MODULE J

ACCIDENT SEQUENCE QUANTIFICATION

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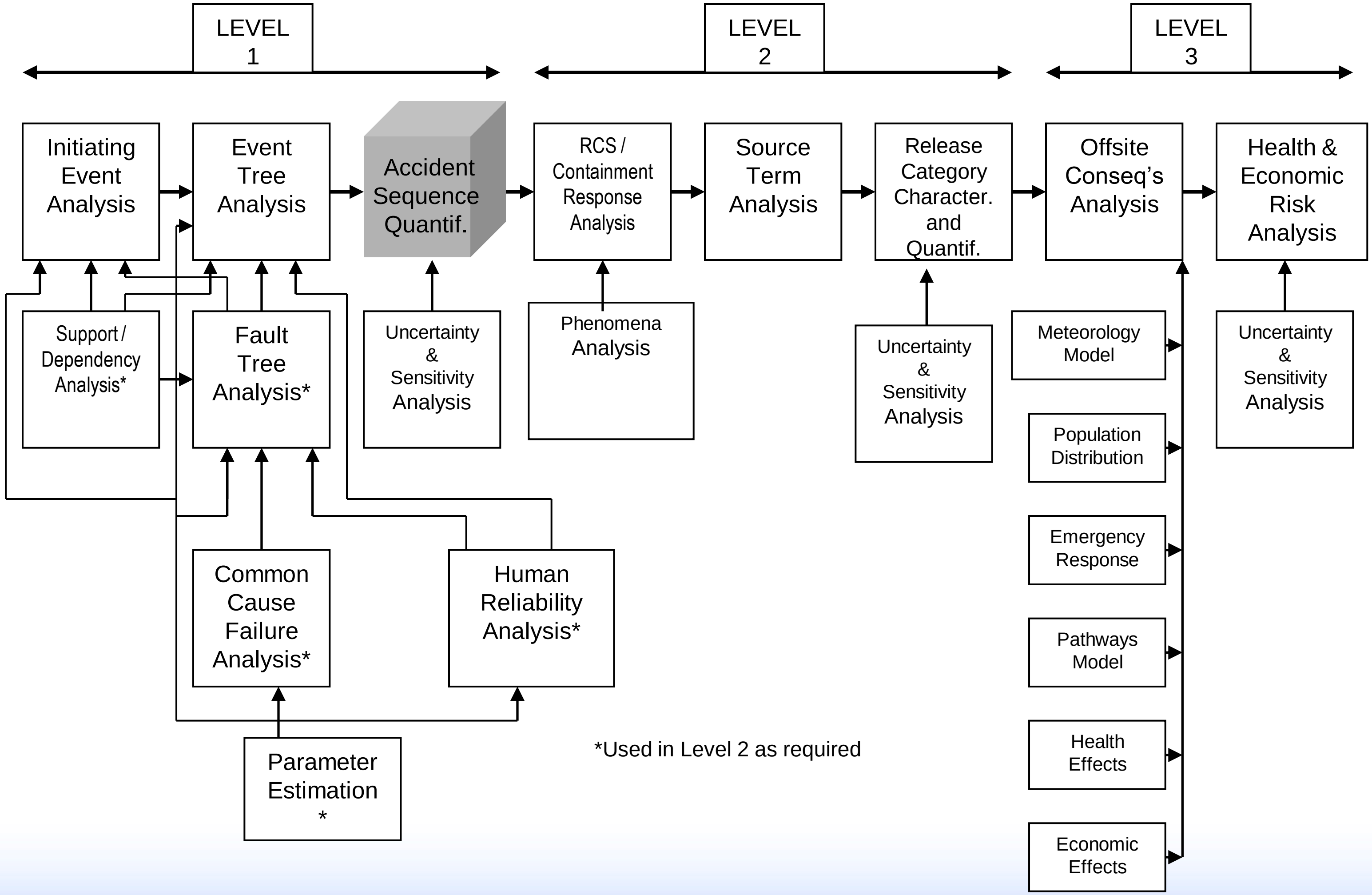
Accident Sequence Quantification

- **Purpose: Introduce the students to the purpose and methods of accident sequence quantification. Students will become familiar with how the accident sequences are quantified and understand the meaning of the results.**
- **Objectives:**
  - **Explain how the various aspects of accident sequence quantification are accomplished, including approximations that are used.**
  - **Describe the major processes for accident sequence quantification**
  - **Describe the relationship between minimal cutsets and accident sequences, for a Fault Tree Linking approach and Event Tree with Boundary Conditions approach**
  - **Given minimal cutsets of varying order (number of basic events), list the defense-in-depth features associated with each which are presumed to fail to get to core damage**
- **References: NUREG/CR-2300**

Principal Steps in PRA



*Used in Level 2 as required

Purpose of Accident Sequence Quantification

- The purpose of accident sequence quantification is to provide qualitative and quantitative insights into the initiating events and associated combinations of equipment failures and/or operational errors that are the dominant contributors to core damage frequency

Generalized Quantification Procedure

- **The following are the basic steps required to quantify accident sequences:**
  - **Identify sequences to be quantified**
  - **Screen sequences to eliminate insignificant contributors or extremely unlikely sequences**
  - **Solve plant logic models, with parameter values included, to obtain sequence minimal cut sets**
    - **In general, models are too large to solve completely; truncation is used to obtain approximate solution**
    - **Remaining analyses (uncertainty, sensitivity, importance) are carried out using this approximate solution**

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Accident Sequence Quantification

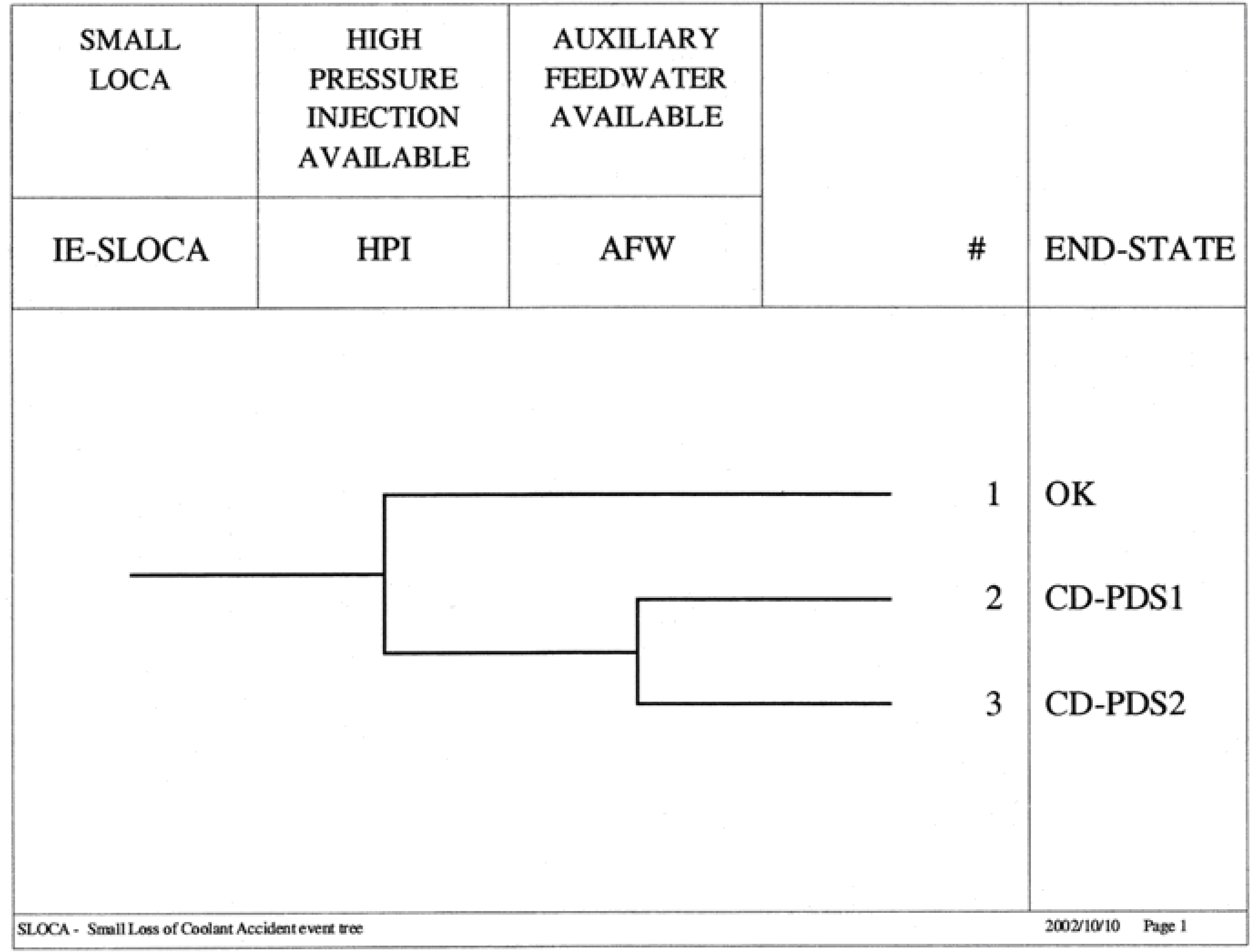
- There are two basic approaches:
  - Fault Tree Linking - Fault trees are linked to their corresponding event tree top events
    - Support system dependencies included in fault tree models
    - Tends to make fault trees complex, but simplifies event trees
  - Event Trees with Boundary Conditions - Support system dependencies explicitly included in event tree models
    - Tends to make fault trees much simpler but complicates event trees.

Fault Tree Linking

- Fault tree linking involves development of accident- sequence fault trees, which includes inputs from
  - an initiating event,
  - fault trees for failed systems in sequence logic
- Process accounts for system successes in the sequence being solved.

Simplified Example of Quantification Process

(A number of the actual event tree top events and fault tree basic events pruned for quantification illustration)



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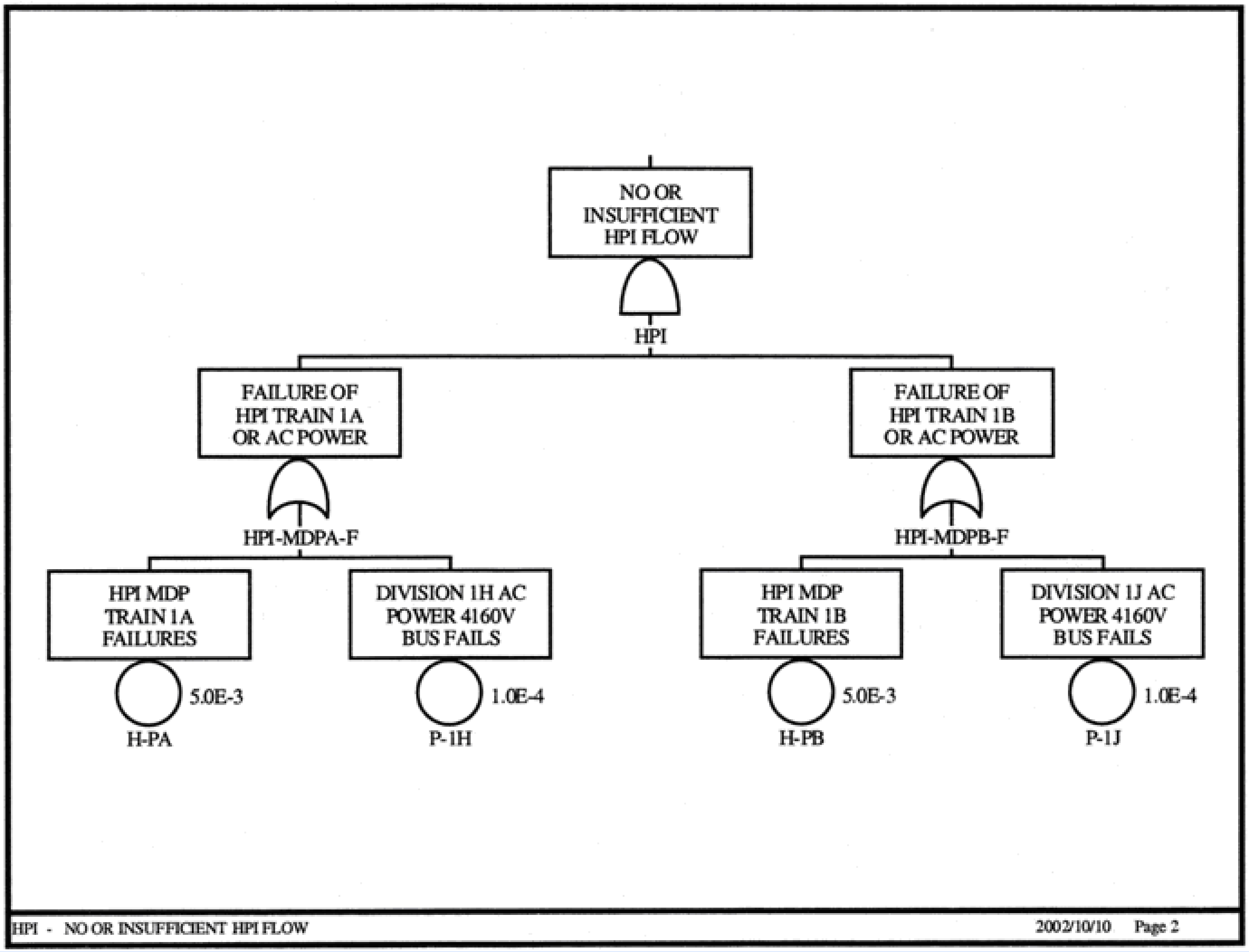
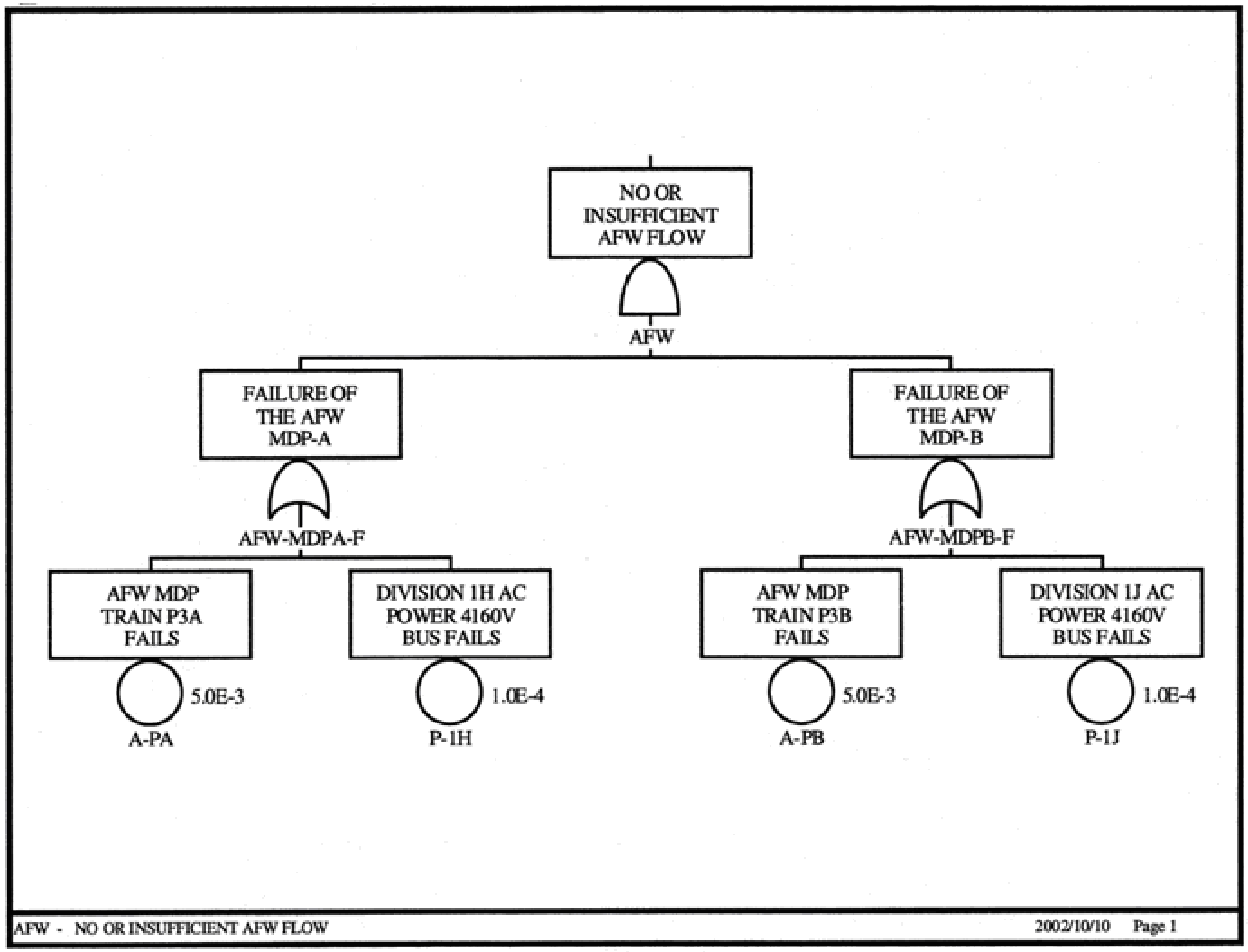
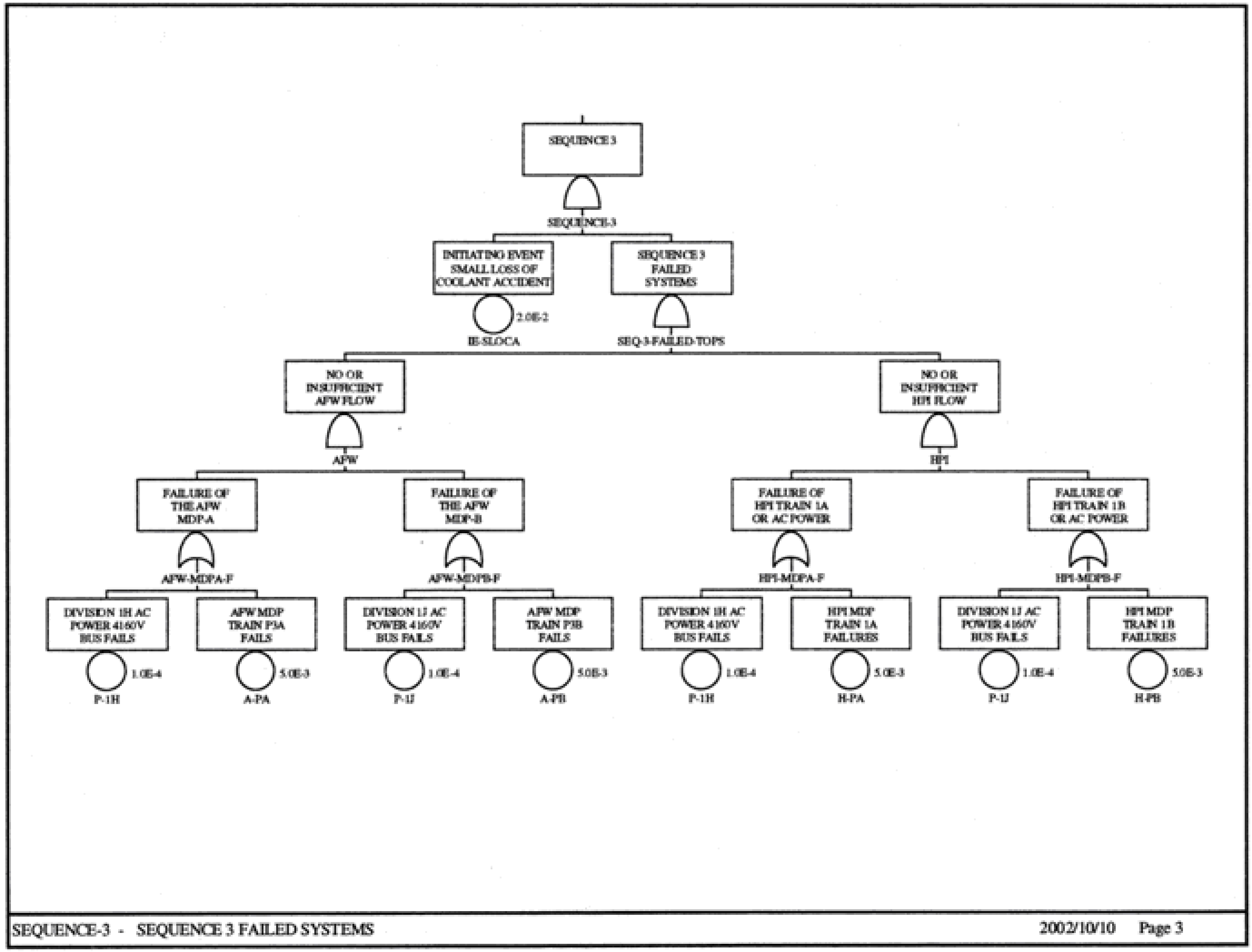
Simplified Example of Quantification Process (cont.)



Simplified Example of Quantification Process (cont.)



Simplified Example of Quantification Process (cont.)



Simplified Example of Quantification Process (cont.)

Seq3 = IE-SLOCA * System HPI Fails * System AFW Fails

= (IE-SLOCA) * (H-PA * H-PB + P-1J * H-PA + P-1H * H-PB + P-1H * P-1J) * (A-PA * A-PB + A-PA * P-1J + A-PB * P-1H + P-1H * P-1J)

= (IE-SLOCA) *

[(H-PA * H-PB * A-PA * A-PB + H-PA * H-PB * A-PA * P-1J + H-PA * H-PB * A-PB * P-1H + H-PA * H-PB * P-1H * P-1J)
+ (P-1J * H-PA * A-PA * A-PB + P-1J * H-PA * A-PA * P-1J + P-1J * H-PA * A-PB * P-1H + P-1J * H-PA * P-1H * P-1J)
+ (P-1H * H-PB * A-PA * A-PB + P-1H * H-PB * A-PA * P-1J + P-1H * H-PB * A-PB * P-1H + P-1H *H-PB * P-1H * P-1J)
+ (P-1H * P-1J * A-PA * A-PB + P-1H * P-1J * A-PA * P-1J + P-1H * P-1J * A-PB * P-1H+ P-1H * P-1J * P-1H * P-1J)]

= IE-SLOCA * (P-1H * P-1J + A-PA * H-PA * P-1J + APB * H-PB * P-1H + A-PA * A-PB * H-PA * H-PB)

Seq3 = (2E-2/Year) * (1E-4 * 1E-4 + 5E-3 * 5E-3 * 1E-4 + 5E-3 * 5E-3 * 1E-4 + 5E-3 * 5E-3 * 5E-3 * 5E-3)

= (2E-2/Year) * (1E-8 + 2.5E-9 + 2.5E-9 + 6.25E-10)

= 3.125E-10/Year

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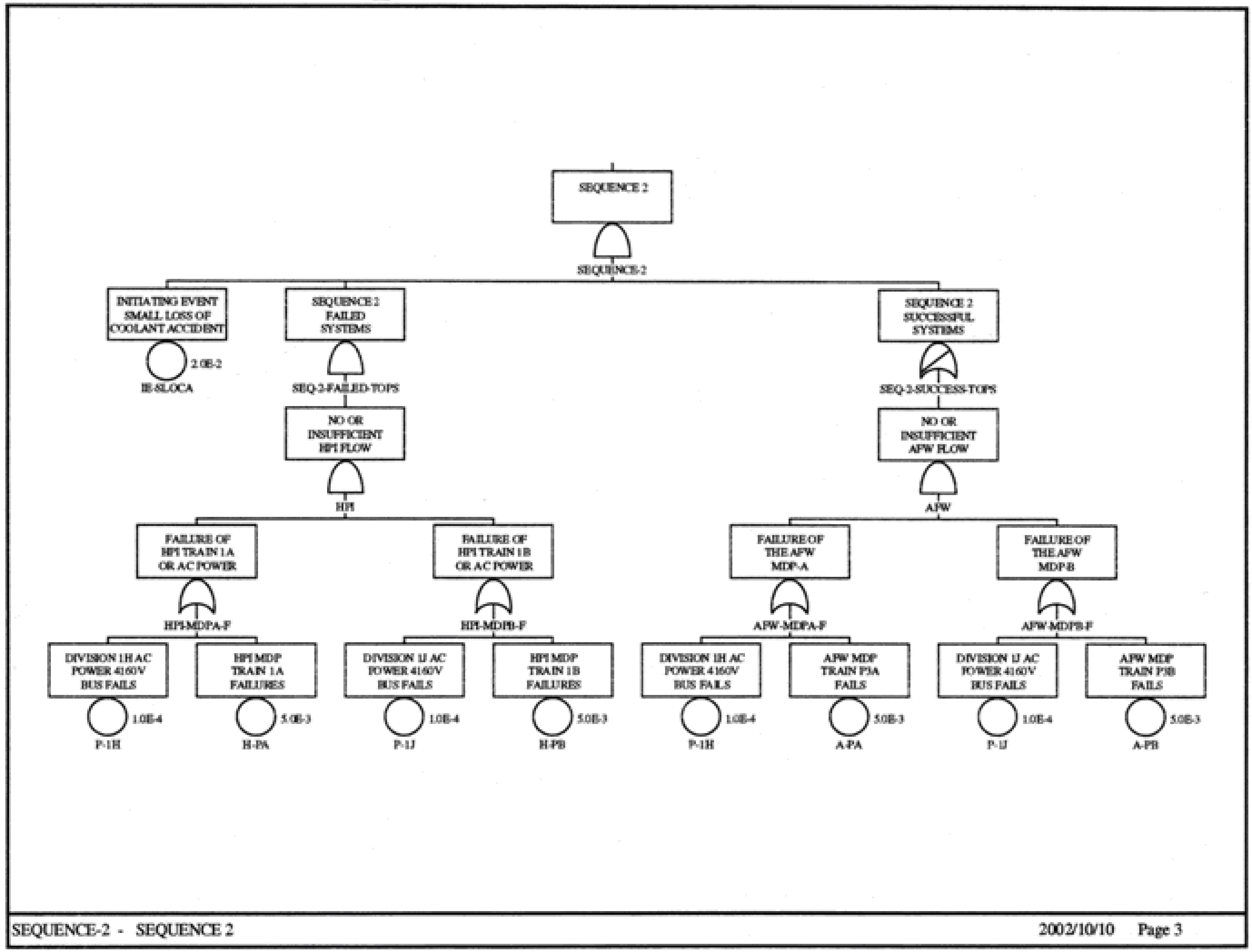
Simplified Example of Quantification Process (cont.)



Simplified Example of Quantification Process (cont.)

Seq2= IE-SLOCA * System HPI Fails * [System AFW Successful – typically a delete term process]

= (IE-SLOCA) * (H-PA * H-PB + P-1J * H-PA + P-1H * H-PB + P-1H * P-1J) * [(/A-PA * /P-1H + /A-PB * /P-1J)]

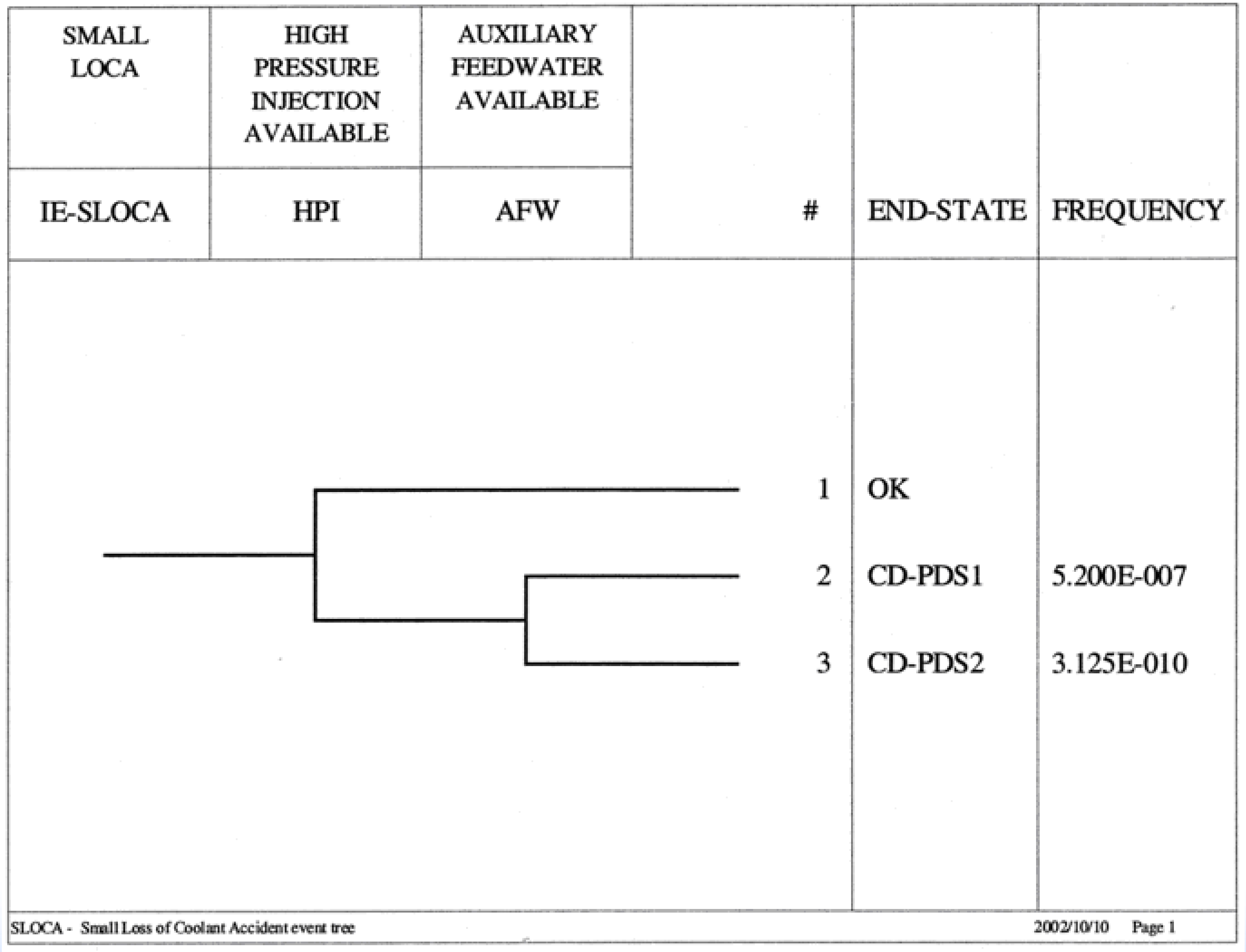
= (IE-SLOCA) * (H-PA * H-PB + P-1J * H-PA + P-1H * H-PB)

Seq2 = (2E-2/Year) * (5E-3 * 5E-3 + 1E-4 * 5E-3 + 1E-4 * 5E-3)

= (2E-2/Year) * (2.5E-5 + 5E-7 + 5E-7)

= 5.2E-7/Year

Simplified Example of Quantification Process (cont.)



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Truncation and Minimal Cut Sets

- **Truncation is practical necessity because of size of models**
  - **- Eliminates some cut sets**
- **If conservative assumptions were made regarding such things as potential recovery actions or common cause failures, then a more detailed analysis can be performed to obtain less conservative values.**

Summary of Sequence $T_2L_1P_1$

- **This sequence is initiated by a loss of main feedwater (T2), followed by failure of the auxiliary feedwater (AFW) system, and failure of feed and bleed cooling due to the inability to open both power operated relief valves (PORVs).**

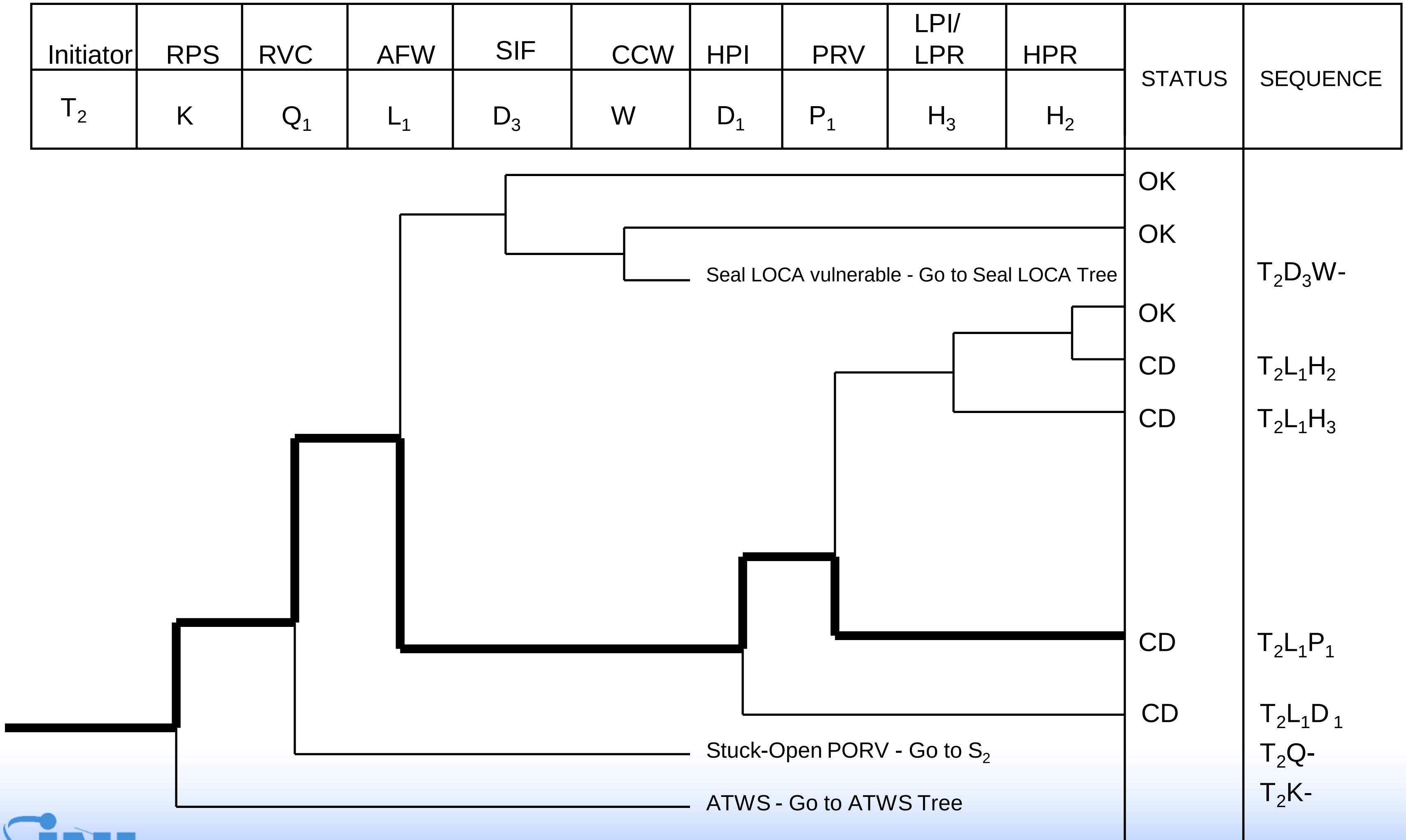
- **The loss of main feedwater initiator places a demand on auxiliary feedwater to remove core decay heat. Failure of the AFW system causes a demand for feed and bleed cooling. Failure to initiate feed and bleed and various failures which prevent one of the two PORVs from opening contribute to this sequence. Success criteria require that two PORVs open for successful feed and bleed.**

- **The dominant contributors to AFW failure are common cause failure of the air-operated steam generator level control valves and the common cause failure of all three AFW pumps due to steam binding. The dominant contributor to failure of feed and bleed is operator failure to open PORVs, followed by mechanical failures of the PORV block valves and PORVs.**

Identifiers for T_2 Event Tree

Event Identifier	Description	System Identifier
D_1	Failure of charging pump system with 1 of 4 success requirements	HPI
D_3	Failure of charging pump system in seal injection flow mode	SIF
H_2	Failure of charging pump system in the high pressure recirculation mode	HPR
H_3	Failure of low pressure injection/recirculation	LPI/LPR
K	Failure of reactor protection system	RPS
L_1	Failure of auxiliary feedwater required for transients with reactor trip	AFW
P_1	Failure of both pressurizer PORVs to open for feed & bleed	PRV
Q_1	Failure of any relief valve to reclose	RVC
W	Failure of component cooling water to the thermal barrier of all reactor coolant pumps	CCW

Event Tree for T_2 - Loss of Main Feedwater



Term Descriptions

T_2	Loss of main feedwater	7.2E-1/reactor year
STEAM-BINDING	Steam-binding of all AFWS pumps	1.0E-5
PPS-SOV-FT-334	PORV 334 fails to open	6.3E-3
PPS-SOV-FT-340A	PORV 340A fails to open	6.3E-3
AFW-TDP-FS-1AS	AFWS turbine pump fails to start	3.0E-2
AFW-TDP-FR-1AS6H	AFWS turbine pump fails to run 6 hours	3.0E-2
AFW-TDP-TM-1AS	AFWS turbine pump unavailable test and maintenance	1.0E-2
AFW-AOV-CC	AFWS AOV fails to open	1.0E-3
BETA-AFW	Common cause failure factor of 2 motor pumps	5.6E-2
BETA-8AOV	Common cause failure factor of 8 AOVs	3.4E-2
AFW-MDP-FS	AFWS motor pump fails to start	3.0E-3
HPI-XHE-FO-FDBLD	Operator fails to initiate feed and bleed	2.2E-2
AFW-ACT-FA-TRNA	AFWS Train A actuation fails	1.6E-3
AFW-ACT-FA-TRNB	AFWS Train B actuation fails	1.6E-3

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Dominant Contributors to Sequence $T_2L_1P_1$

Minimal Cut Set	Minimal Cut Set Frequency
T_2 * (AFW-AOV-CC * BETA-8AOV) * HPI-XHE-FO-FDBLD	5.4E-7
T_2 * STEAM-BINDING * HPI-XHE-FO-FDBLD	1.6E-7
T_2 * (AFW-AOV-CC * BETA-8AOV) * PPS-SOV-FT-334	1.6E-7
T_2 * (AFW-AOV-CC * BETA-8AOV) * PPS-SOV-FT-340A	1.6E-7
T_2 * AFW-TDP-FS-1AS * (AFW-MDP-FS * BETA-AFW) * HPI-XHE-FO-FDBLD	8.0E-8
T_2 * AFW-TDP-FR-1AS6H * (AFW-MDP-FS * BETA-AFW) * HPI-XHE-FO-FDBLD	8.0E-8
T_2 * STEAM-BINDING * PPS-SOV-FT-334	4.6E-8
T_2 * STEAM-BINDING * PPS-SOV-FT-340A	4.6E-8
T_2 * AFW-ACT-FA-TRNA * AFW-ACT-FA-TRNB * HPI-XHE-FO-FDBLD	4.1E-8
T_2 * AFW-TDP-TM-1AS * (AFW-MDP-FS * BETA-AFW) * HPI-XHE-FO-FDBLD	2.7E-8
Total $T_2L_1P_1$	**1.3E-6**

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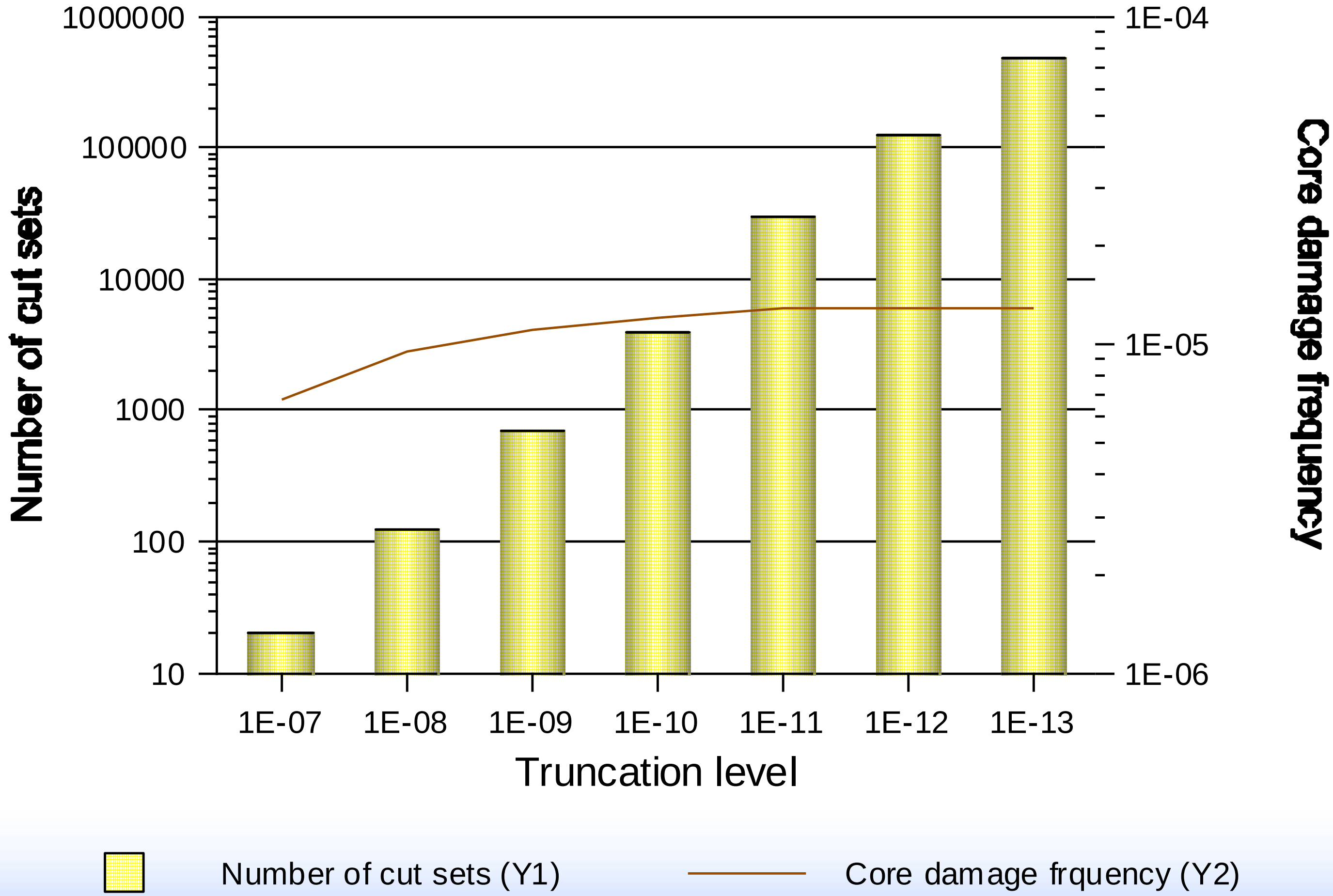
Core Damage Frequency and Number of Cut Sets Sensitive to Truncation Limits



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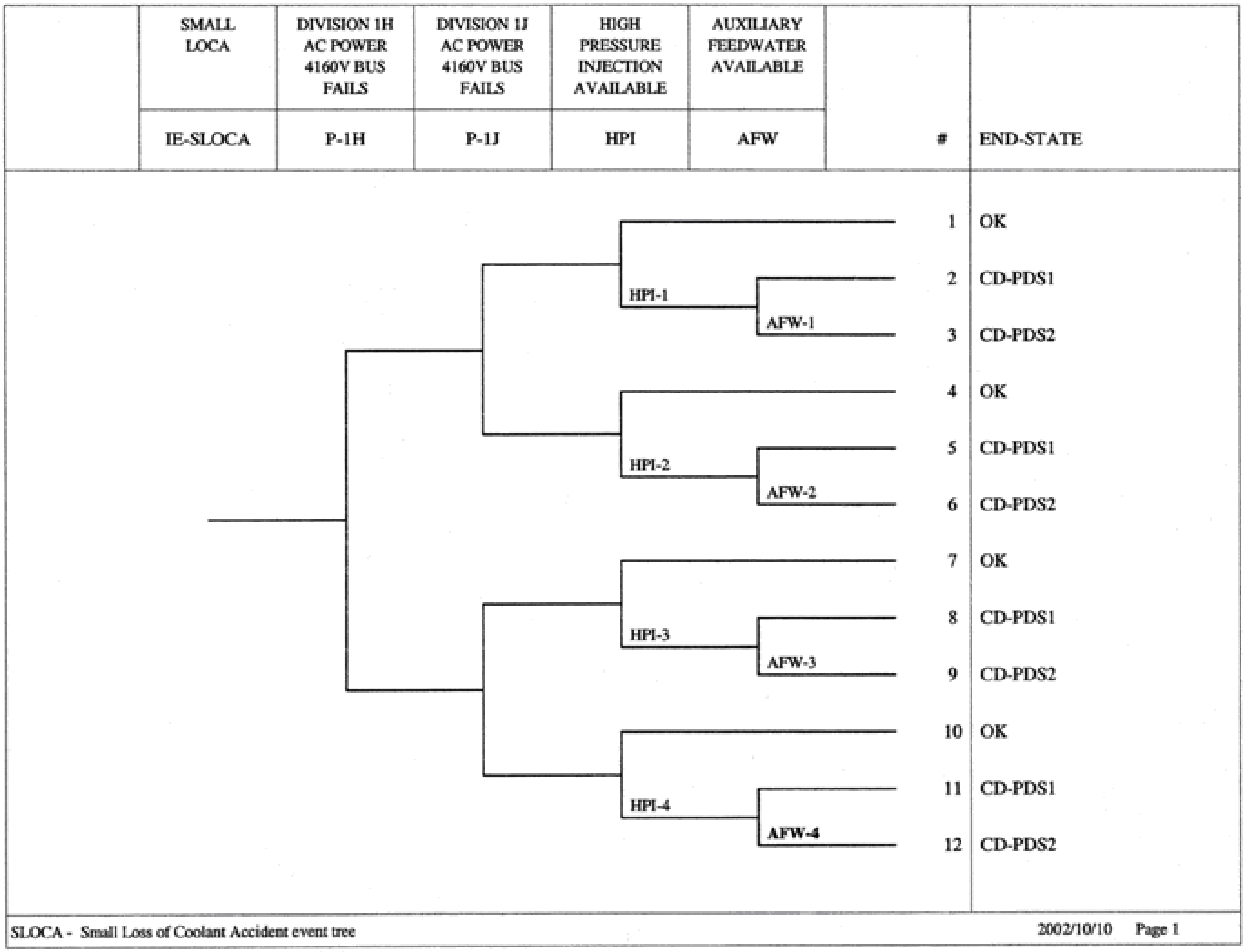
Event Trees with Boundary Conditions

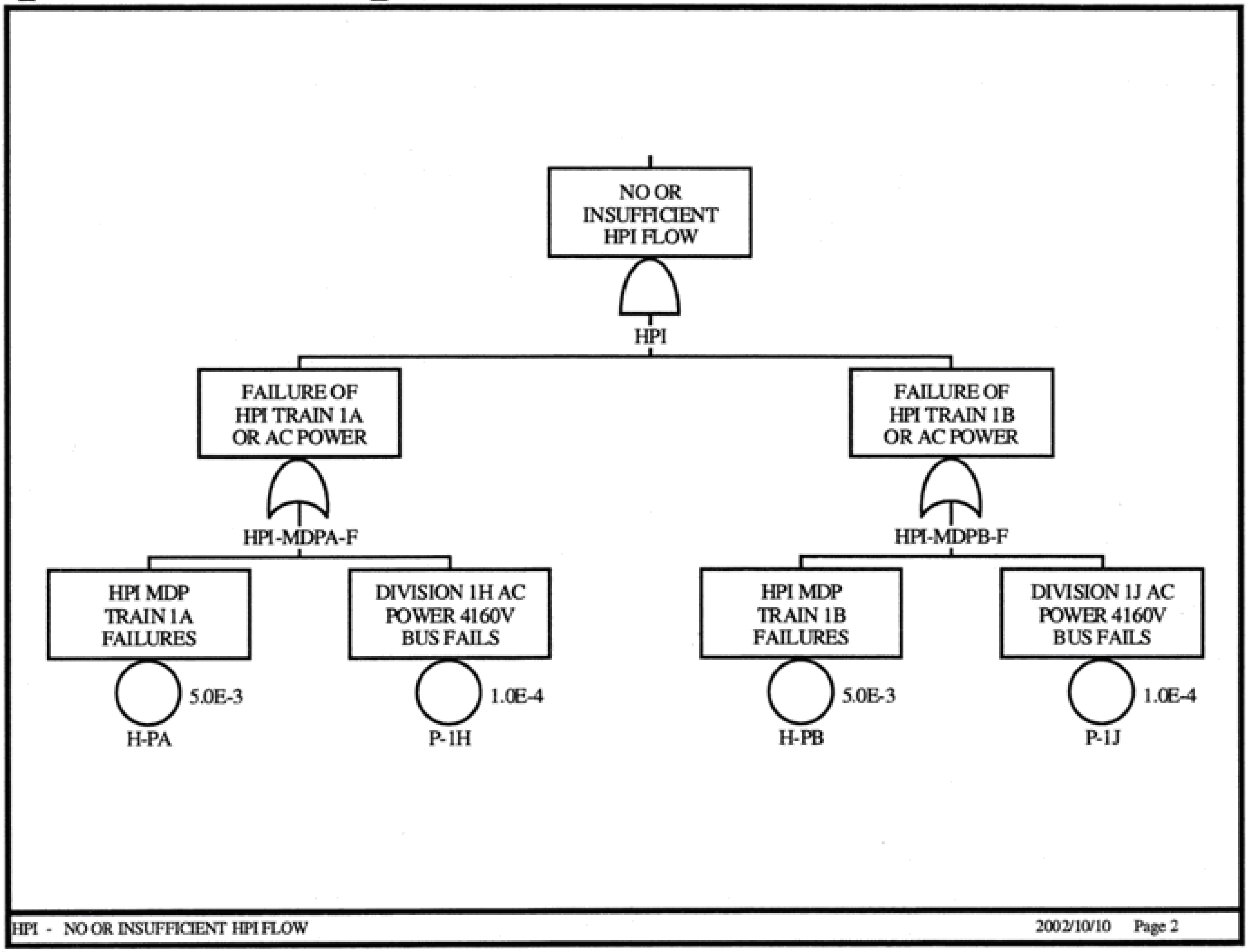
- **Event trees with boundary conditions include all of the following significant intersystem dependencies in the event trees:**
  - **Front-line system to front-line system dependencies,**
  - **Front-line system to support system dependencies,**
  - **Support system to support system dependencies,**
  - **Human errors**
  - **Environmental considerations.**
- **Split fractions are determined from system logic models for conditions represented by each particular branch point or node in question**
- **The frequency of each accident-sequence path can be calculated as the product of the initiating event frequency and all split fractions along the sequence path**

Simplified Example of Large Event Tree Quantification Process

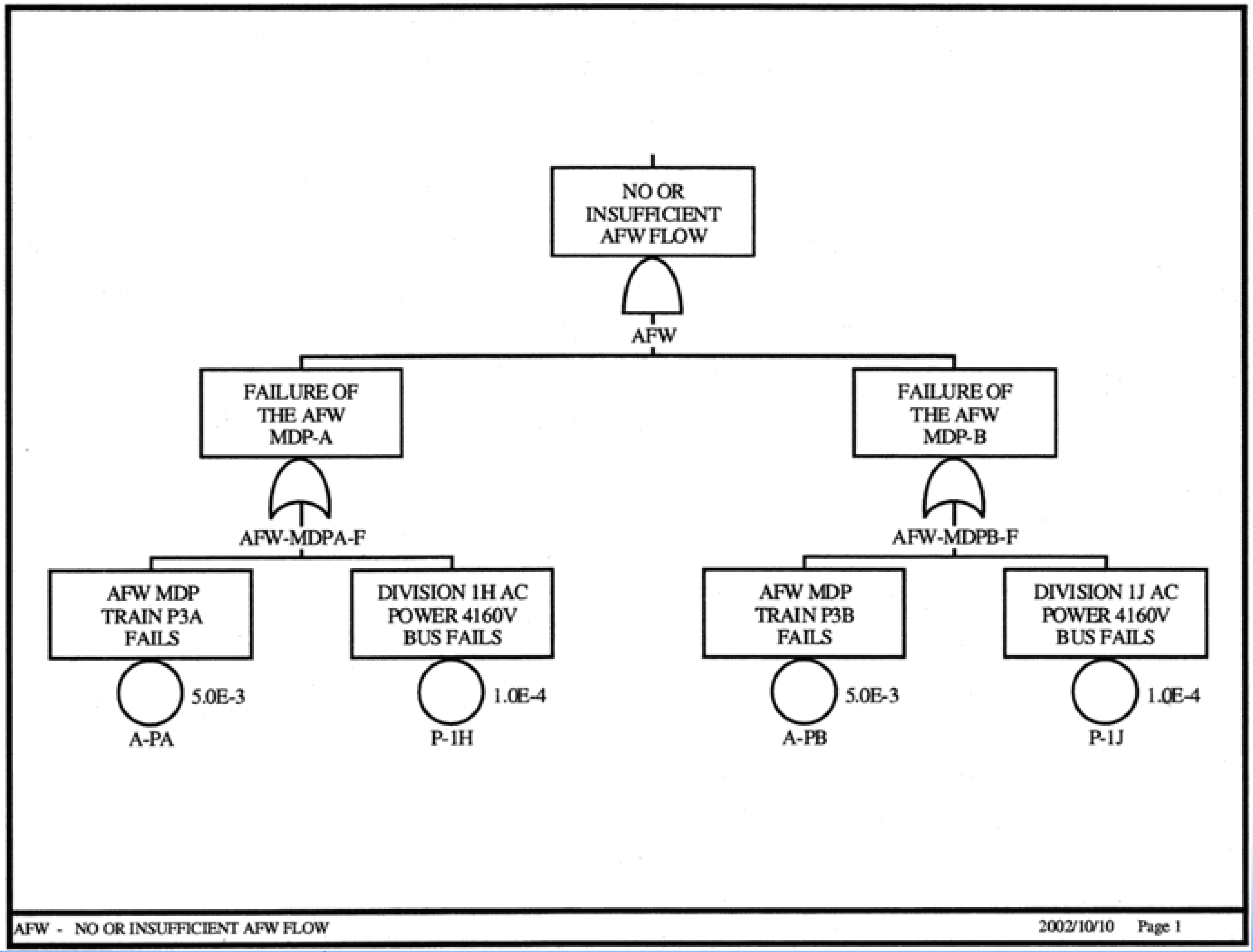
(A number of the actual event tree top events and fault tree basic events pruned for quantification illustration)



Simplified Example of Large Event Tree Quantification Process (cont.)



Simplified Example of Large Event Tree Quantification Process (cont.)



Simplified Example of Large Event Tree Quantification Process (cont.)

- **Fault Tree Split Fractions**
  - AFW-1 2.500E-005
  - AFW-2 5.000E-003
  - AFW-3 5.000E-003
  - AFW-4 1.000E+000

  - HPI-1 2.500E-005
  - HPI-2 5.000E-003
  - HPI-3 5.000E-003
  - HPI-4 1.000E+000

  - P-1H 1.000E-004
  - P-1J 1.000E-004

  - IE-SLOCA 2.000E-2/year

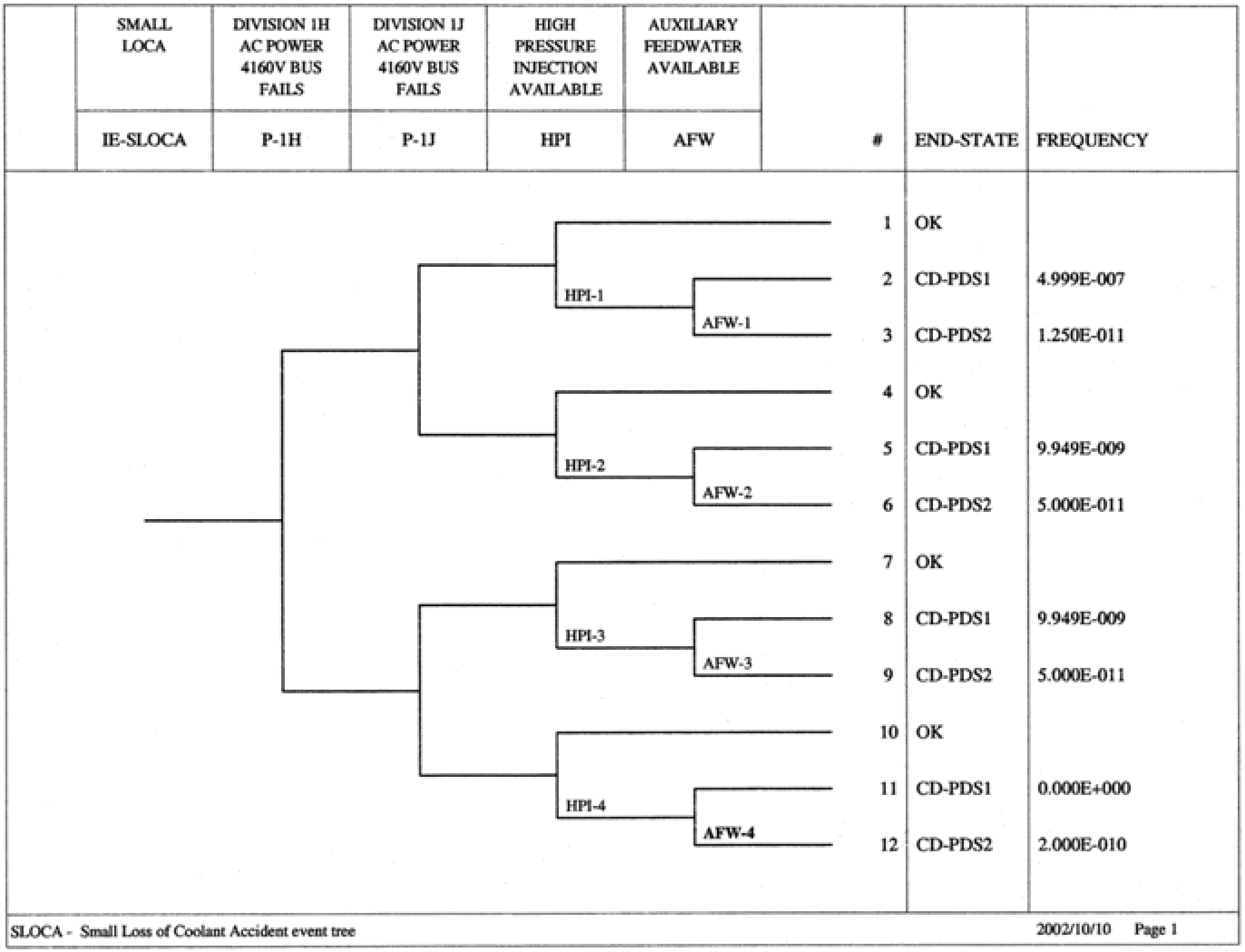
Simplified Example of Large Event Tree Quantification Process (cont.)

Sequence 2=	IE-SLOCA * /P-1H * /P-1J * HPI-1* /AFW-1
Sequence 3=	IE-SLOCA * /P-1H * /P-1J * HPI-1 * AFW-1
Sequence 5=	IE-SLOCA * /P-1H * P-1J * HPI-2* /AFW-2
Sequence 6=	IE-SLOCA * /P-1H * P-1J * HPI-2* AFW-2
Sequence 8=	IE-SLOCA * P-1H * /P-1J * HPI-3* /AFW-3
Sequence 9=	IE-SLOCA * P-1H * /P-1J * HPI-3* AFW-3
Sequence 11=	IE-SLOCA * P-1H * P-1J * HPI-4* /AFW-4
Sequence 12=	IE-SLOCA * P-1H * P-1J * HPI-4* AFW-4

Sequence 2=	4.999E-007 = 2E-2/YEAR * 0.9999 * 0.9999 * 2.5E-5* 0.999975
Sequence 3=	1.250E-011 = 2E-2/YEAR * 0.9999 * 0.9999 * 2.5E-5 * 2.5E-5
Sequence 5=	9.949E-009 = 2E-2/YEAR * 0.9999 * 1.0E-4 * 5.0E-3* 0.995
Sequence 6=	4.999E-011 = 2E-2/YEAR * 0.9999 * 1.0E-4 * 5.0E-3* 5.0E-3
Sequence 8=	9.949E-009 = 2E-2/YEAR * 1.0E-4 * 0.9999 * 5.0E-3* 0.995
Sequence 9=	4.999E-011 = 2E-2/YEAR * 1.0E-4 * 0.9999 * 5.0E-3* 5.0E-3
Sequence 11=	0.000E-000 = 2E-2/YEAR * 1.0E-4 * 1.0E-4 * 1.0E+0* 0.0E+0
Sequence 12=	2.000E-010 = 2E-2/YEAR * 1.0E-4 * 1.0E-4 * 1.0E+0* 1.0E+0

Total = 5.201E-7/Year

Simplified Example of Large Event Tree Quantification Process (cont.)



Quantification Results

- **The results of accident sequence quantification require careful scrutiny to ensure that errors in the analysis have not been made (test of reasonableness).**
  - **Cut sets or sequences that violate sequence success logic or otherwise do not reflect expected plant response**
  - **Cut sets or sequences containing event combinations precluded by Technical Specifications**
  - **Data input errors**
  - **Other errors (e.g., an AFW fault tree's transfers were defaulted to an improper value resulting in the top two AFW cut sets being missed, an order of magnitude error in AFW failure probability, and a CDF too low by a factor of two).**

Current PRA Software Codes Used by NRC and the Nuclear Plant Industry

Code and Developer:

- R&R Workstation by EPRI
  - Fault Tree linking with Event Trees
- RISKMAN by ABS Consulting
  - Event Trees with Boundary Conditions
- WinNUPRA by Scientech
  - Fault Tree linking with Event Trees
- RiskSpectrum by Relcon Scandpower AB in Sweden
  - Fault Tree linking with Event Trees
- SAPHIRE by INL
  - Fault Tree linking with Event Trees
  - Event Trees with Boundary Conditions

Student Exercise

- Answer the following from your plant's IPE/PRA
  - Which accident sequence quantification approach (i.e., Fault Tree Linking or Event Tree with Boundary Conditions) was used in your plant's IPE/PRA?
  - What are the two initiating event groups that contribute the most to the plant's CDF from a percentage contribution basis
  - What two classes of accidents or specific accident sequences (depends upon how results were presented) contribute the most to the plant's CDF?