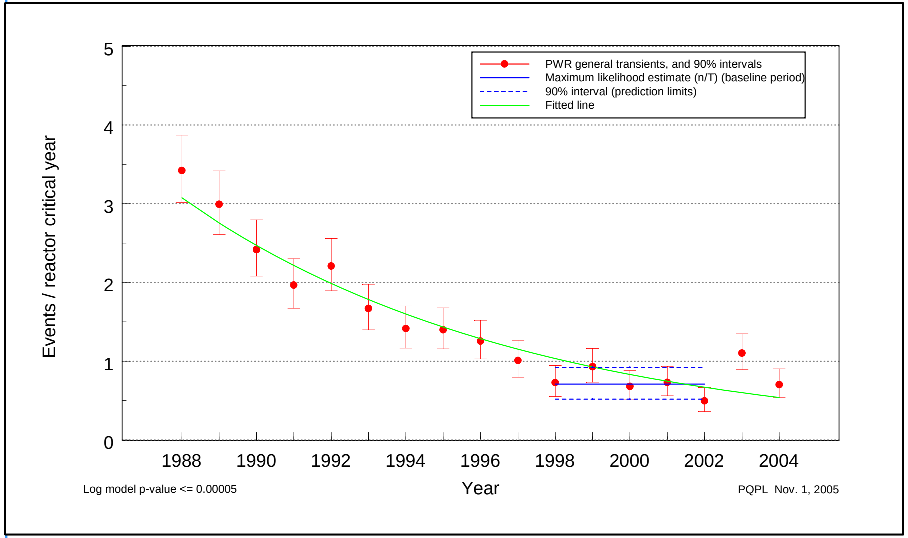
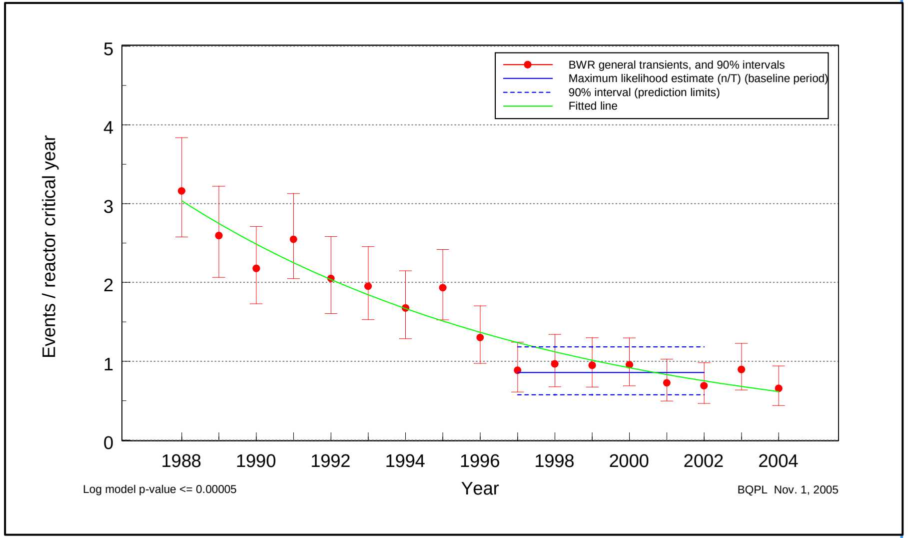
INITIATING EVENT TRENDS

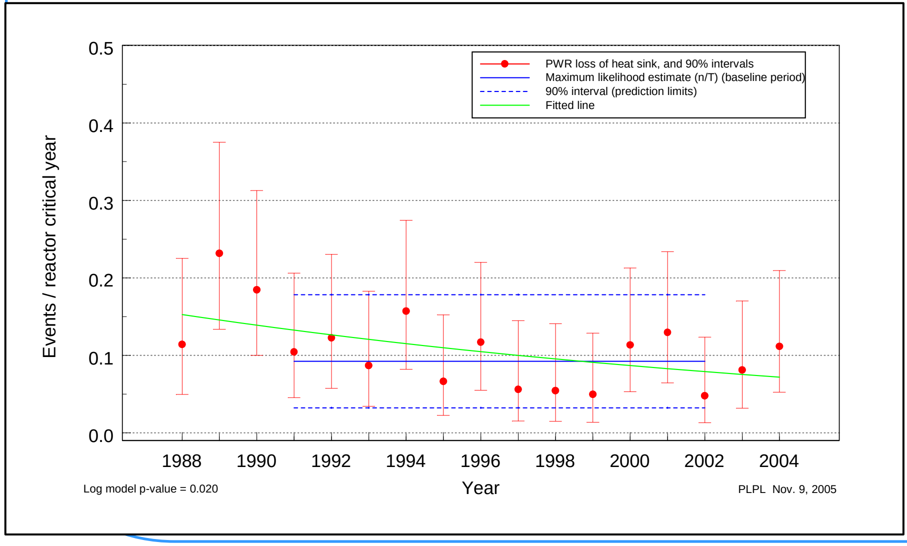
PWR General Transients



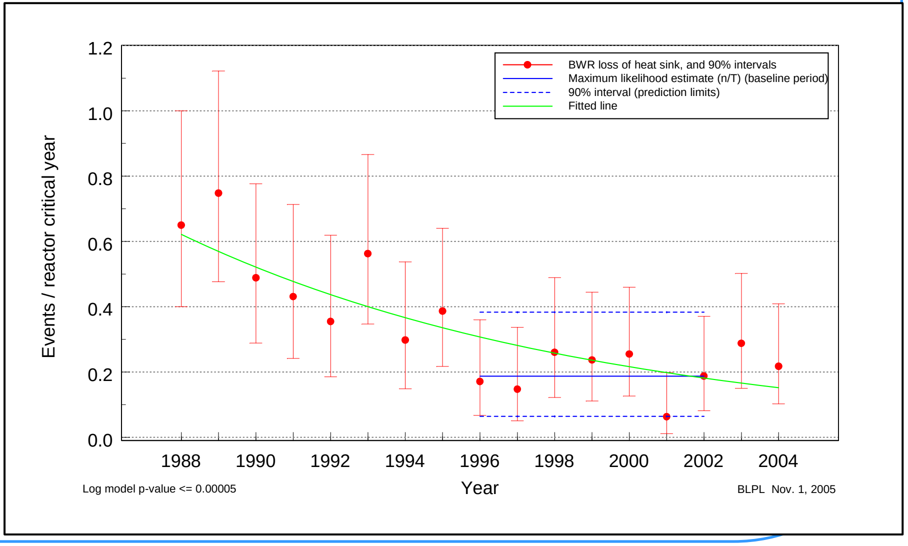
BWR General Transients



PWR Loss of Heat Sink



BWR Loss of Heat Sink



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INITIATING EVENTS INSIGHTS

- **Most initiating events have decreased in frequency over past 10 years.**
- **Combined initiating event frequencies are 4 to 5 times lower than values used in NUREG-1150 and IPEs.**
- **General transients constitute majority of initiating events; more severe challenges to plant safety systems are about one-quarter of events.**

P. Baranowsky, RIODM Lecture, MIT, 2006

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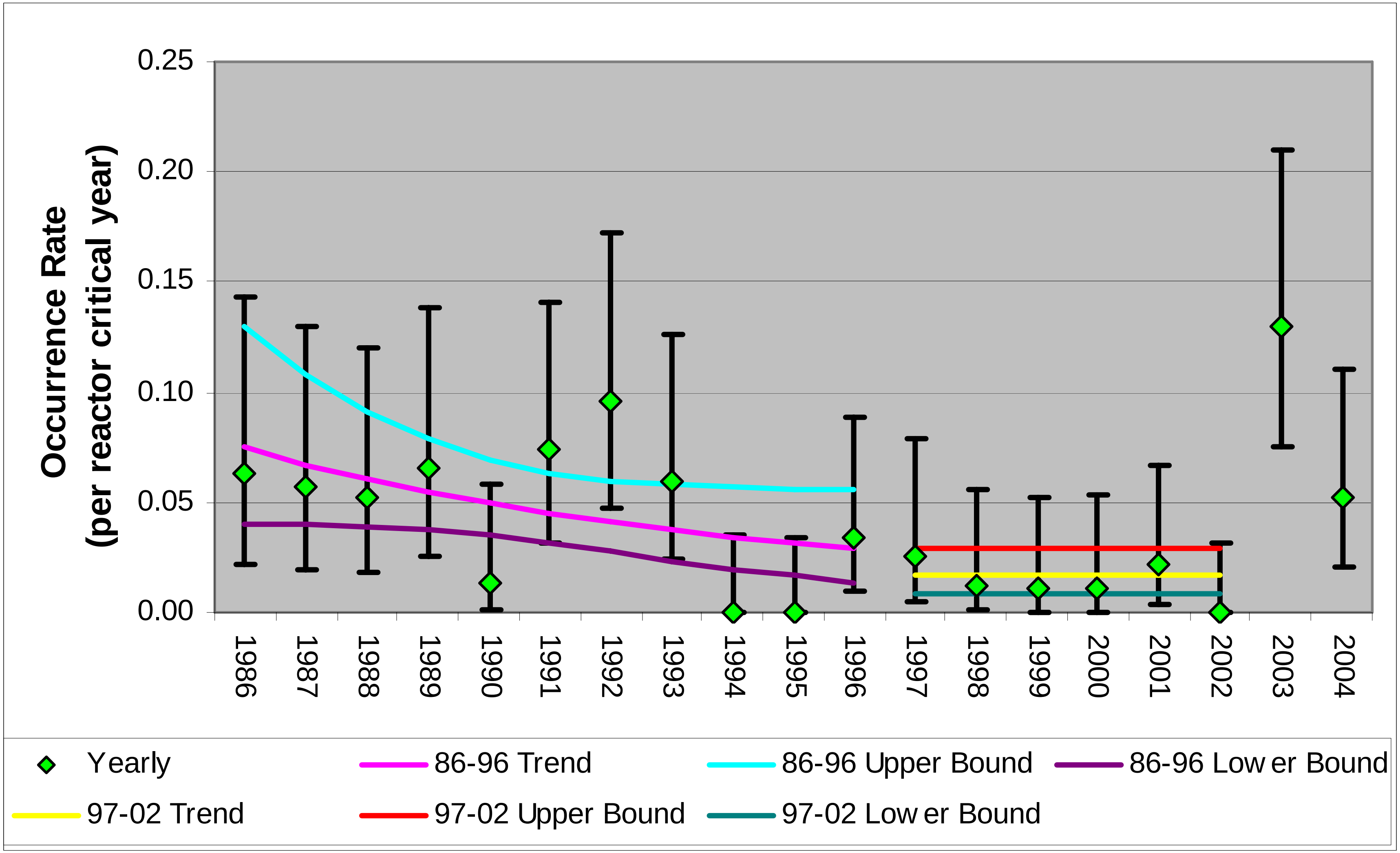
ANNUAL LOOP FREQUENCY TREND



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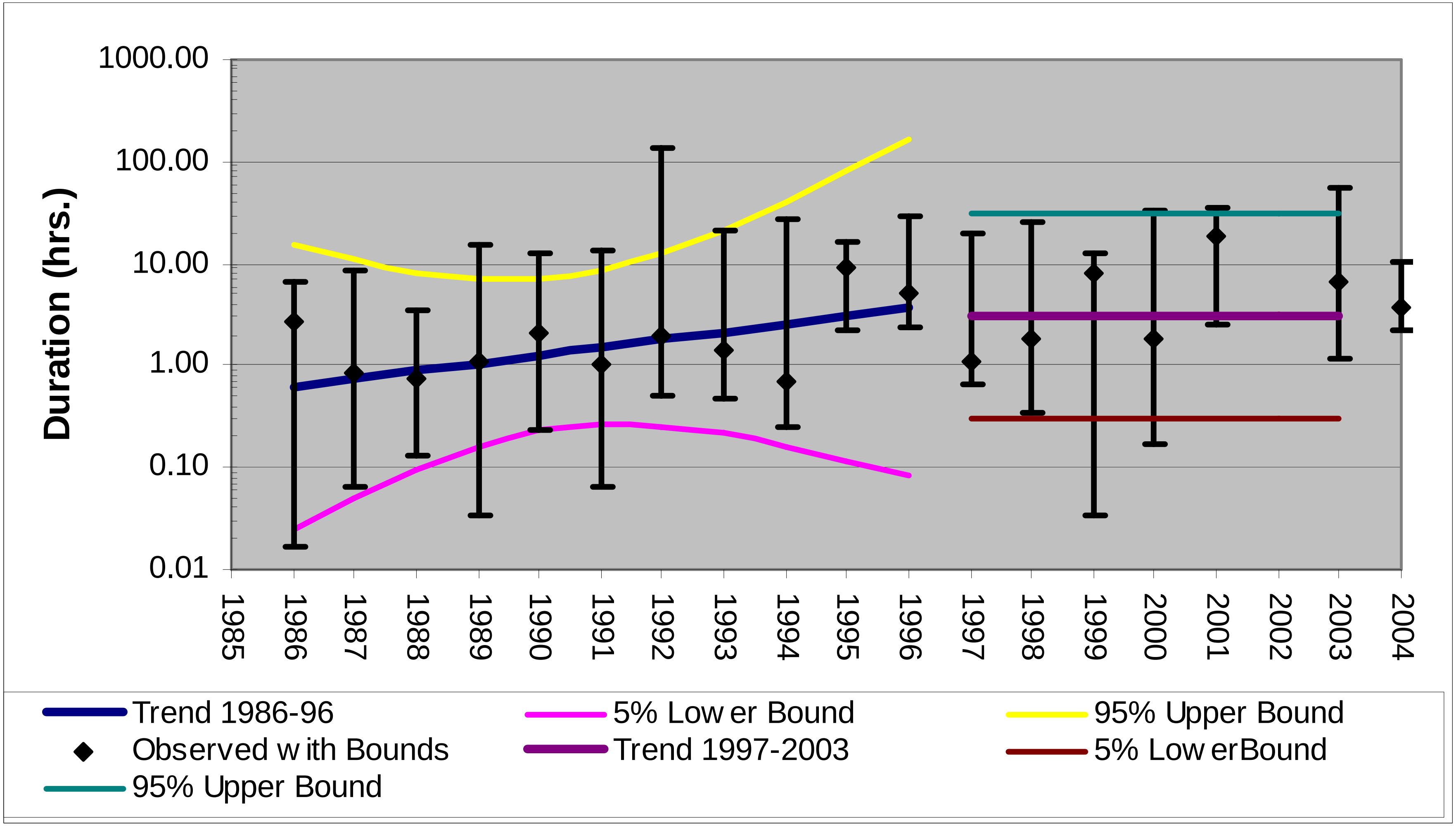
ANNUAL LOOP DURATION TREND



Department of Nuclear Science and Engineering

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LOOP FREQUENCY INSIGHTS

- Overall LOOP frequency during critical operation has decreased over the years (from 0.12/ry to 0.036/ry)
- Average LOOP duration has increased over the years:
  - Statistically significant increasing trend for 1986–1996
  - Essentially constant over 1997–2004
- 24 LOOP events between 1997 and 2004; 19 during the “summer” period
- No grid-related LOOP events between 1997 and 2002; 13 in 2003 and 2004
- Decrease in plant-centered and switchyard-centered LOOP events; grid events are starting to dominate

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SYSTEM RELIABILITY STUDY RESULTS

STUDY	MEAN UNRELIABILITY	UNPLANNED DEMAND TREND	FAILURE RATE TREND	UNRELIABILITY TREND
AFW (1987–2004)	5.19E-4	↓	↓	↔
EDG (1997–2004)	2.18E-2	N/A	N/A	↔
HPCI (1987–2004)	6.25E-2	↓	↓	↓
HPCS (1987–2004)	9.48E-2	↓	↔	↔
HPI (1987–2004)	1.09E-3	↓	↓	↔
IC (1987–2004)	2.77E-2	↓	↓	↔
RCIC (1987–2004)	5.18E-2	↓	↓	↔

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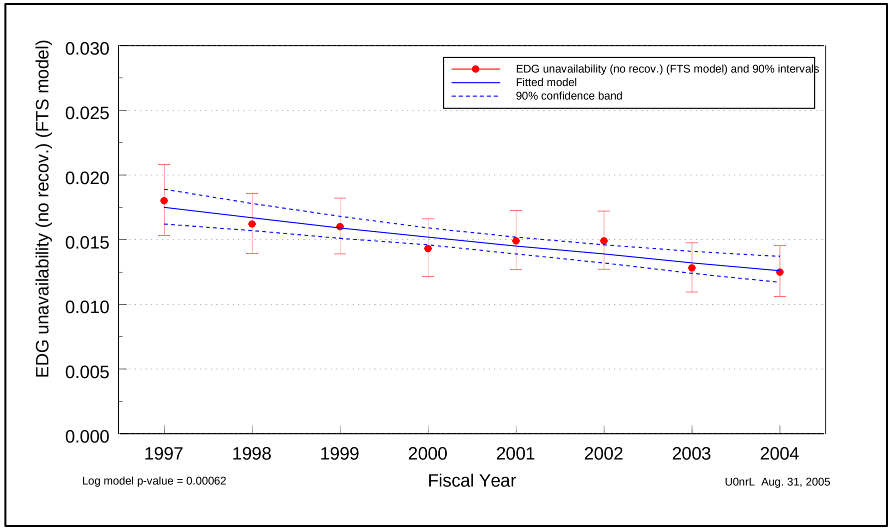
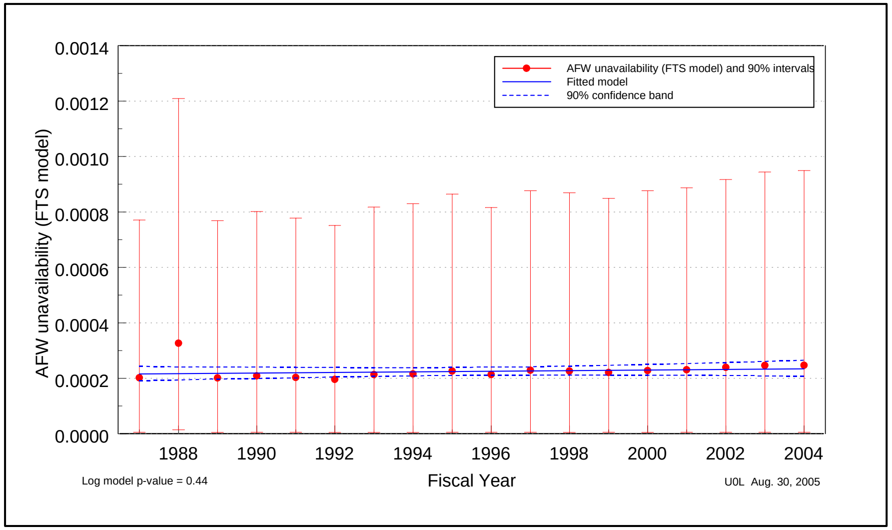
PWR SYSTEM RELIABILITY STUDIES

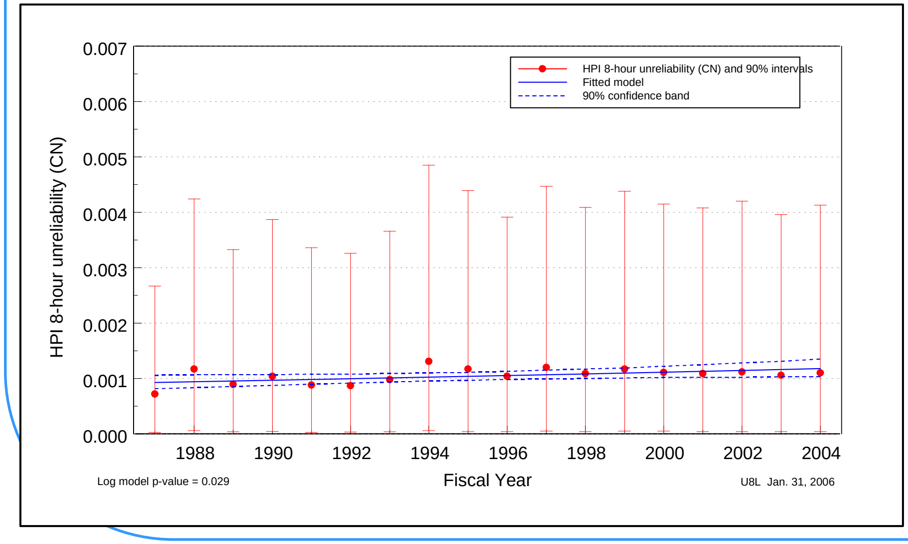
EDG Unavailability (FTS)



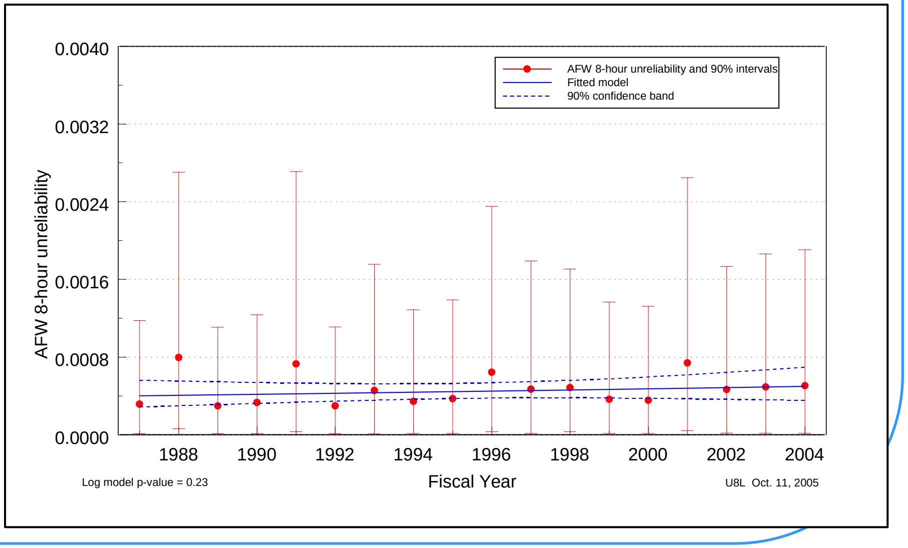
AFW Unavailability (FTS)



HPI Unreliability (8 hr mission)



AFW Unreliability (8 hr mission)



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PWR SYSTEM INSIGHTS

- **EDG**
  - **EDG start reliability much improved over past 10 years.**
  - **Failure-to-run rates lower than in most PRAs.**
- **AFW**
  - **Industry average reliability consistent with or better than Station Blackout and ATWS rulemaking.**
  - **Wide variation in plant specific AFW reliability primarily due to configuration.**
  - **Failure of suction source identified as a contributor (not directly modeled in some PRAs).**
- **HPI**
  - **Wide variation in plant specific HPI reliability due to configuration.**
  - **Various pump failures are the dominant failure contributor.**

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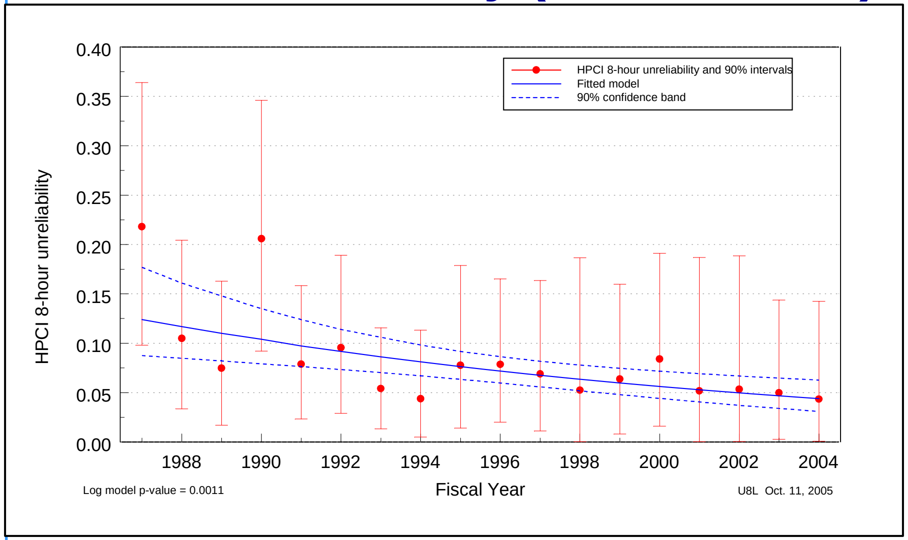
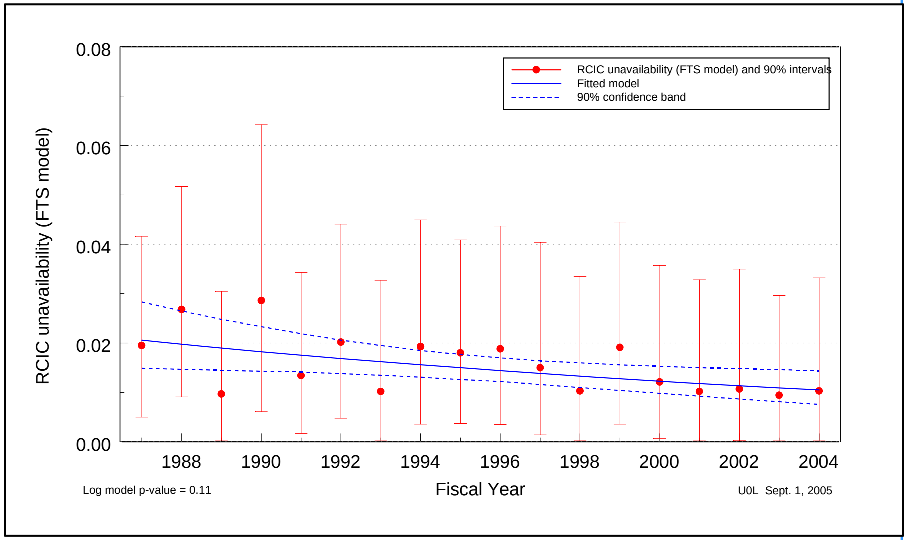
BWR SYSTEM RELIABILITY STUDIES

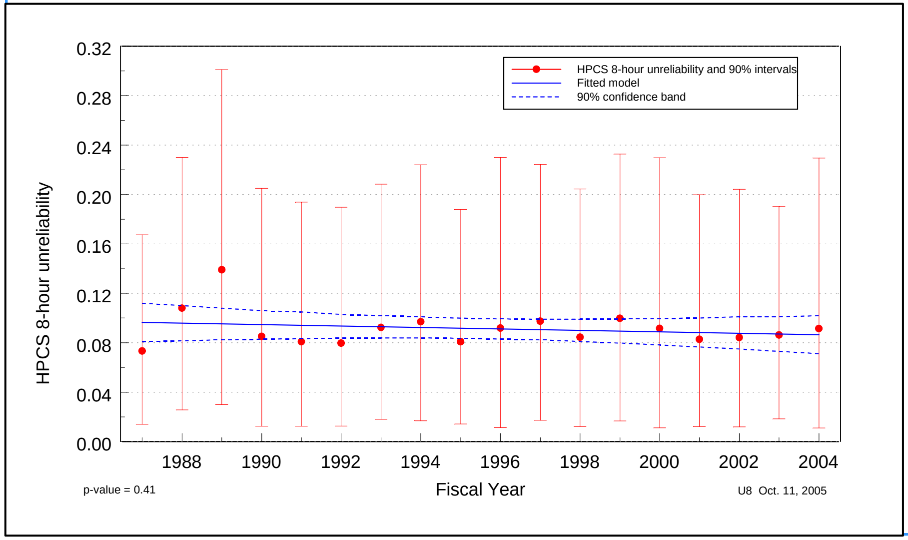
HPCI Unreliability (8 hr mission)



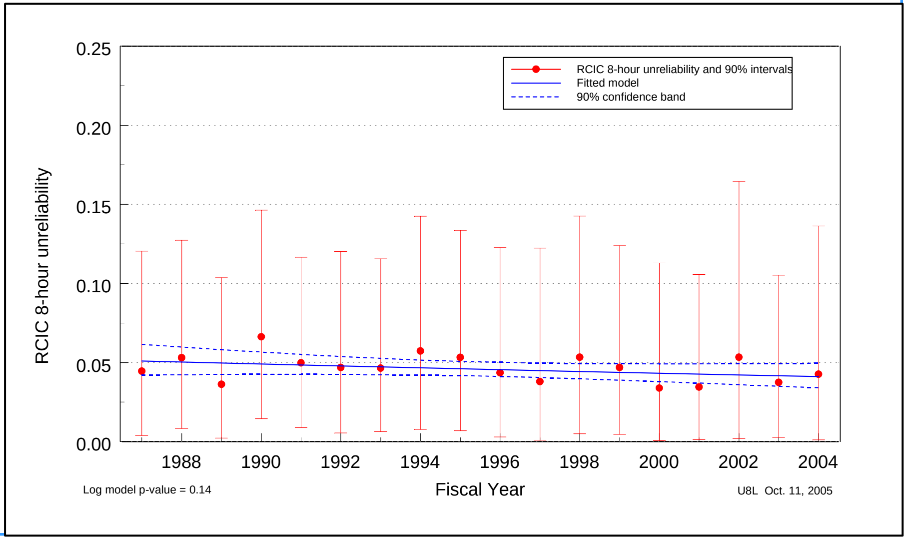
RCIC Unavailability (FTS)



HPCS Unreliability (8 hr mission)



RCIC Unreliability (8 hr mission)



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BWR SYSTEM INSIGHTS

- HPCI
  - Industry-wide unreliability shows a statistically significant decreasing trend.
  - Dominant Failure: failure of the injection valve to reopen during level cycling.
- HPCS
  - Industry average unreliability indicates a constant trend.
  - Dominant Failure: failure of the injection valve to open during initial injection.
- RCIC
  - Industry average unreliability indicates a constant trend.
  - Dominant Failure: failure of the injection valve to reopen during level cycling.

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COMMON-CAUSE FAILURE (CCF) EVENTS

- Criteria for a CCF Event:
  - Two or more components fail or are degraded at the same plant and in the same system.
  - Component failures occur within a selected period of time such that success of the PRA mission would be uncertain.
  - Component failures result from a single shared cause and are linked by a coupling mechanism such that other components in the group are susceptible to the same cause and failure mode.
  - Equipment failures are not caused by the failure of equipment outside the established component boundary.

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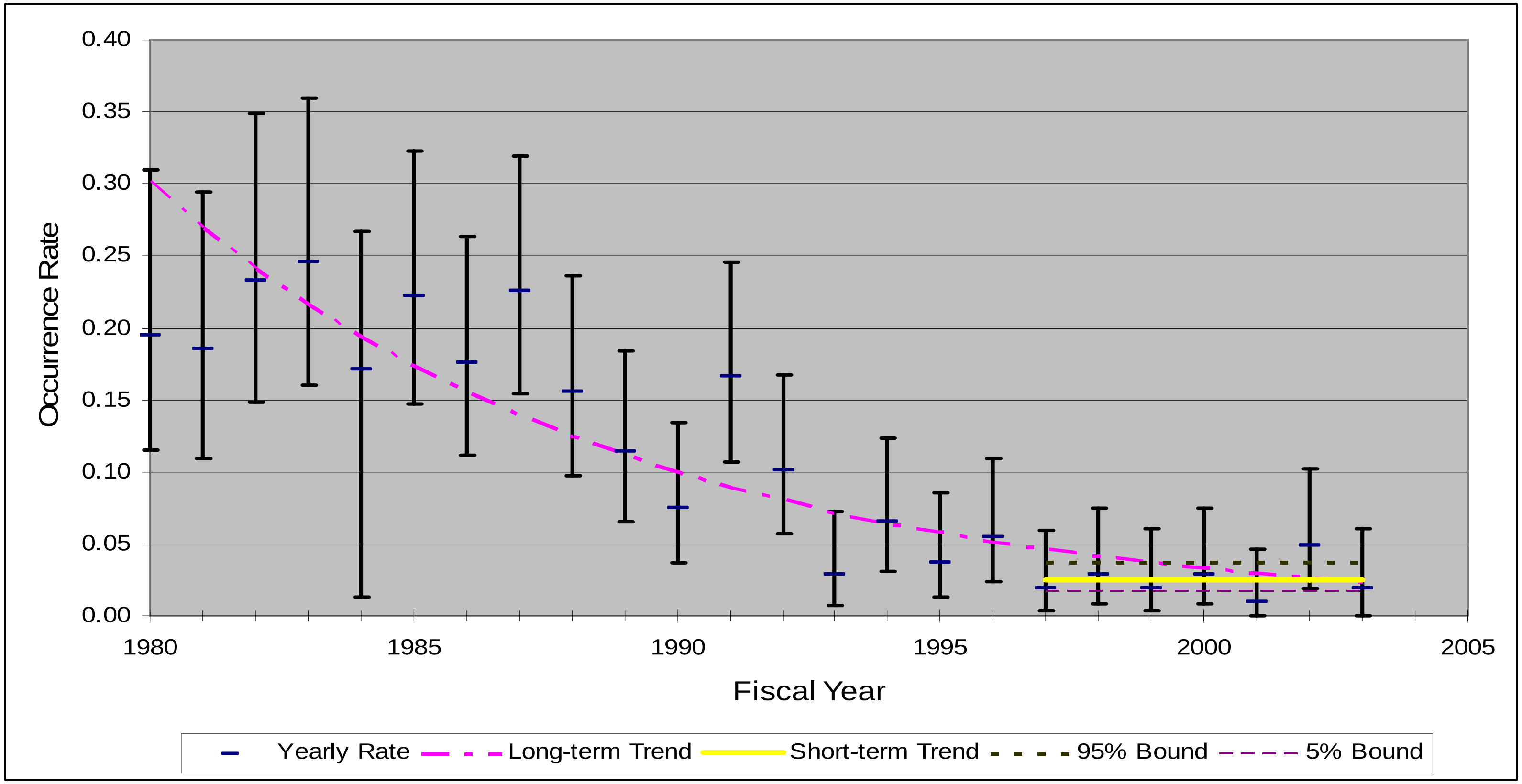
CCF OCCURRENCE RATE



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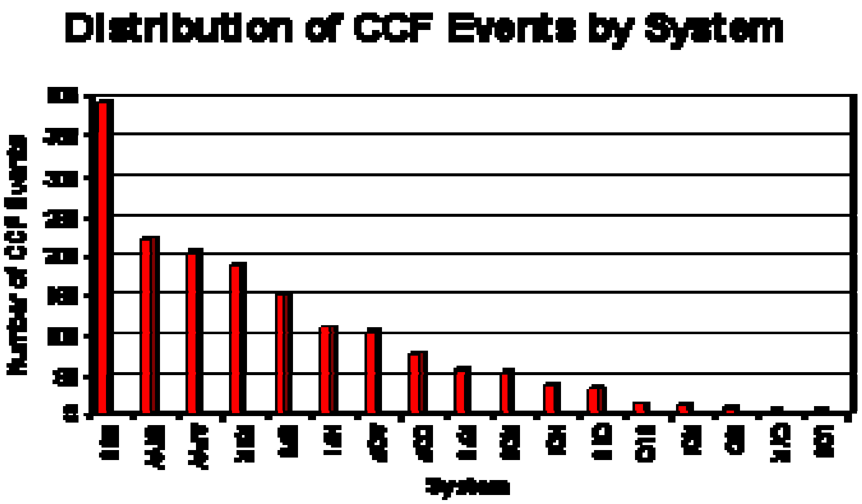

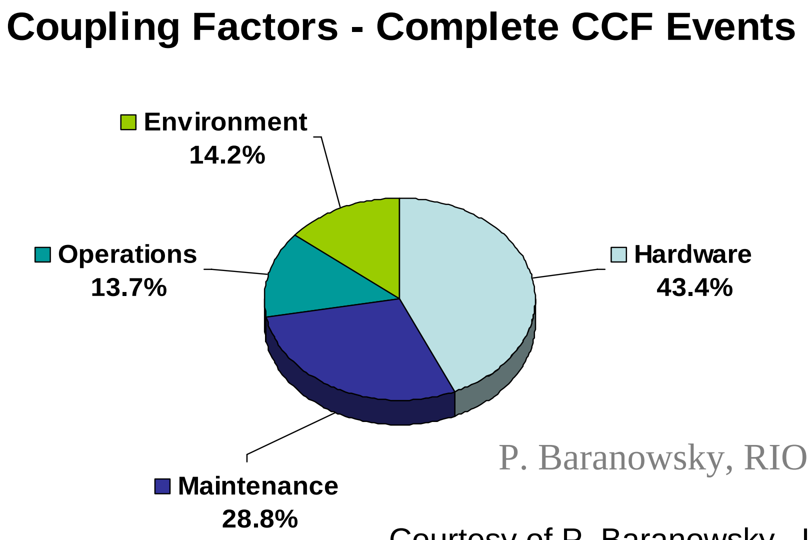

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