Integrating Dual Error Propagation into Dynamic Event Trees to Support Fission Battery Probabilistic Risk Assessments

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Biography

- Graduated from University of California, Los Angeles (UCLA) in 2017 with a BS in electrical engineering.

- 2018 - 2020:
  - Developed PRA tools at The B. John Garrick Institute for the Risk Sciences, UCLA

PRA: Probabilistic Risk Assessment

Funding

- **INL LDRD -** “Quantitative Reliability Analysis for Unattended Operation of Fission Batteries”

- Nuclear Reactor Sustainment and Expanded Deployment - Fission Battery Initiative

- **Objective -** Develop R&D methods for enabling risk and reliability modeling of autonomous control systems and adversarial human actions for fission batteries.

INL: Idaho National Lab, LDRD: Lab Directed Research and Development

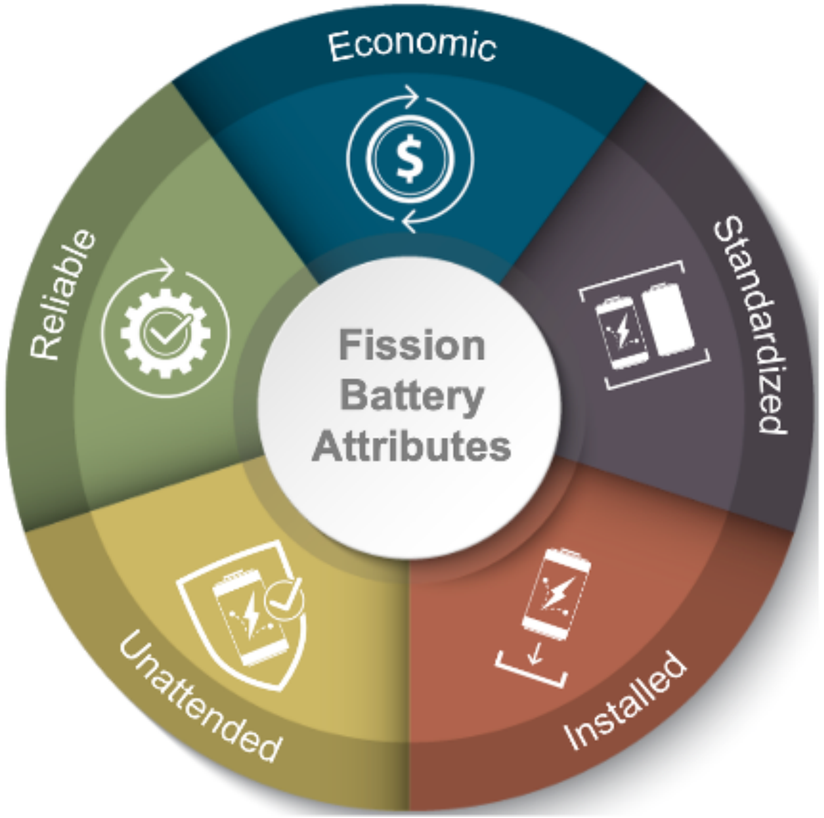
Outline

- **Introduction**
  - Fission Batteries
  - Need for Dynamic PRA
- **Methodology**
  - The Dual Error Propagation Method
- **Case Study**
  - System & Scenario
  - Three Modeling Variations
- **Results & Discussion**
  - Dynamic Event Trees with DEPM
  - DEPM vs Alternatives
- **Conclusion**
  - Limitations
  - Future Work

Fission Batteries

- Plug-&-play nuclear reactor
- Should function just like a battery

- **Attributes**
  - Economical
  - Standardized
  - Installed
  - Unattended
  - Reliable



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The Dual Error Propagation Method

Motivation

- Need for accurately modeling digital I&C reliability.

- Some challenges include:
  - Exploding state-spaces
  - CCF effects
  - Hardware-Software combination failures

CCF: Common Cause Failure, I&C: Instrumentation and Control

What is DEPM?

- DEPM
  - is a method for mapping system states onto failure states.
  - combines two* Markov chains.
  - splits state transitions into control flows and data paths.
  - can be used for fault injection, error propagation analysis, etc.

*hence, dual

A Software DEPM Example

#	Example Source Code
1	`{DATA_1, DATA_3} = function A();`
2	`DATA_2 = function B(DATA_1);`
3	`DATA_4 = function C(DATA_2, DATA_3);`

The Dual Error Propagation Method - Software Example

#	Example Source Code
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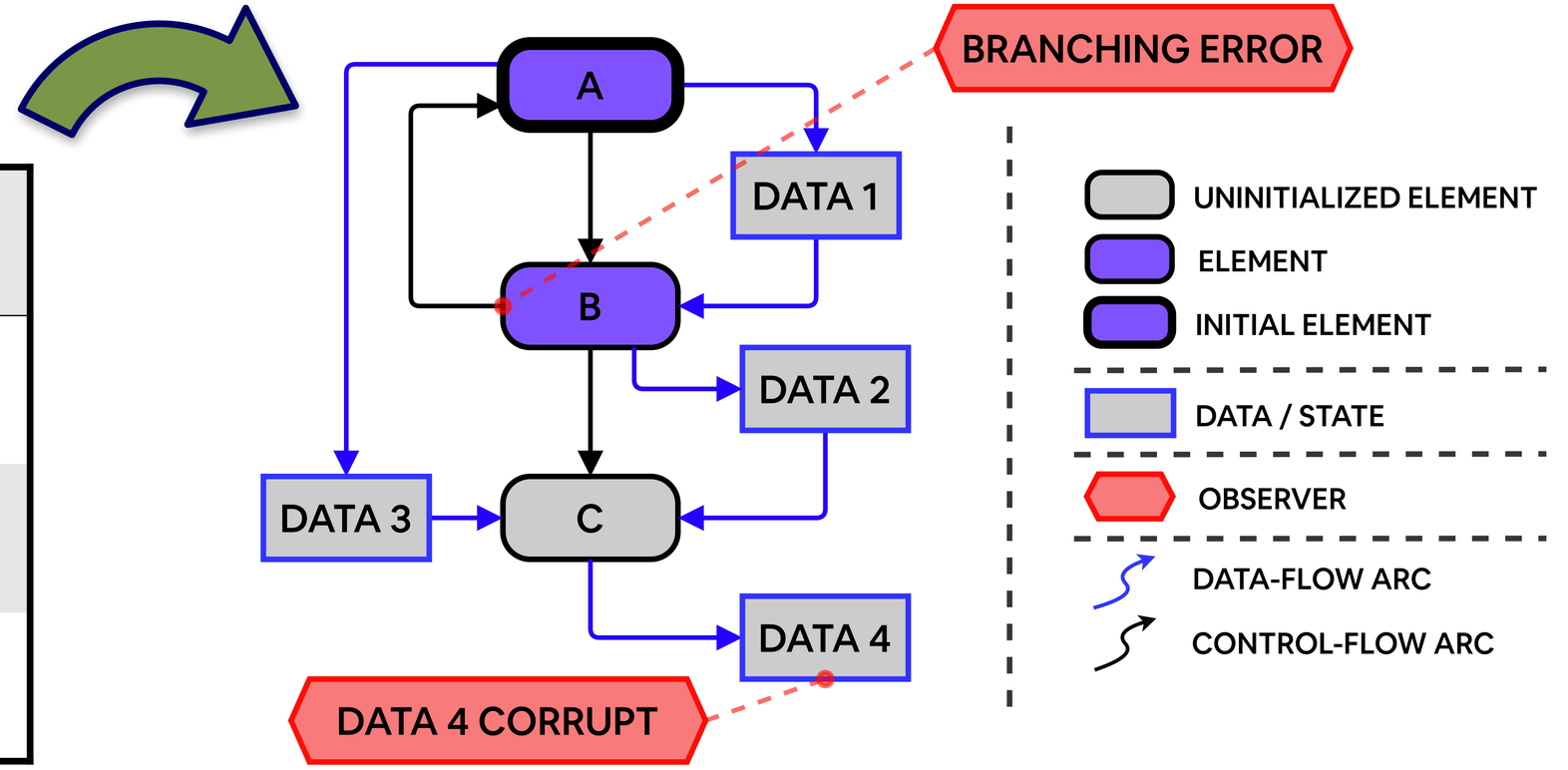
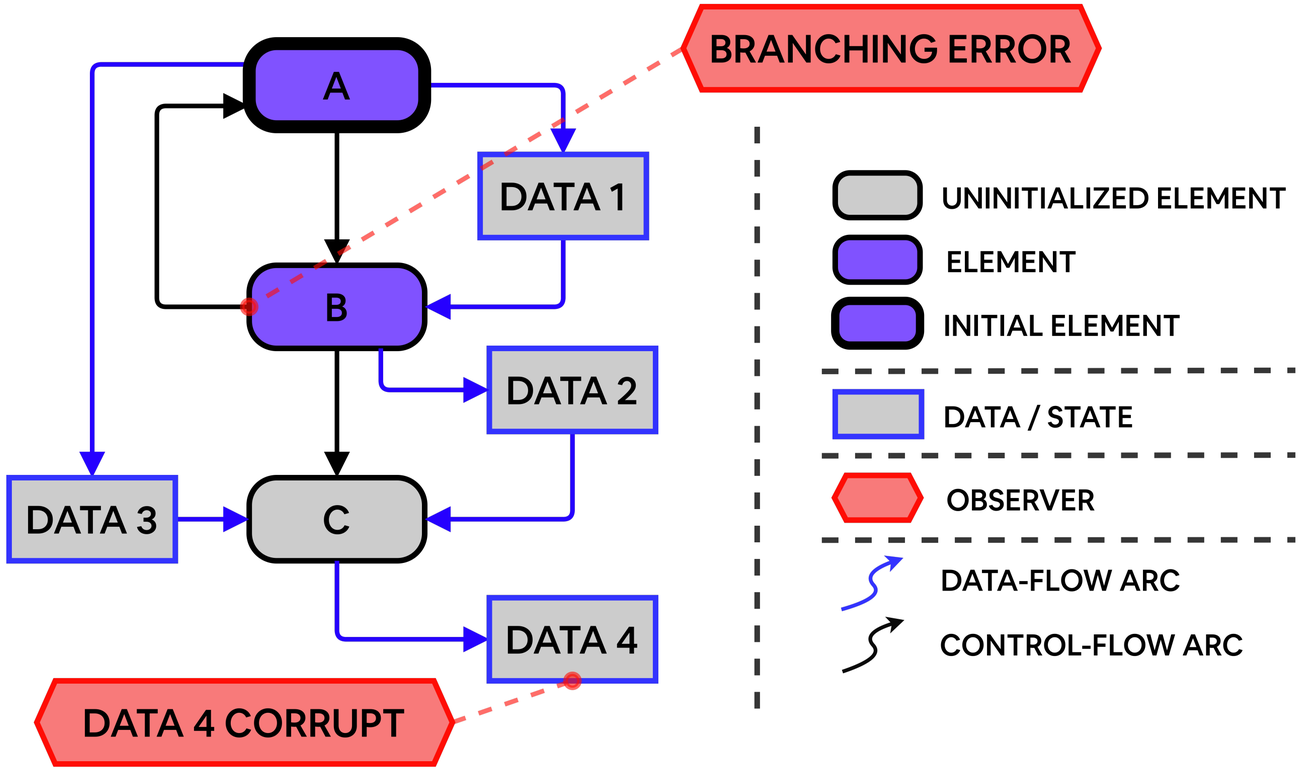


The Dual Error Propagation Method - Software Example

ID	Data Flow (DF)	Control Flow (CF)
A	always: • with P(0.9): DATA 1 = ok & DATA 3 = ok • with P(0.1): DATA 1 = error & DATA 3 = error	always: • with P(1.0): GOTO **B**

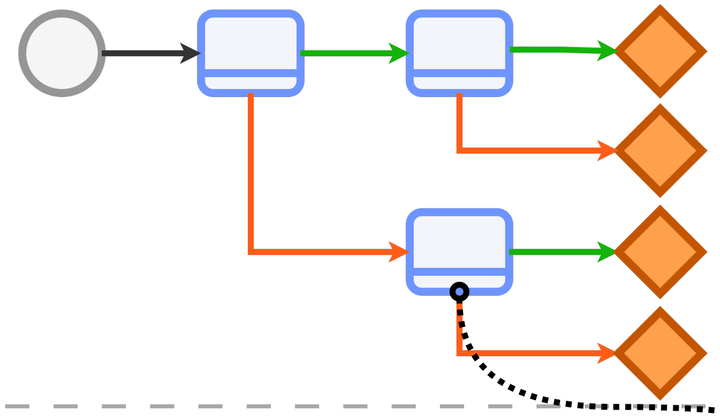
B	if DATA 1 = ok, then:
	• with P(1.0): DATA 2 = ok
	else:
	• with P(0.8): DATA 2 = ok
	• with P(0.2): DATA 2 = error
		always:
		• with P(0.3): GOTO **A**
		• with P(0.7): GOTO **C**

C	if DATA 2 = ok & DATA 3 = ok, then:
	• with P(1.0): DATA 4 = ok
	else:
	• with P(0.8): DATA 4 = error
	• with P(0.2): DATA 4 = ok
		–

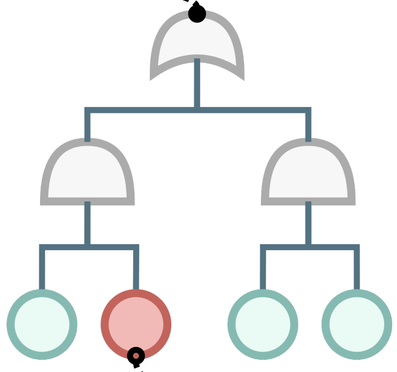


Observer Term	Logical Expression
BRANCHING ERROR	(CF = B) AND (CF′ = A)
DATA 4 CORRUPT	(DATA 4) != (‘OK’)

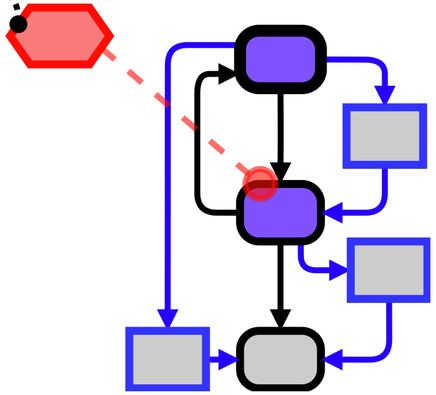
The Dual Error Propagation Method - Integration



Event Sequence Diagram / Event Tree



Fault Tree



Dual Error Propagation Graph

Case Study

Case Study - Scenario Description

- Wildfire
- Four Phases
  - Ignition
  - Propagation
  - Peak
  - Mitigation

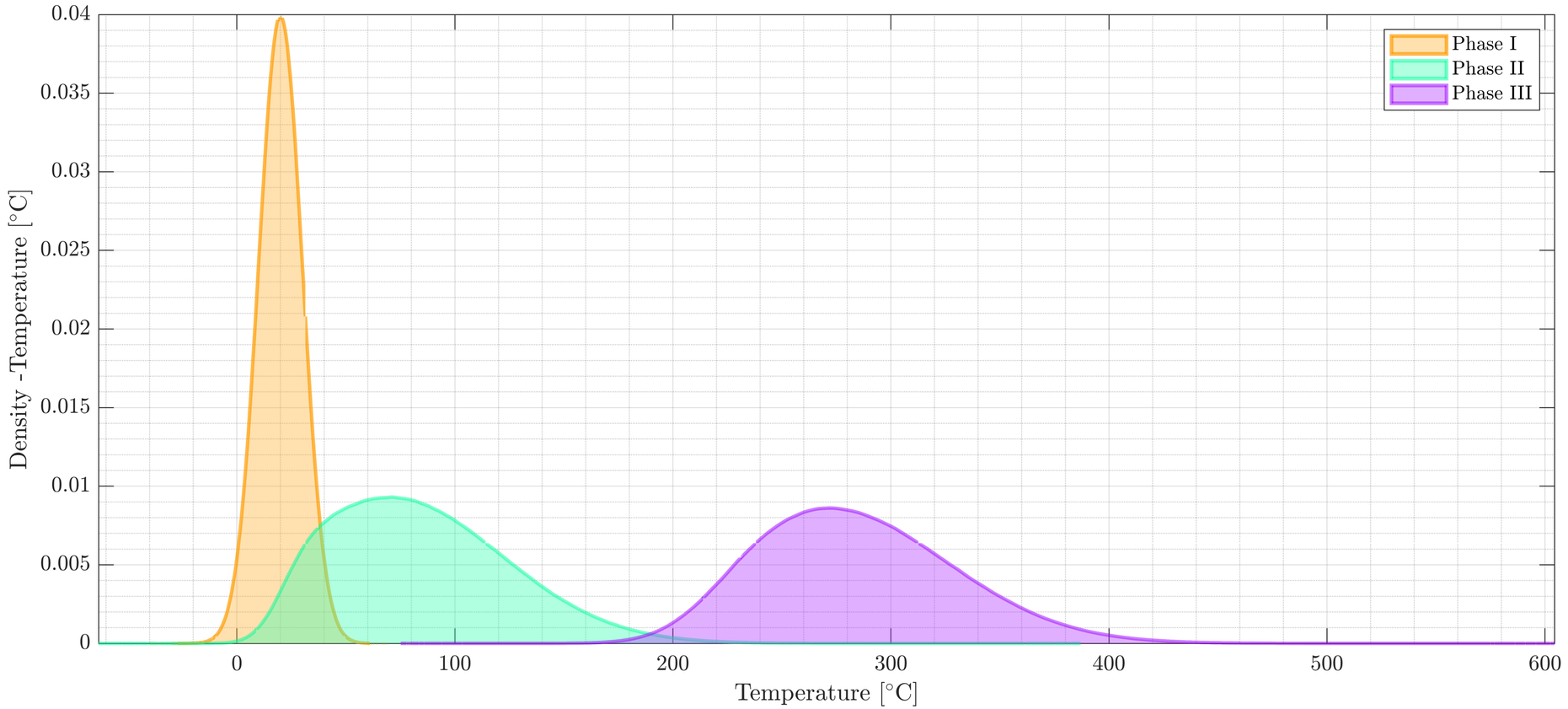


Table 4.3. Ambient temperature, phase durations and total elapsed time since ignition for fire phases I through IV.

Ø	Phase	Temperature [˚C]	Phase Duration [min]	Elapsed Time t_{Φ_i} $[min]$
I	Ignition	$\mathcal{N}(\mu = 20\,℃, \sigma = 10\,℃)$	$\mathcal{N}(\mu = 120m, \sigma = 10m)$	$0m$
II	Propagation	$\mathcal{N}(\mu = 75\,℃, \sigma = 45\,℃)$	$\mathcal{N}(\mu = 15m, \sigma = 5m)$	$\mathcal{N}(\mu = 120m, \sigma = 10m)$
III	Peak	$\mathcal{N}(\mu = 275\,℃, \sigma = 50\,℃)$	$\mathcal{N}(\mu = 30m, \sigma = 10m)$	$\mathcal{N}(\mu = 135m, \sigma \approx 11.2m)$
IV	Mitigation	$\mathcal{N}(\mu = 20\,℃, \sigma = 10\,℃)$	–	$\mathcal{N}(\mu = 165m, \sigma = 15m)$

Case Study - Scenario Description

- However, notification of wildfire event may be delayed
- Lagged notification is modeled as Phase Alert Delay

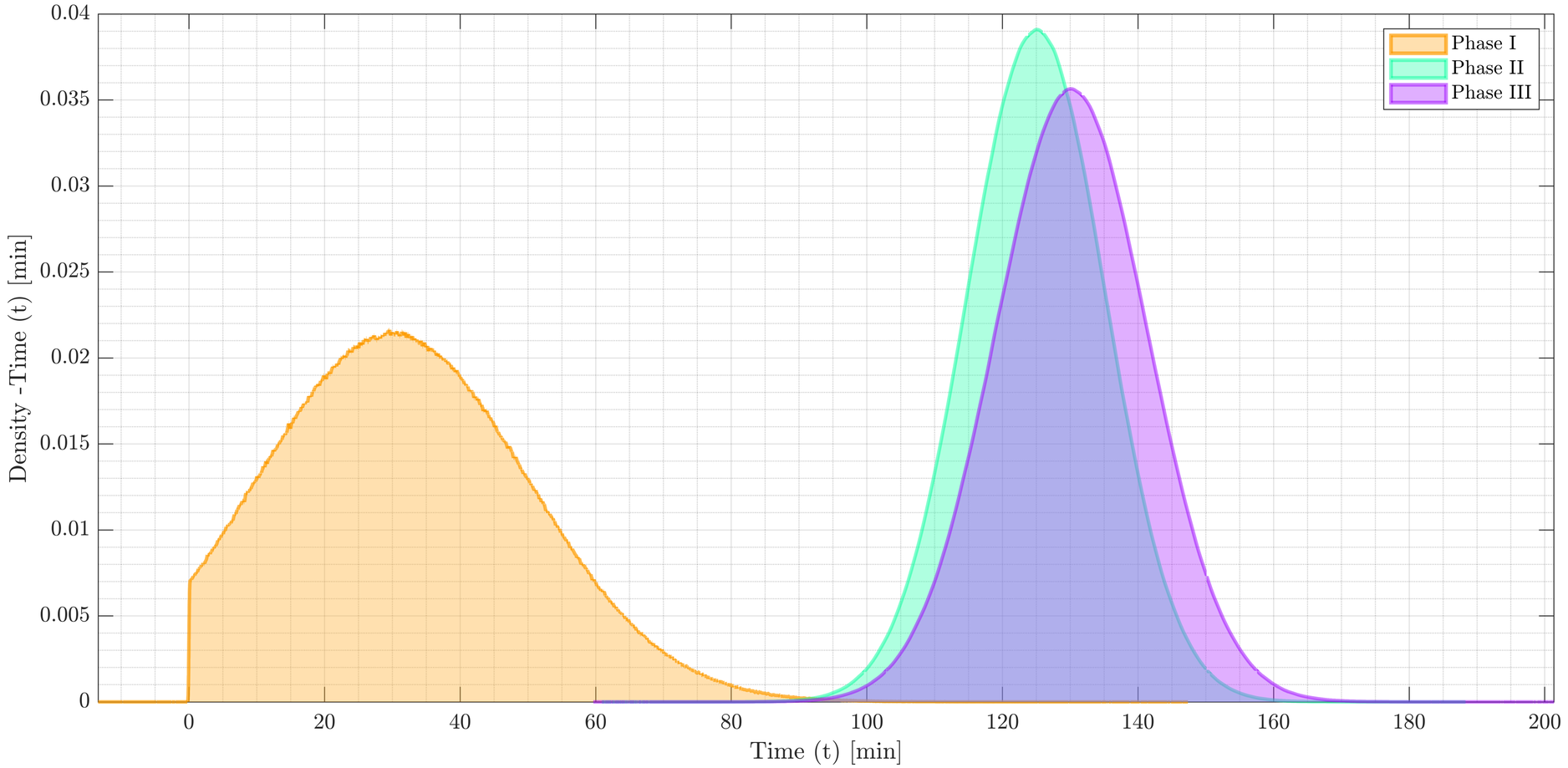


Table 4.4: Alert delays and elapsed time for fire alerts during phases I, II, and III.

Ø	Phase	Phase Alert Delay $\delta_i t\ [min]$	Elapsed Time $t_{\alpha_i}[min]$
I	Ignition	$\mathcal{N}(\mu = 30\ min\ , \sigma = 20\ min)$	$\mathcal{N}(\mu = 30\ min\ , \sigma = 20\ min)$
II	Propagation	$\mathcal{N}(\mu = 5\ min\ , \sigma = 2\ min)$	$\mathcal{N}(\mu = 125\ min\ , \sigma \approx 10.2\ min)$
III	Peak	$\mathcal{N}(\mu = 10\ sec\ , \sigma = 5\ sec)$	$\mathcal{N}(\mu \approx 135.17\ min\ , \sigma \approx 11.1\ min)$

Case Study - Scenario Description

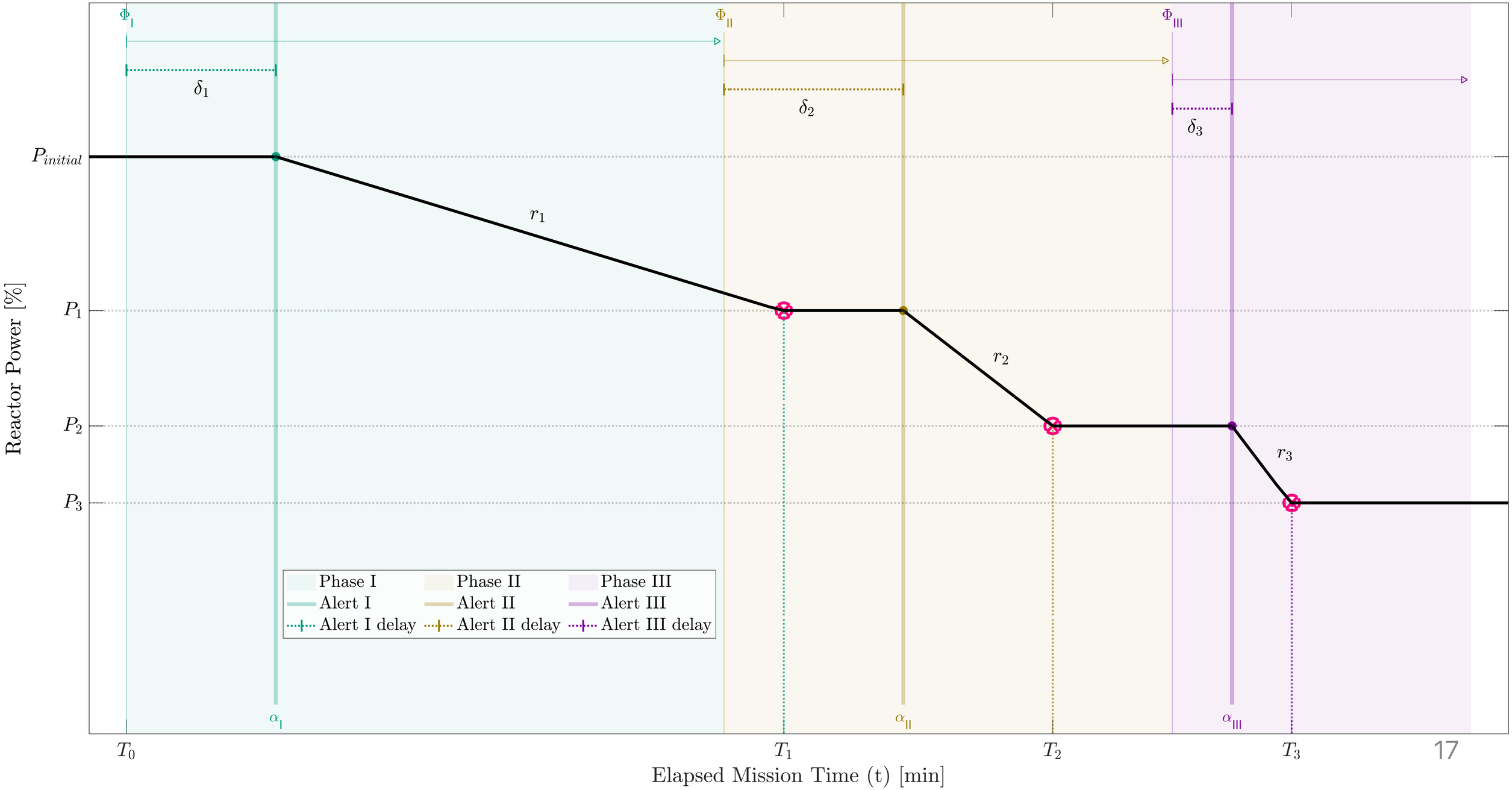
Fission Battery Response

- Graded Shutdown
- Success Criteria - Target power levels and times

Table 4.2: Success Criteria Definition for Reactor Power Level Reduction Events

Ø	Phase	Target Power $P(T_i)$ [%]	Power Reduction Rate r_i [%/time]	Time to Target Power [duration]	Elapsed Time at Target Power T_i $[min]$
I	Ignition	50%	50% *per hour*	60 *min*	$\mathcal{N}(\mu \approx 92.8\,, \sigma \approx 17.6)$
II	Propagation	20%	6% *per min*	5 *min*	$\mathcal{N}(\mu \approx 130.0, \sigma \approx 10.2)$
III	Peak	0%	1% *per sec*	20 *sec*	$\mathcal{N}(\mu \approx 130.8, \sigma \approx 11.1)$

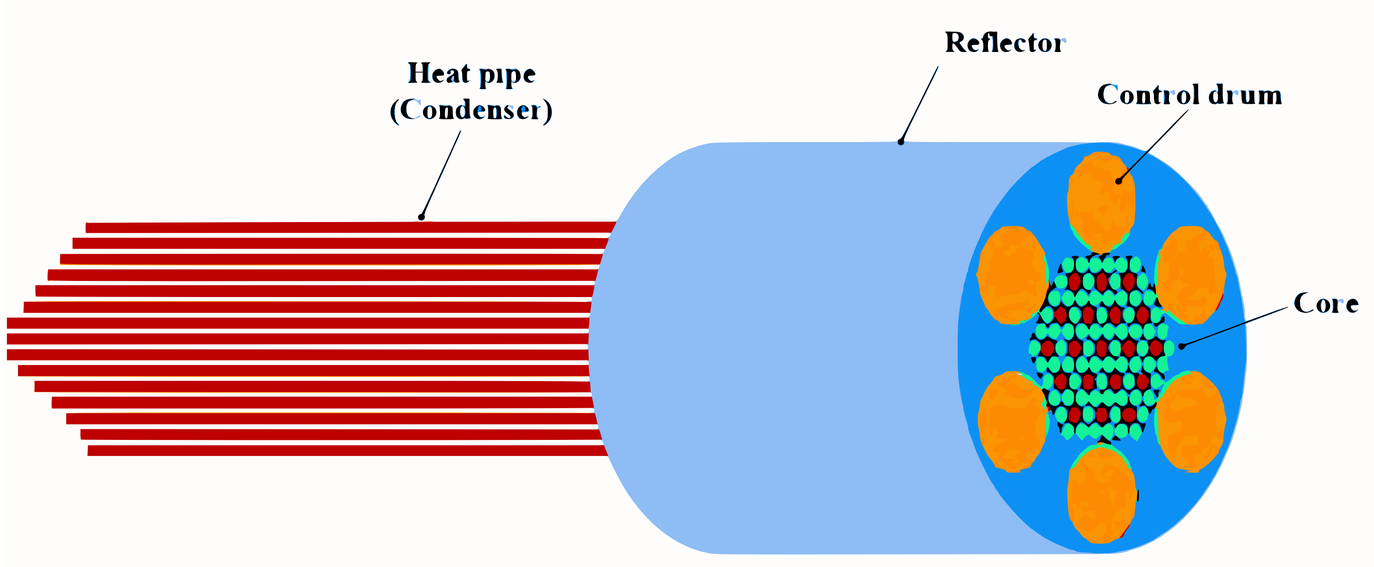
Graded Shutdown - Target Reactor Power Levels



Case Study - System Description

Reactor Control System (RCS)

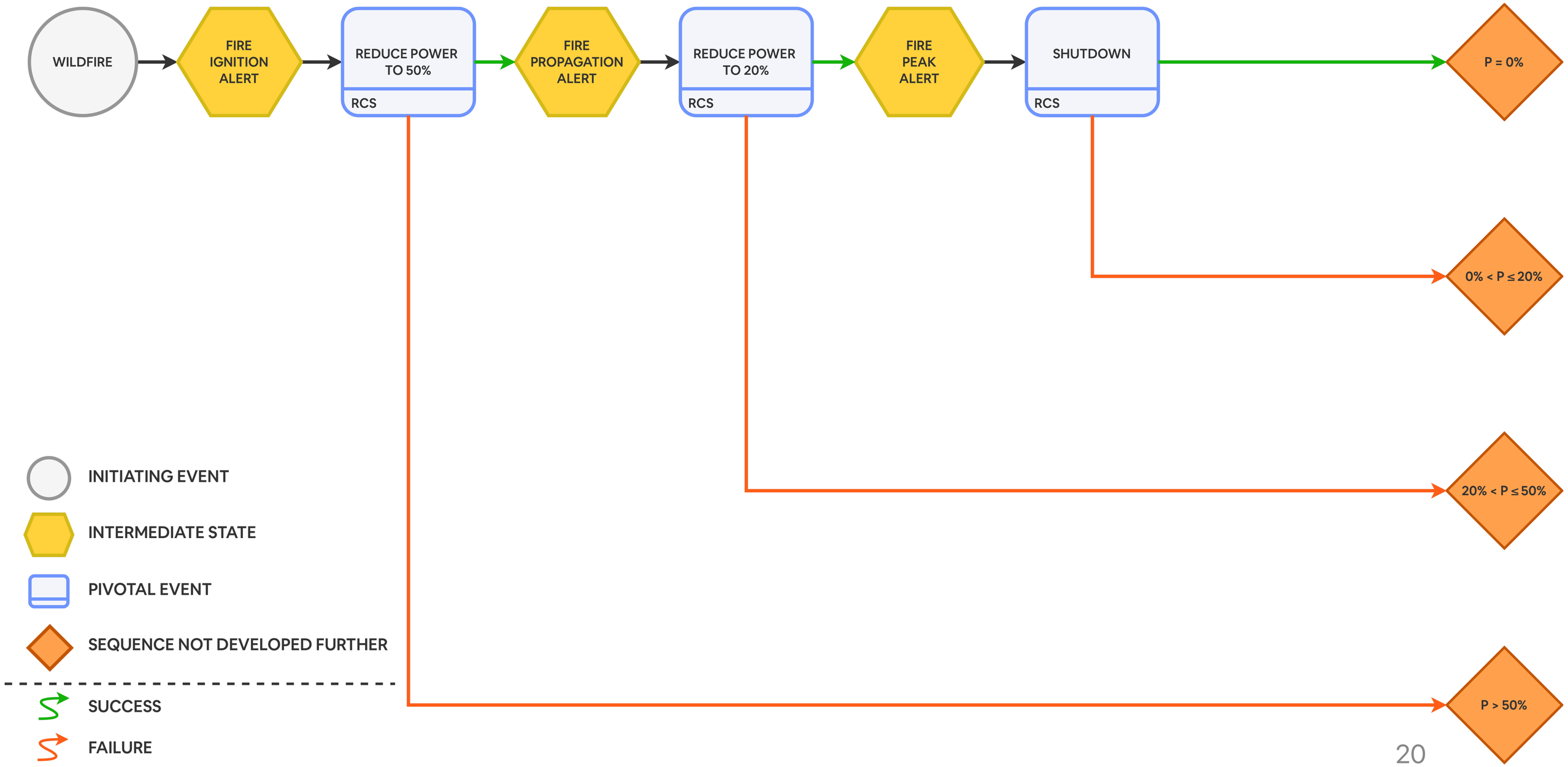
- Fully automated control
- Actuates 6 Control Drums
- Uses 3 PLCs for redundancy
- Each PLC implements a software PID loop - 6 total PID Loops



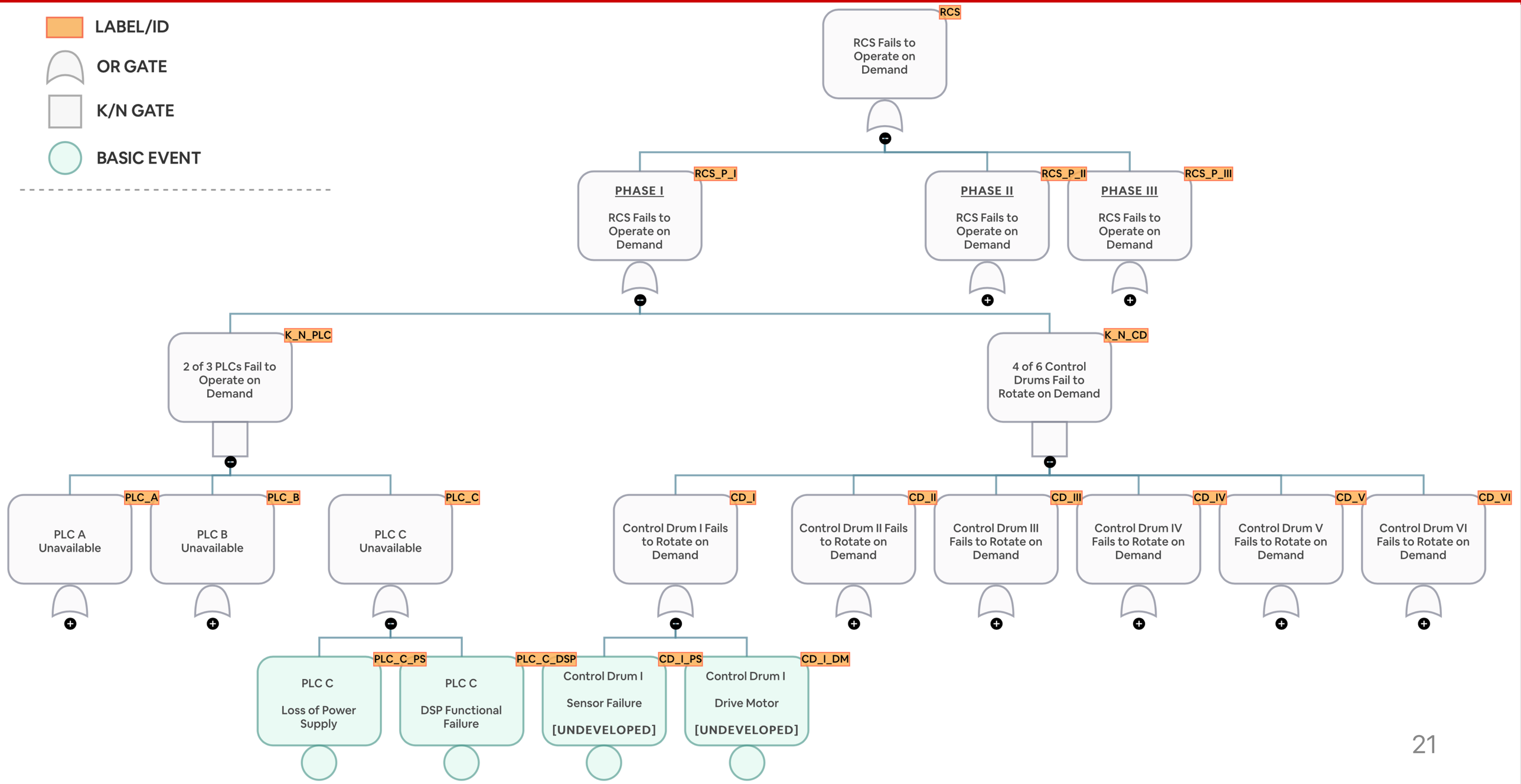
PLC: Programmable Logic Controller, PID: Proportional Integral Derivate

CASE 1: Event Sequence Diagram / Fault Tree Approach

CASE 1: RCS Power Down ESD



CASE 1: RCS Unavailability Fault Tree



CASE 1: DSP Hardware Failure Rate Estimation

#	TMS320 Variant	Failure Rate $[failures/hr]$
1	C25-GBL	1.80×10^{-9}
2	C28-343-ZFEQ	1.82×10^{-9}
3	C55-34-AZAY10	2.10×10^{-9}
4	C28-01-PZA	2.26×10^{-9}
5	C67-48-EZWT4	4.50×10^{-9}
6	C20-3PZ	5.60×10^{-9}
7	C66-78ACYP	6.55×10^{-9}
8	C20-6PZ80	14.40×10^{-9}

$$\lambda_{derated} = \mathcal{N}(\mu \approx 5.89, \sigma \approx 3.50) \times 10^{-9}$$

Arrhenius Model

$$AF_{DSP} = exp\left[\left(\frac{-E_a}{k_B}\right)\left(\frac{1}{T_{test}} - \frac{1}{T_{phase}}\right)\right]$$

$$\lambda_{DSP} = AF_{DSP} \times \lambda_{derated}$$

$$E_a = \mathcal{U}(0.45, 1.00)$$

$$T_{test} = 328.15\ K$$

CASE 1: DSP Temperate Adjusted Failure Rate

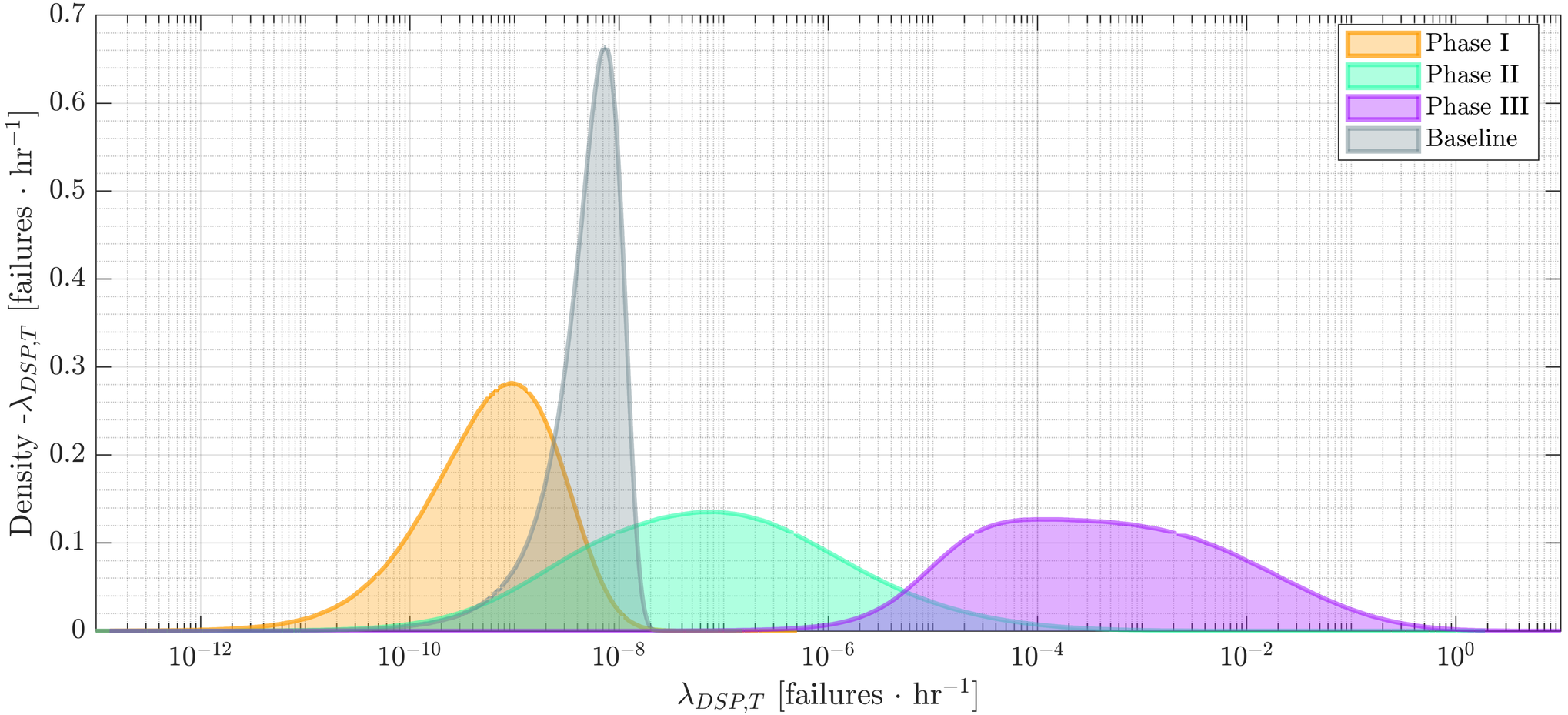


Table 4.6. Phase-dependent, temperature adjusted, digital signal processor failure rates.

Ø	Phase	Acceleration Factor AF_{DSP}	DSP failure rate λ_{DSP} $[failures/hr]$
-	Baseline	-	$\mathcal{N}(\mu \approx 5.89 \times 10^{-9}, \sigma \approx 3.50 \times 10^{-9})$
I	Ignition	$LN(\bar{m} \approx 2.57 \times 10^{-1}, EF \approx 7.36)$	$LN(\bar{m} \approx 1.74 \times 10^{-9}, EF \approx 11.9)$
II	Propagation	$LN(\bar{m} \approx 7.01 \times 10^{2}, EF \approx 90.2)$	$LN(\bar{m} \approx 4.73 \times 10^{-6}, EF \approx 114)$
III	Peak	$LN(\bar{m} \approx 2.82 \times 10^{6}, EF \approx 73.1)$	$LN(\bar{m} \approx 1.90 \times 10^{-2}, EF \approx 93.7)$

CASE 1: Temperature Dependent Hardware Failure Rates

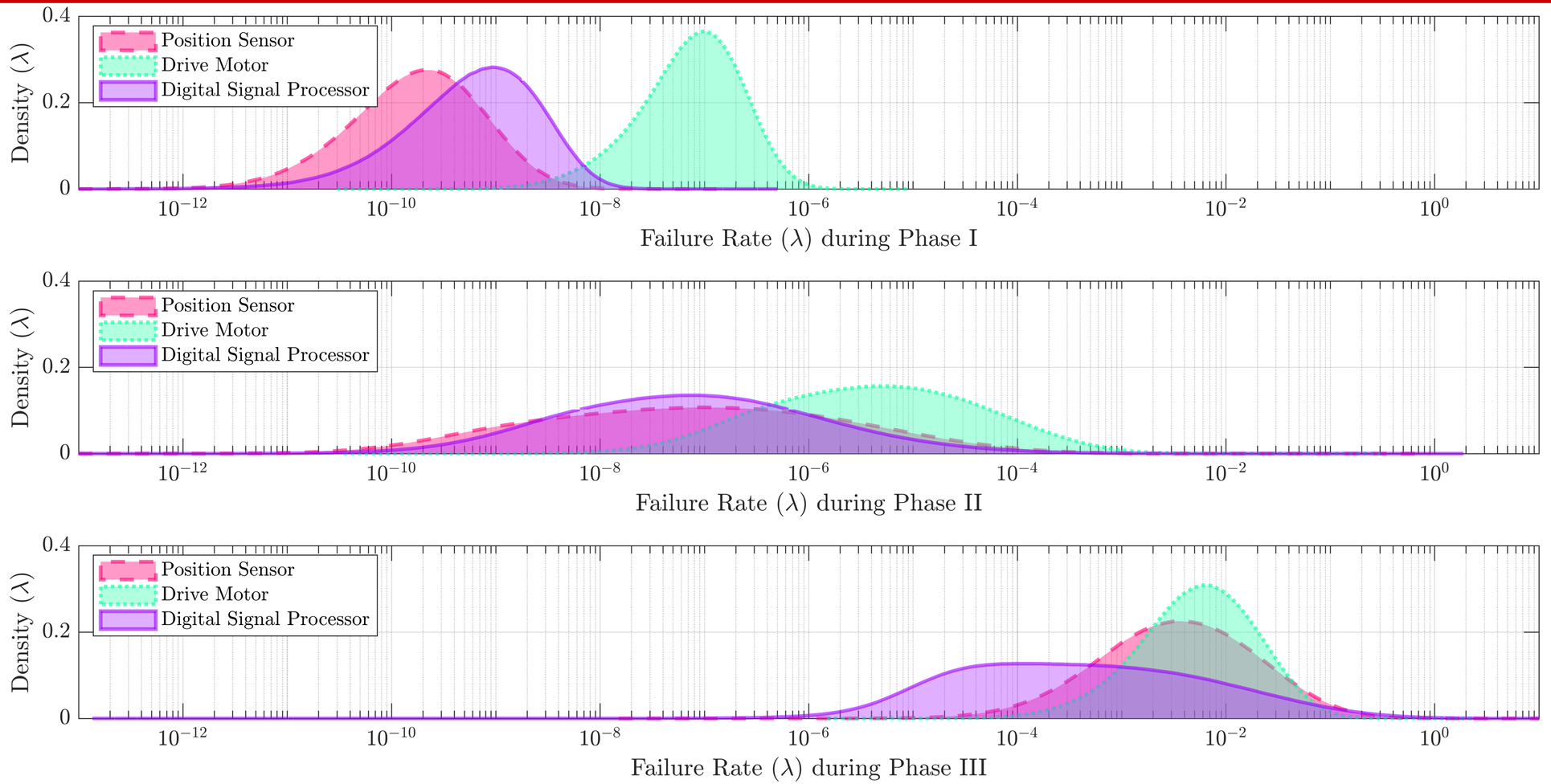


Table 4.8: Temperature Dependent Failure Rates for Programmable Logic Controller, Control Drum Failure Modes

Phase	Phase I	Phase II	Phase III
Position Sensor	$\mathcal{LN}(\bar{m} \approx 4.93 \times 10^{-10}, EF \approx 11.3)$	$\mathcal{LN}(\bar{m} \approx 2.26 \times 10^{-5}, EF \approx 262)$	$\mathcal{LN}(\bar{m} \approx 1.49 \times 10^{-2}, EF \approx 17.2)$
Drive Motor	$\mathcal{LN}(\bar{m} \approx 1.38 \times 10^{-7}, EF \approx 6.73)$	$\mathcal{LN}(\bar{m} \approx 6.31 \times 10^{-5}, EF \approx 47.0)$	$\mathcal{LN}(\bar{m} \approx 1.22 \times 10^{-2}, EF \approx 8.58)$
PLC DSP	$\mathcal{LN}(\bar{m} \approx 1.74 \times 10^{-9}, EF \approx 11.9)$	$\mathcal{LN}(\bar{m} \approx 4.73 \times 10^{-6}, EF \approx 114)$	$\mathcal{LN}(\bar{m} \approx 1.90 \times 10^{-2}, EF \approx 96.8)$

CASE 1: Temperature Dependent Hardware Failure Rates

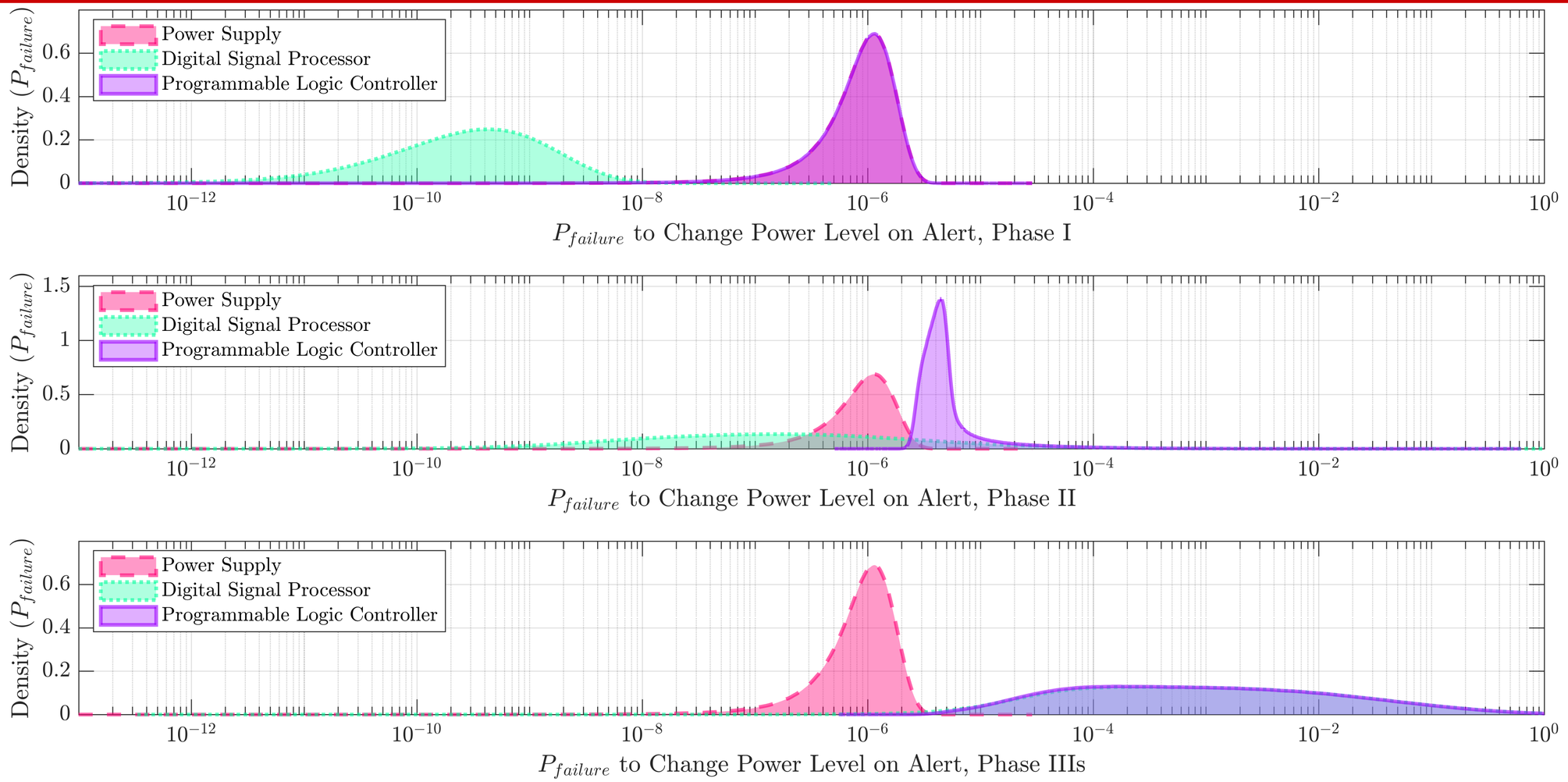


Table 4.9: Intermediate Event Probabilities, Programmable Logic Controller Failure to Change Power Level on Phase Alert

Phase	**Phase I**	**Phase II**	**Phase III**
PLC Failure	$\mathcal{LN}(\bar{m} \approx 1.10 \times 10^{-6}, EF \approx 3.90)$	$\mathcal{LN}(\bar{m} \approx 6.90 \times 10^{-6}, EF \approx 3.52)$	$\mathcal{LN}(\bar{m} \approx 3.19 \times 10^{-2}, EF \approx 78.2)$
Power Supply	$\mathcal{LN}(\bar{m} \approx 1.10 \times 10^{-6}, EF \approx 3.90)$	$\mathcal{LN}(\bar{m} \approx 3.77 \times 10^{-6}, EF \approx 1.41)$	$\mathcal{LN}(\bar{m} \approx 3.93 \times 10^{-6}, EF \approx 1.41)$
DSP Failure	$\mathcal{LN}(\bar{m} \approx 1.06 \times 10^{-9}, EF \approx 16.7)$	$\mathcal{LN}(\bar{m} \approx 9.86 \times 10^{-6}, EF \approx 115)$	$\mathcal{LN}(\bar{m} \approx 3.83 \times 10^{-2}, EF \approx 90.3)$

CASE 1: Temperature Dependent Hardware Failure Rates

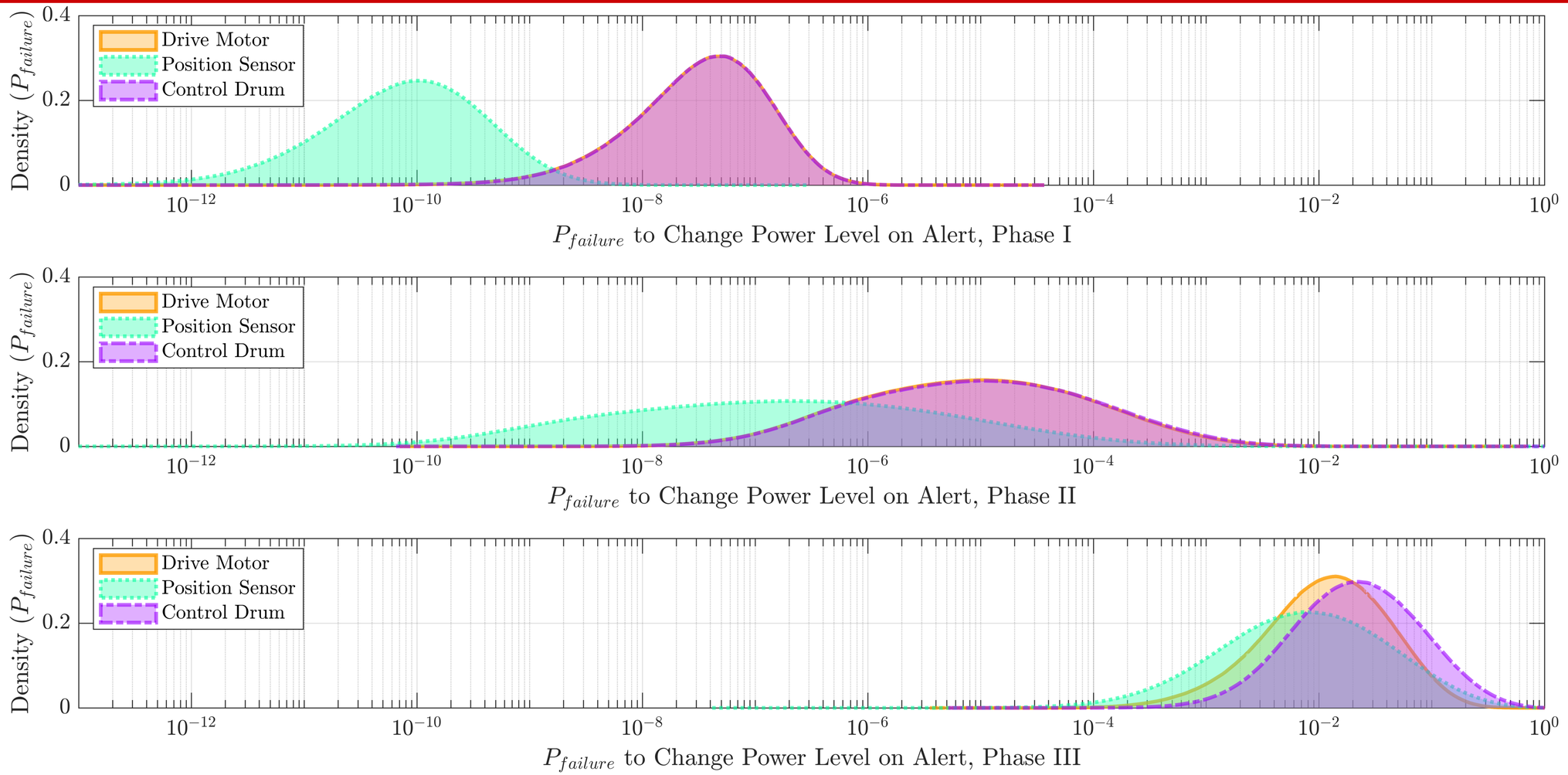


Table 4.10 Control Drum, Drive Motor, Position Sensor, failure to change power level on demand, by phase

Phase	Phase I	Phase II	Phase III
CD Failure	$\mathcal{LN}(\bar{m} \approx 8.42 \times 10^{-8}, EF \approx 10.1)$	$\mathcal{LN}(\bar{m} \approx 1.48 \times 10^{-4}, EF \approx 49.3)$	$\mathcal{LN}(\bar{m} \approx 4.95 \times 10^{-2}, EF \approx 8.48)$
Position Sensor	$\mathcal{LN}(\bar{m} \approx 3.00 \times 10^{-10}, EF \approx 15.8)$	$\mathcal{LN}(\bar{m} \approx 4.70 \times 10^{-5}, EF \approx 263)$	$\mathcal{LN}(\bar{m} \approx 3.08 \times 10^{-2}, EF \approx 16.7)$
Drive Motor	$\mathcal{LN}(\bar{m} \approx 8.41 \times 10^{-8}, EF \approx 10.2)$	$\mathcal{LN}(\bar{m} \approx 1.31 \times 10^{-4}, EF \approx 47.1)$	$\mathcal{LN}(\bar{m} \approx 2.58 \times 10^{-2}, EF \approx 8.44)$

CASE 1: RCS Unavailability Fault Tree

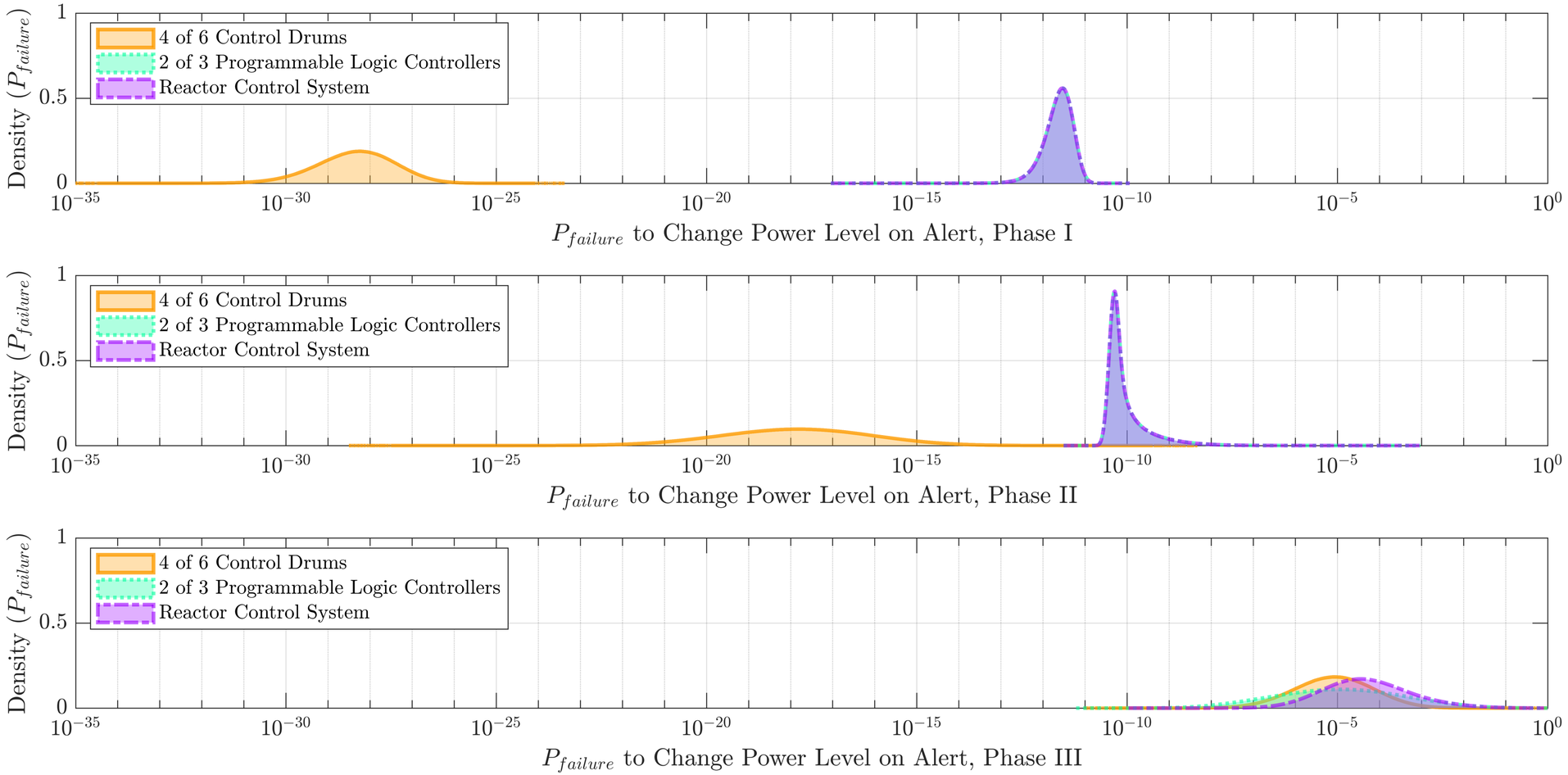


Table 4.11: Top, Intermediate Event Probabilities, Reactor Control System Failure to Change Power Level on Demand

Phase	**Phase I**	**Phase II**	**Phase III**
RCS Failure	$\mathcal{LN}(\overline{m} \approx 3.09 \times 10^{-12}, EF \approx 3.65)$	$\mathcal{LN}(\overline{m} \approx 1.68 \times 10^{-10}, EF \approx 6.20)$	$\mathcal{LN}(\overline{m} \approx 8.07 \times 10^{-4}, EF \approx 44.9)$
4 of 6 CDs Fail	$\mathcal{LN}(\overline{m} \approx 4.40 \times 10^{-28}, EF \approx 34.1)$	$\mathcal{LN}(\overline{m} \approx 5.34 \times 10^{-15}, EF \approx 831)$	$\mathcal{LN}(\overline{m} \approx 8.14 \times 10^{-5}, EF \approx 34.4)$
2 of 3 PLCs	$\mathcal{LN}(\overline{m} \approx 3.09 \times 10^{-12}, EF \approx 3.65)$	$\mathcal{LN}(\overline{m} \approx 1.68 \times 10^{-10}, EF \approx 6.20)$	$\mathcal{LN}(\overline{m} \approx 3.71 \times 10^{-3}, EF \approx 274)$

CASE 1: RCS Power Down End-State Likelihoods

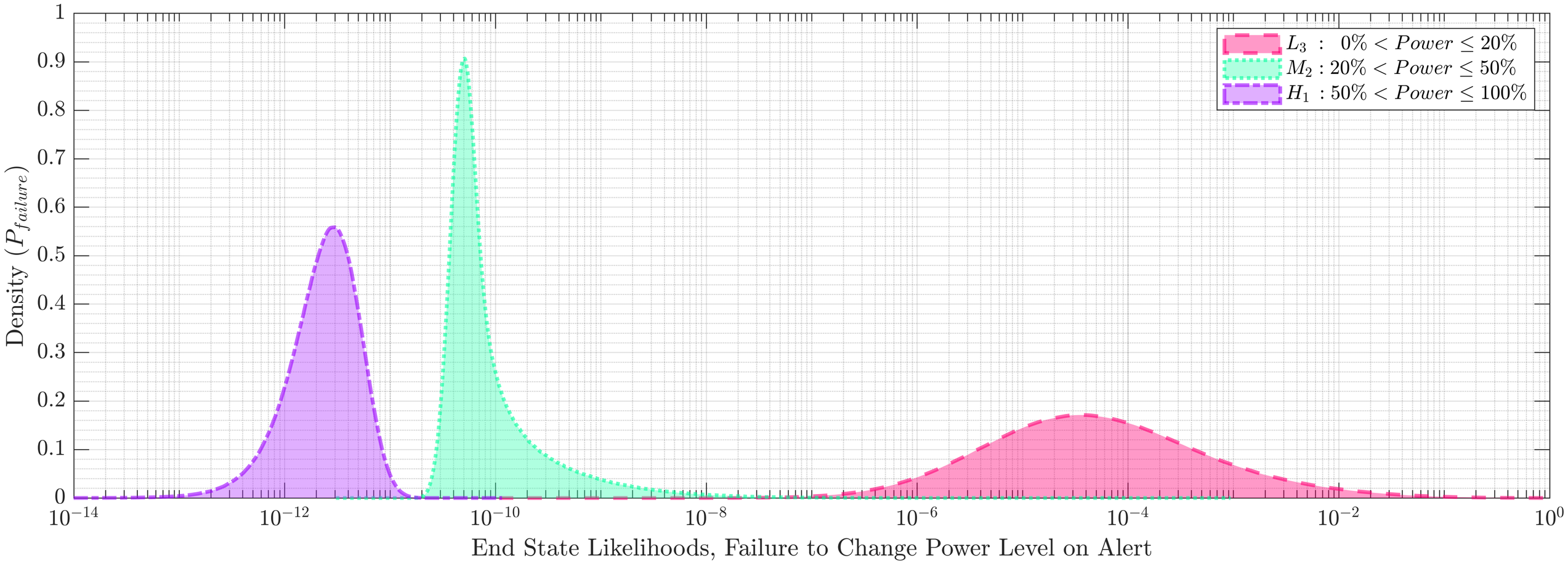
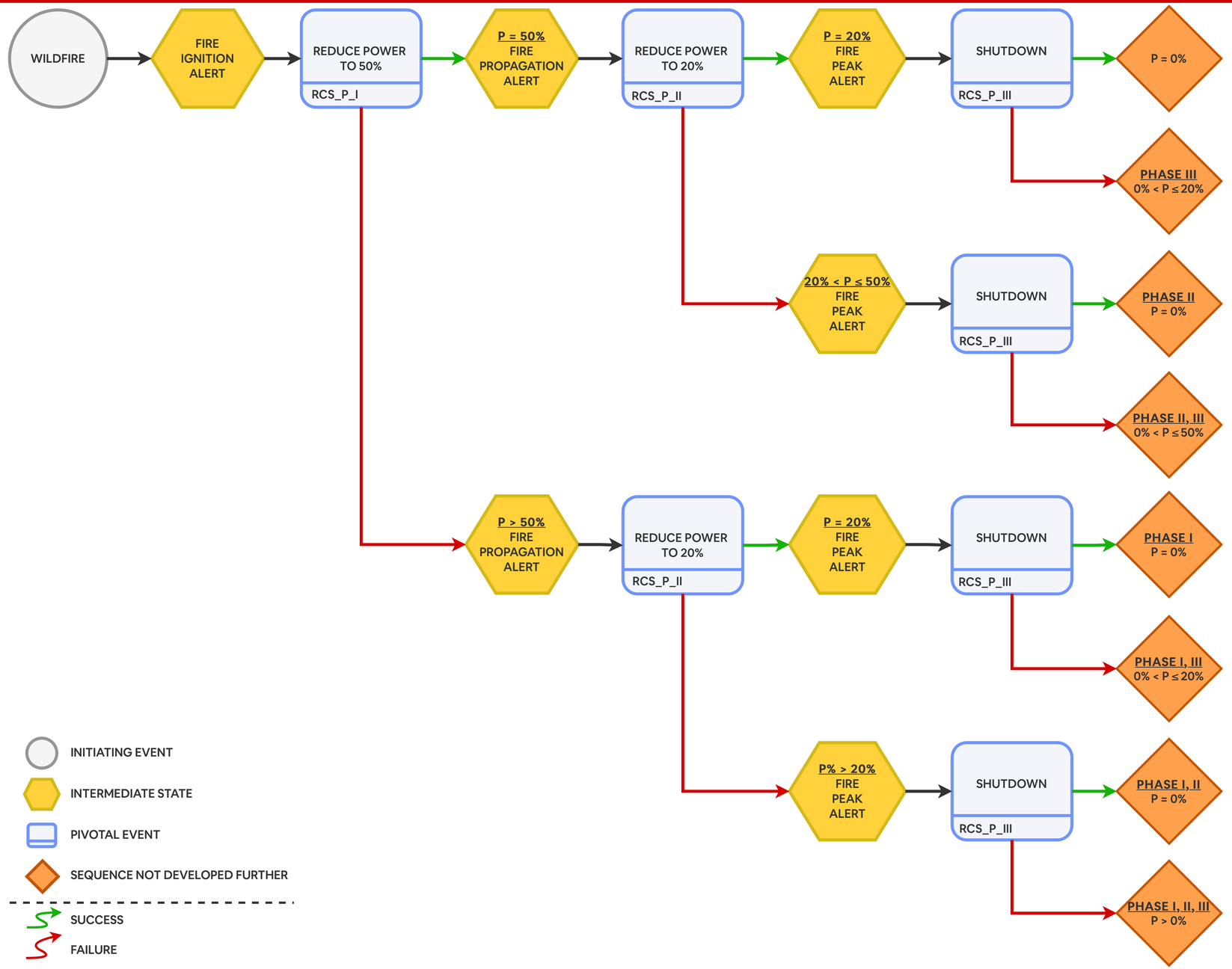


Table 4.12: Traditional PRA: Reactor power level likelihoods following shutdown, given external fire event.

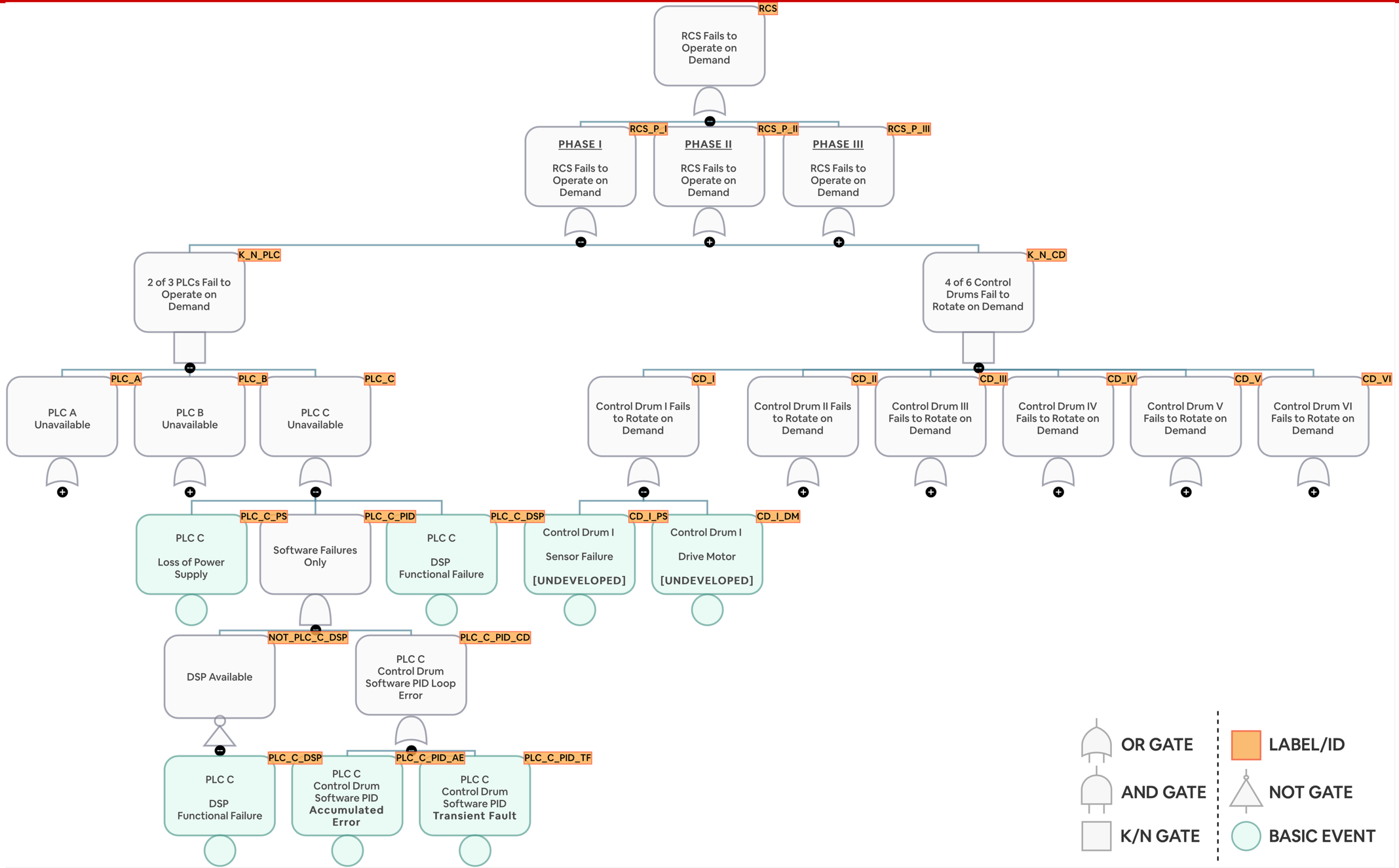
ID[5]	End State	P(End State)
S_0	Shutdown	$\mathcal{LN}(\bar{m} \approx 9.99 \times 10^{-1}, EF \approx 1.02)$
L_3	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 8.07 \times 10^{-4}, EF \approx 44.9)$
M_2	20% < Power ≤ 50%	$\mathcal{LN}(\bar{m} \approx 1.68 \times 10^{-10}, EF \approx 6.20)$
H_1	50% < Power ≤ 100%	$\mathcal{LN}(\bar{m} \approx 3.09 \times 10^{-12}, EF \approx 3.65)$

CASE 2: ESD/FT with DEPM & Recoveries

CASE 2: Reactor Control System Power Down ESD



CASE 2: RCS Unavailability Fault Tree



CASE 2: PID Software Failure Rate Estimation

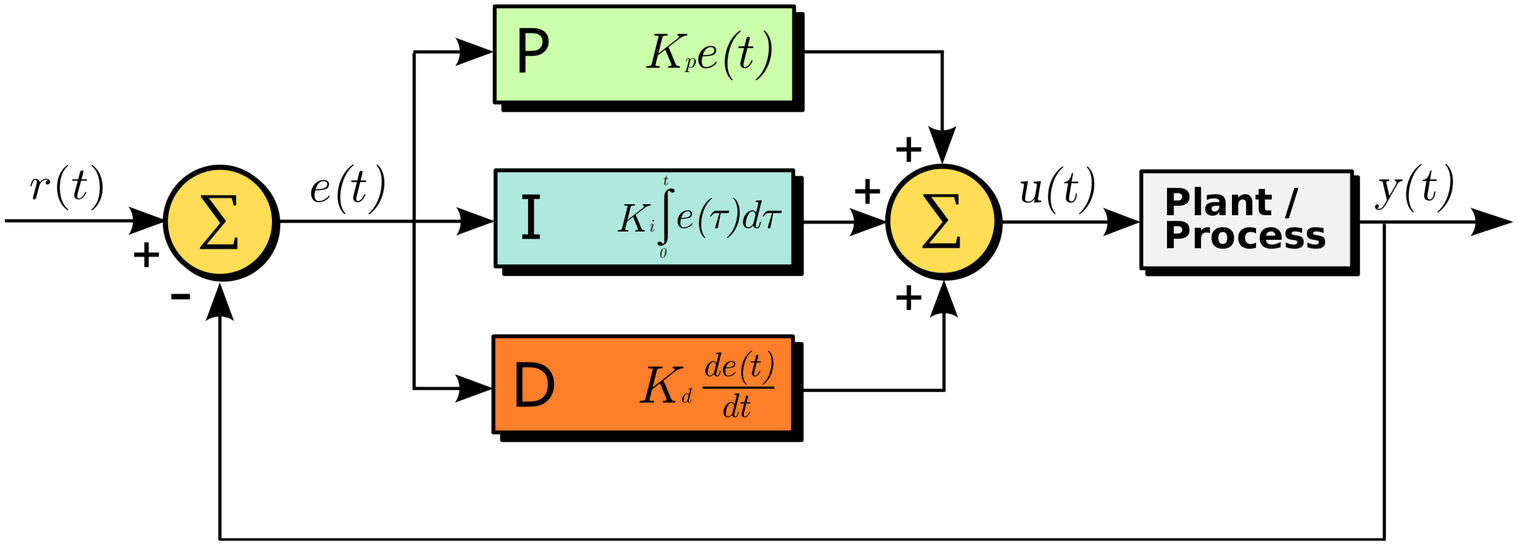


Table 4.14: Assembler code for proposed zero-order PID control algorithm.

define float @__calculate__(float %SET_POINT, %P_{VAR}, %K_p, %K_i, %K_d, %dT)		
0:	%C_{ERR}	**fsub** %SET_POINT, %P_{VAR}
1:	%P_{ERR}	load float, float* @P_{ERR}
2:	%D_{ERR}	**fsub** %C_{ERR}, %P_{ERR}
3:	%OUTPUT	**fmul** %K_d, %D_{ERR}
4:		store %C_{ERR}, float* @P_{ERR}
5:	%tmp1	**fmul** %K_p, %C_{ERR}
6:	%OUTPUT	**fadd** %OUTPUT, %tmp1
7:	%(Σ)	load float, float* @(Σ)
8:	%(Σ_{CUR})	**fmul** %dT, %C_{ERR}
9:	%(Σ)	**fadd** %(Σ), %(Σ_{CUR})
10:		store %(Σ), float* @(Σ)
11:	%(Σ)	**fmul** %K_i, %(Σ)
12:	%OUTPUT	**fadd** %(Σ), %OUTPUT
13:		return %OUTPUT

CASE 2: PID Software Failure Rate Estimation

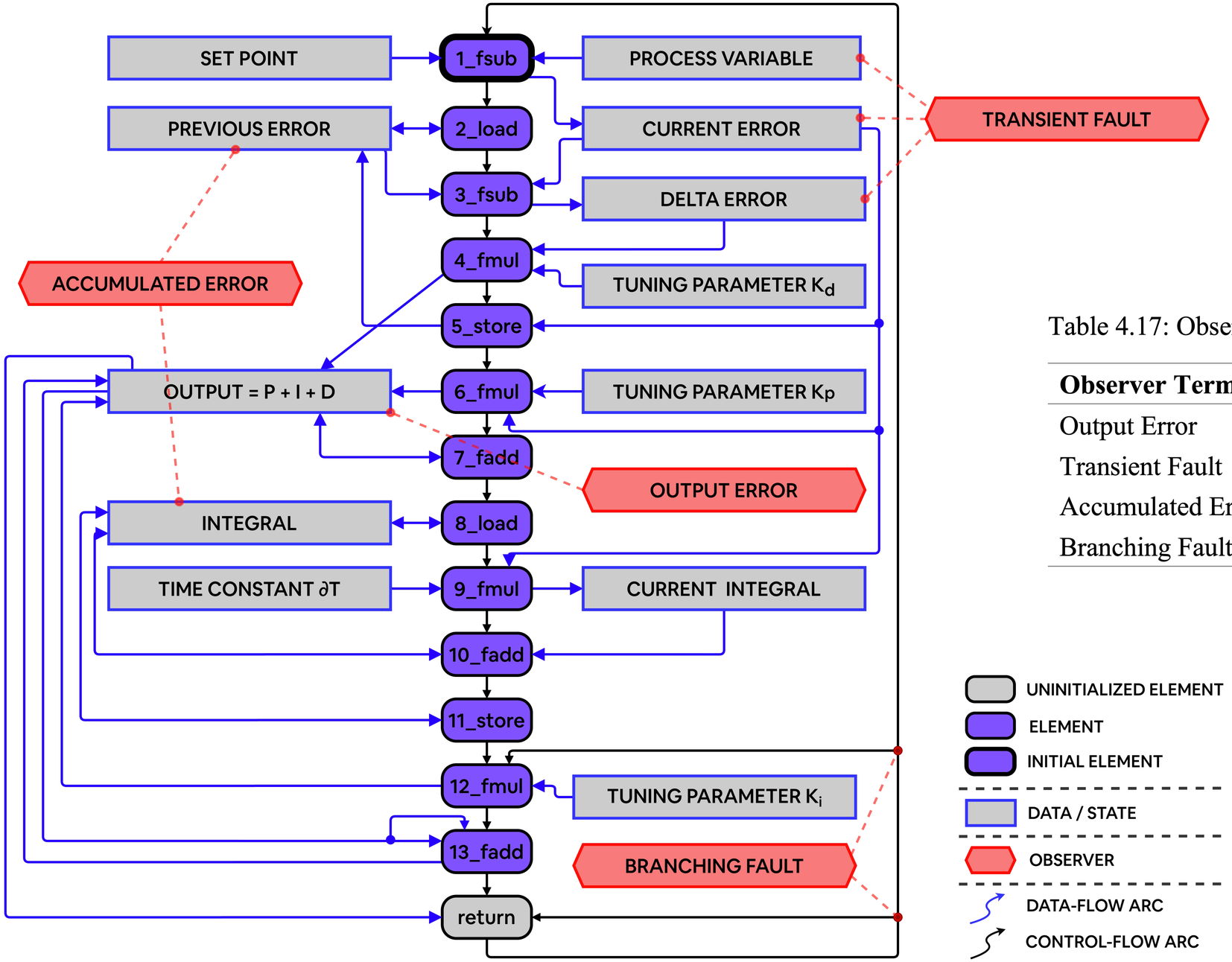


Table 4.17: Observer Terms - PID Assembler Instructions DEPM

Observer Term	Evaluated Expression
Output Error	$\sim(OUTPUT = OK)$
Transient Fault	$\sim(P_{VAR} = OK \;\&\; C_{ERR} = OK \;\&\; D_{ERR} = OK)$
Accumulated Error	$\sim(P_{ERR} = OK \;\&\; \Sigma = OK)$
Branching Fault	$(CF = return) \;\&\; \sim(CF_{next} = 1\_fsub)$

CASE 2: PID Software Failure Rate Estimation

- Calculate instruction failure rate by estimating bit error rate and adjust it for temperature dependent failure mechanisms.

$$\lambda_{BER} = AF_{DSP} \times \left(\frac{1}{2^{10}}\right)\left[\frac{\text{error}}{\text{bit}}\right] \times \left(\frac{1}{365 \times 24}\right)\left[\frac{1}{\text{hour}}\right]$$

$$\approx AF_{DSP} \times 1.12 \times 10^{-7}\left[\frac{\text{error}}{\text{bit} \times \text{hour}}\right]$$

- Since 1 SRAM bit is implemented using 6 CMOS transistors, estimate transistor use per instruction for this CPU to get instruction failure rate $\lambda_{op} = U_{op} \times \lambda_{BER}$

Table 4.16: Hardware acceleration factor adjusted instruction soft error rate [error/hour], segmented by phase.

λ_{op}	U_{op}	Instruction Soft Error Rate [error/hour]		
		Phase I	**Phase II**	**Phase III**
λ_{add}	6.12	$\mathcal{LN}(\bar{m} \approx 1.52 \times 10^{-8}, EF \approx 7.36)$	$\mathcal{LN}(\bar{m} \approx 1.48 \times 10^{-5}, EF \approx 90.2)$	$\mathcal{LN}(\bar{m} \approx 9.96 \times 10^{-3}, EF \approx 73.1)$
λ_{sub}	6.86	$\mathcal{LN}(\bar{m} \approx 1.71 \times 10^{-8}, EF \approx 7.36)$	$\mathcal{LN}(\bar{m} \approx 1.66 \times 10^{-5}, EF \approx 90.2)$	$\mathcal{LN}(\bar{m} \approx 8.93 \times 10^{-3}, EF \approx 73.1)$
λ_{mul}	11.9	$\mathcal{LN}(\bar{m} \approx 2.96 \times 10^{-8}, EF \approx 7.36)$	$\mathcal{LN}(\bar{m} \approx 2.87 \times 10^{-5} EF \approx 90.2)$	$\mathcal{LN}(\bar{m} \approx 1.55 \times 10^{-2}, EF \approx 73.1)$
λ_{store}	3.90	$\mathcal{LN}(\bar{m} \approx 9.71 \times 10^{-9}, EF \approx 7.36)$	$\mathcal{LN}(\bar{m} \approx 9.42 \times 10^{-6}, EF \approx 90.2)$	$\mathcal{LN}(\bar{m} \approx 5.07 \times 10^{-3}, EF \approx 73.1)$
λ_{load}	1.00	$\mathcal{LN}(\bar{m} \approx 2.86 \times 10^{-9}, EF \approx 7.36)$	$\mathcal{LN}(\bar{m} \approx 2.78 \times 10^{-6}, EF \approx 90.2)$	$\mathcal{LN}(\bar{m} \approx 1.49 \times 10^{-3}, EF \approx 73.1)$
λ_{return}	0.08	$\mathcal{LN}(\bar{m} \approx 2.86 \times 10^{-9}, EF \approx 7.36)$	$\mathcal{LN}(\bar{m} \approx 2.78 \times 10^{-6}, EF \approx 90.2)$	$\mathcal{LN}(\bar{m} \approx 1.49 \times 10^{-3}, EF \approx 73.1))$

CASE 2: PID Software Failure Likelihoods

Table 4.18: Observed Events, PID Software Failure to Change Power Level on Alert

Ø	$\textbf{alert} \Rightarrow \boldsymbol{P}_{=?}[\Diamond^{\leq \boldsymbol{T}_{alert}}$ **Transient Fault**$]^{8}$	$\textbf{alert} \Rightarrow \boldsymbol{P}_{=?}[\Diamond^{\leq \boldsymbol{T}_{alert}}$ **Accumulated Error**$]$
I	$\mathcal{LN}(\overline{m} \approx 6.93 \times 10^{-9}, EF \approx 9.19)$	$\mathcal{LN}(\overline{m} \approx 5.85 \times 10^{-9}, EF \approx 11.0)$
II	$\mathcal{LN}(\overline{m} \approx 3.69 \times 10^{-3}, EF \approx 376)$	$\mathcal{LN}(\overline{m} \approx 1.11 \times 10^{-4}, EF \approx 127)$
III	$\mathcal{LN}(\overline{m} \approx 6.67 \times 10^{-2}, EF \approx 40.9)$	$\mathcal{LN}(\overline{m} \approx 6.43 \times 10^{-4}, EF \approx 1.42)$

[8] $\Psi \Longrightarrow P_{=?}\left[\Diamond^{\leq k}\, \varphi\right]$: Once event Ψ occurs, the probability that φ is satisfied within k time units

CASE 2: DEPM - Software PID Failure Likelihoods

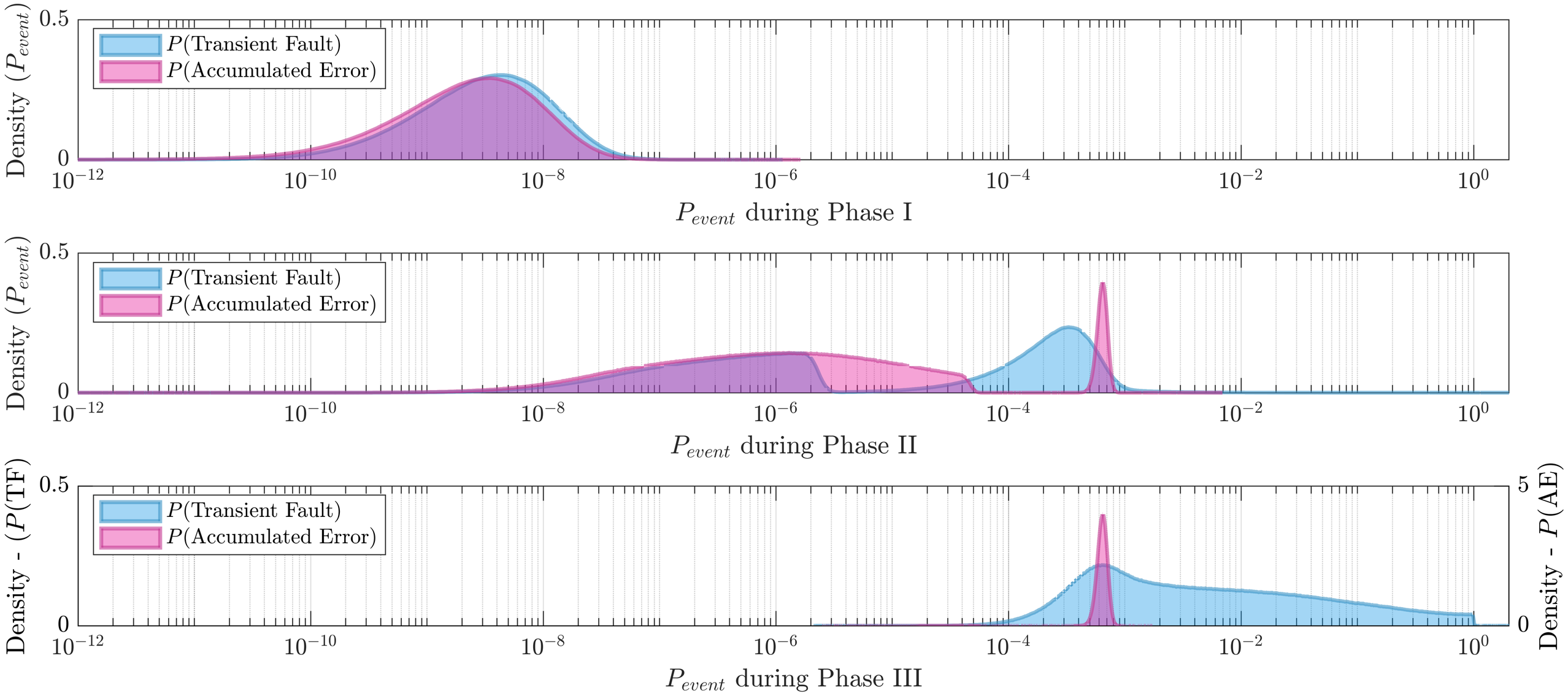


Figure 4.18: Observed Events, PID Software Failure to Change Power Level on Alert

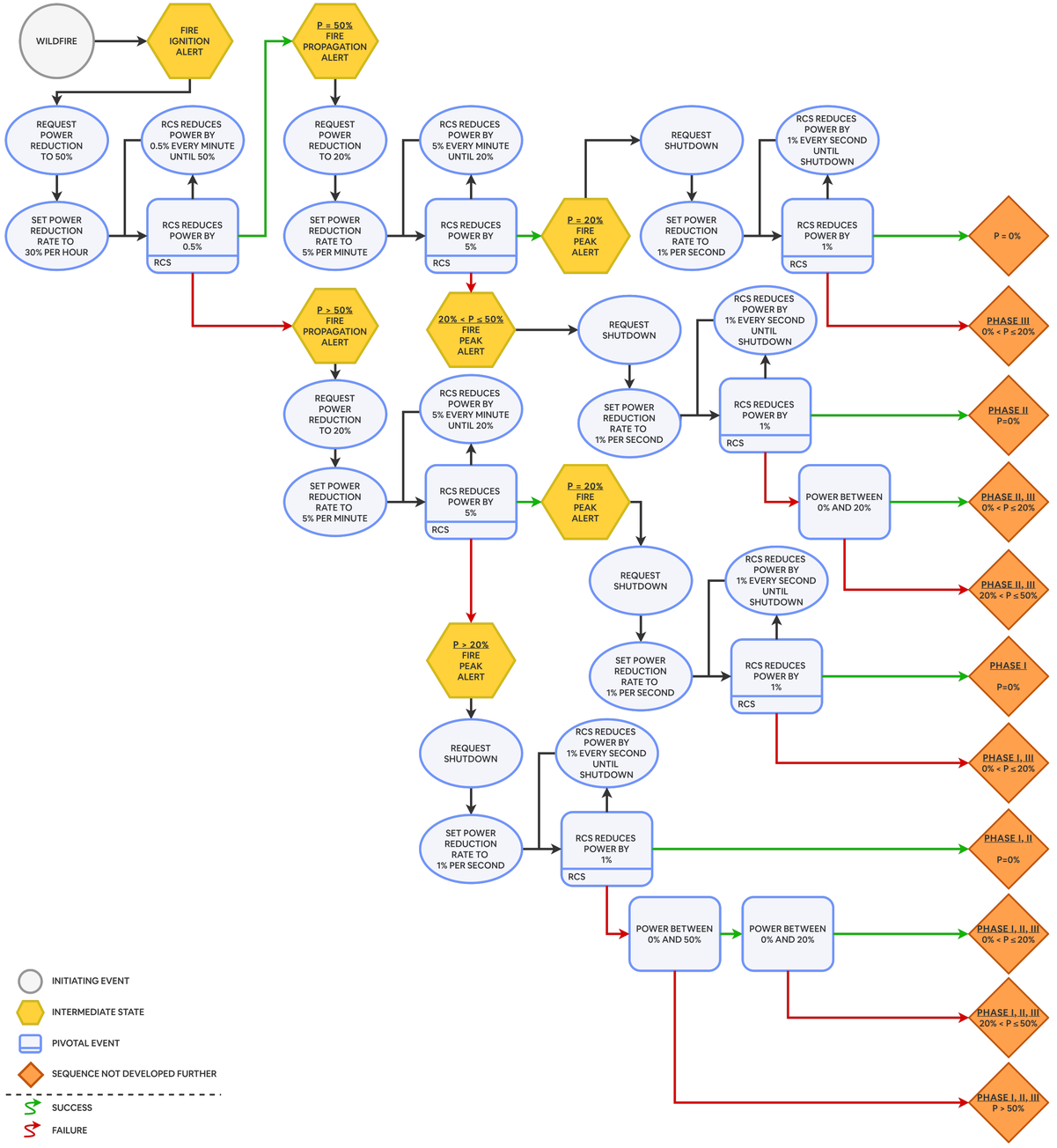
CASE 2: RCS Power Down End-State Likelihoods

Table 4.19: End State Likelihoods, Power Reduction Events for an External Fire Scenario, with Recovery

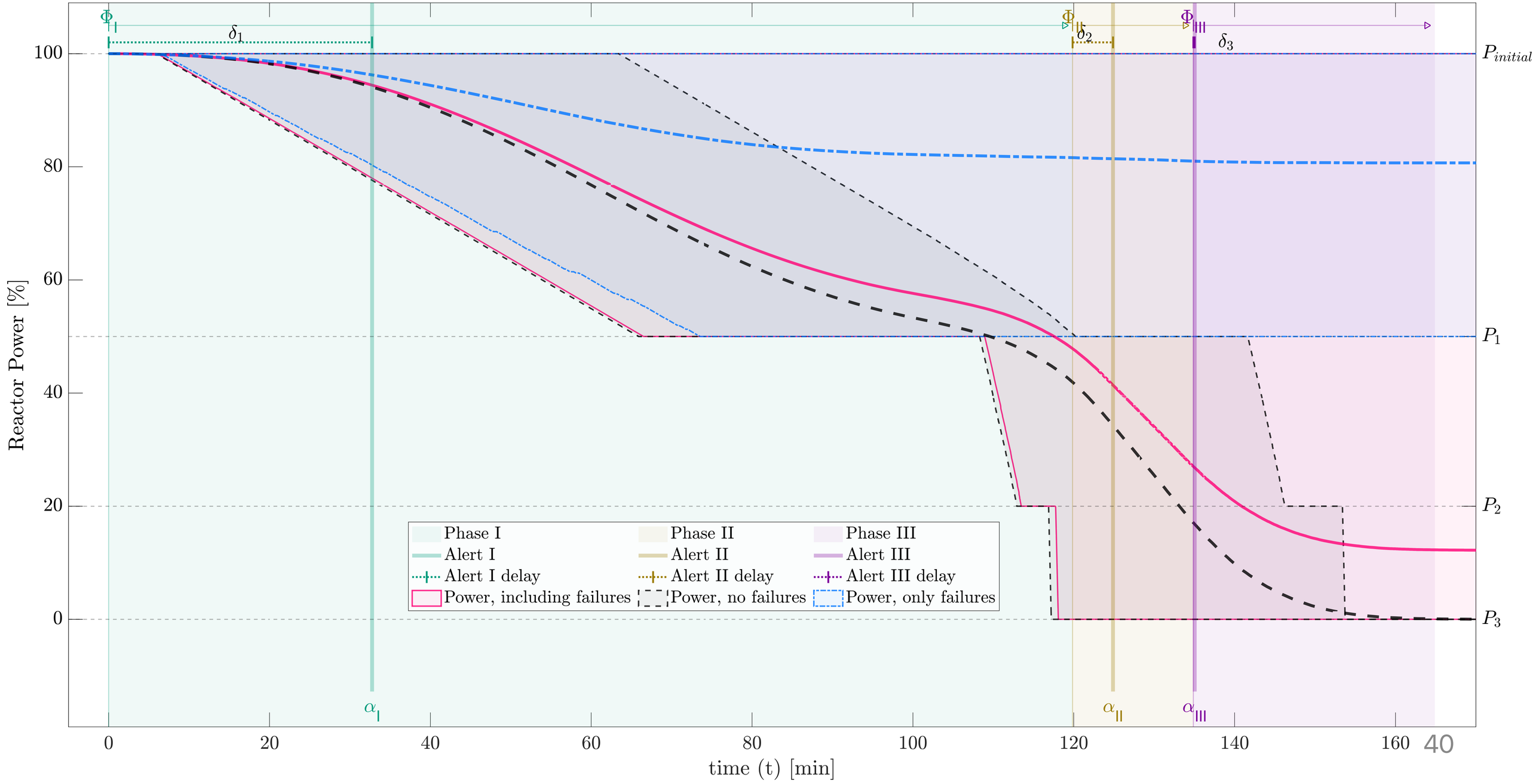
ID	Power Level	P(Power Level)	Phase I	Phase II	Phase III
S_0	Shutdown	$\mathcal{LN}(\bar{m} \approx 9.99 \times 10^{-1}, EF \approx 1.02)$	Success	Success	Success
L_3	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 7.17 \times 10^{-4}, EF \approx 26.8)$	Success	Success	Failure
S_2	Shutdown	$\mathcal{LN}(\bar{m} \approx 1.02 \times 10^{-8}, EF \approx 42.3)$	Success	Failure	Recovery
ML_{23}	0% < Power ≤ 50%	$\mathcal{LN}(\bar{m} \approx 1.05 \times 10^{-11}, EF \approx 177)$	Success	Failure	Failure
S_1	Shutdown	$\mathcal{LN}(\bar{m} \approx 3.14 \times 10^{-12}, EF \approx 3.56)$	Failure	Recovery	Success
L_{13}	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 2.26 \times 10^{-15}, EF \approx 34.0)$	Failure	Recovery	Failure
S_{12}	Shutdown	$\mathcal{LN}(\bar{m} \approx 3.20 \times 10^{-20}, EF \approx 52.2)$	Failure	Failure	Recovery
HML_{123}	Power > 0%	$\mathcal{LN}(\bar{m} \approx 3.31 \times 10^{-23}, EF \approx 207)$	Failure	Failure	Failure

CASE 3: Integrating Dual Error Propagation into Dynamic Event Trees

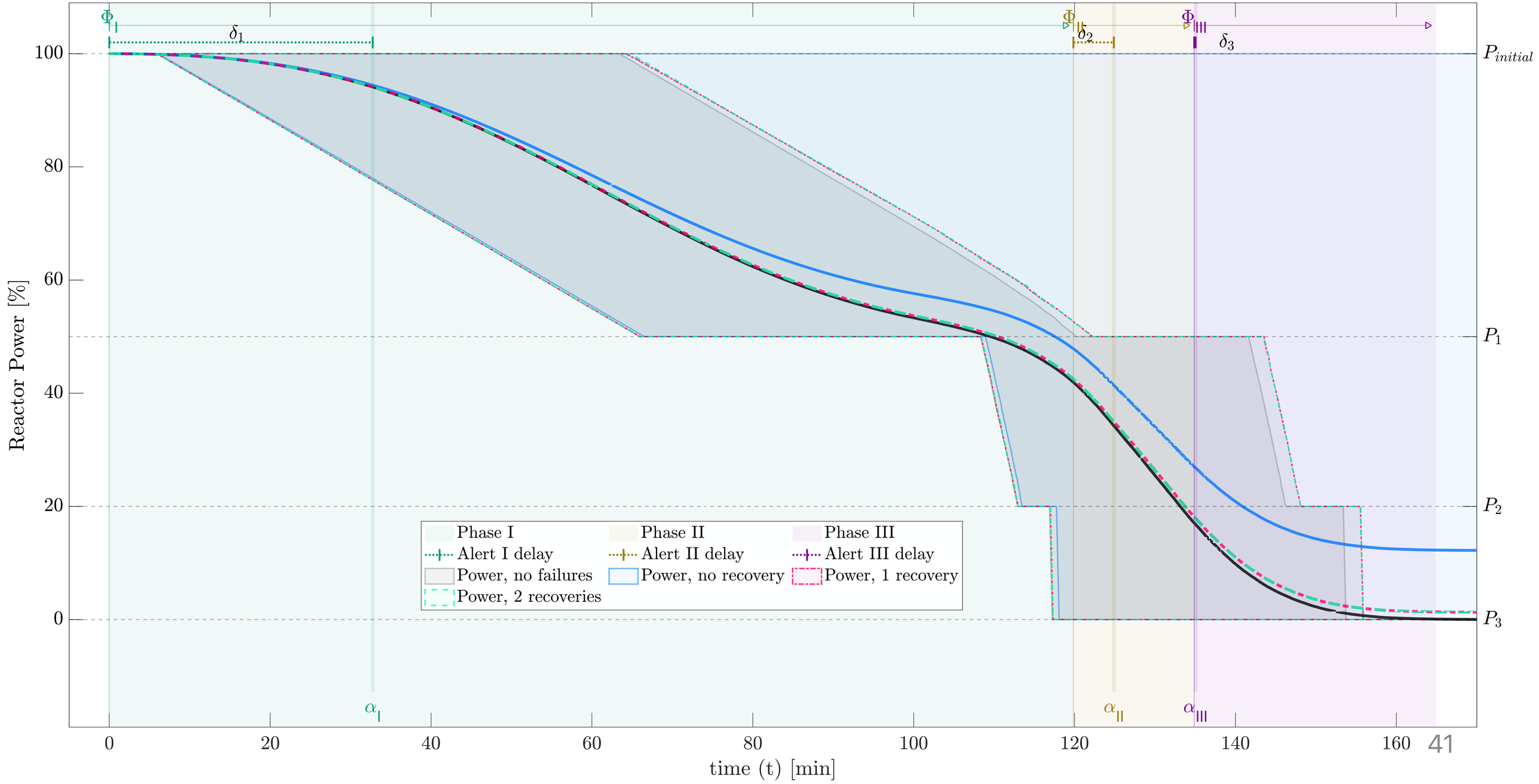
CASE 3: Reactor Control System Power Down ESD



CASE 3: Time Explicit Reactor Power Level, No Recoveries



CASE 3: Time Explicit Reactor Power Level, upto 2 Recoveries



CASE 3: RCS Power Down End-State Likelihoods

Table 4.20: End State Likelihoods, Dynamic Modeling of RCS Power Level Reduction, with Recovery

ID	Power Level	P(Power Level)	Phase I	Phase II	Phase III
S_0	Shutdown	$\mathcal{LN}(\bar{m} \approx 9.69 \times 10^{-1}, EF \approx 1.15)$	Success	Success	Success
L_3	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 2.83 \times 10^{-2}, EF \approx 2.92)$	Success	Success	Failure
S_2	Shutdown	$\mathcal{LN}(\bar{m} \approx 4.15 \times 10^{-6}, EF \approx 20.1)$	Success	Recovery	Success
L_{23}	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 1.16 \times 10^{-7}, EF \approx 24.2)$	Success	Failure	Recovery
M_{23}	20% < Power ≤ 50%	$\mathcal{LN}(\bar{m} \approx 3.15 \times 10^{-9}, EF \approx 28.8)$	Success	Failure	Recovery
S_1	Shutdown	$\mathcal{LN}(\bar{m} \approx 2.40 \times 10^{-12}, EF \approx 1.37)$	Failure	Recovery	Success
L_{13}	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 1.98 \times 10^{-13}, EF \approx 2.01)$	Failure	Recovery	Failure
S_{12}	Shutdown	$\mathcal{LN}(\bar{m} \approx 1.03 \times 10^{-17}, EF \approx 20.4)$	Failure	Failure	Recovery
L_{123}	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 1.80 \times 10^{-20}, EF \approx 6.32)$	Failure	Failure	Failure
M_{123}	20% < Power ≤ 50%	$\mathcal{LN}(\bar{m} \approx 1.64 \times 10^{-15}, EF \approx 3.58)$	Failure	Failure	Failure
H_{123}	50% < Power ≤ 100%	$\mathcal{LN}(\bar{m} \approx 1.26 \times 10^{-24}, EF \approx 79.7)$	Failure	Failure	Failure

CASE 2, CASE 3 Comparison

Table 5.1: Comparative Analysis of End-State Likelihoods for Phased Reactor Shutdown on Fire Alert

ID	Power Level	P(Power Level)	
		Traditional Analysis	Dynamic Analysis
$\boldsymbol{S_0}$	Shutdown	$\mathcal{LN}(\bar{m} \approx 9.99 \times 10^{-1}, EF \approx 1.02)$	$\mathcal{LN}(\bar{m} \approx 9.69 \times 10^{-1}, EF \approx 1.15)$
$\boldsymbol{L_3}$	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 7.17 \times 10^{-4}, EF \approx 26.8)$	$\mathcal{LN}(\bar{m} \approx 2.83 \times 10^{-2}, EF \approx 2.92)$
$\boldsymbol{S_2}$	Shutdown	$\mathcal{LN}(\bar{m} \approx 1.02 \times 10^{-8}, EF \approx 42.3)$	$\mathcal{LN}(\bar{m} \approx 4.15 \times 10^{-6}, EF \approx 20.1)$
$\boldsymbol{ML_{23}}$	0% < Power ≤ 50%	$\mathcal{LN}(\bar{m} \approx 1.05 \times 10^{-11}, EF \approx 177)$	$\mathcal{LN}(\bar{m} \approx 1.27 \times 10^{-7}, EF \approx 93.6)$
$\boldsymbol{S_1}$	Shutdown	$\mathcal{LN}(\bar{m} \approx 3.14 \times 10^{-12}, EF \approx 3.56)$	$\mathcal{LN}(\bar{m} \approx 2.40 \times 10^{-12}, EF \approx 1.37)$
$\boldsymbol{L_{13}}$	0% < Power ≤ 20%	$\mathcal{LN}(\bar{m} \approx 2.26 \times 10^{-15}, EF \approx 34.0)$	$\mathcal{LN}(\bar{m} \approx 1.98 \times 10^{-13}, EF \approx 2.01)$
$\boldsymbol{S_{12}}$	Shutdown	$\mathcal{LN}(\bar{m} \approx 3.20 \times 10^{-20}, EF \approx 52.2)$	$\mathcal{LN}(\bar{m} \approx 1.03 \times 10^{-17}, EF \approx 20.4)$
$\boldsymbol{HML_{123}}$	Power > 0%	$\mathcal{LN}(\bar{m} \approx 3.31 \times 10^{-23}, EF \approx 207)$	$\mathcal{LN}(\bar{m} \approx 1.63 \times 10^{-15}, EF \approx 3.58)$

But How Does DEPM Compare?

DEPM Comparison

- Use the ESD from CASE 1 and FT from CASE 2.
- Replace PID software failure DEPM basic event with alternative models.
- Re-run CASE 1 analysis for each model.

$$M_A := \text{No Model}$$

$$M_B := e^{(\lambda_{BER},\ t)}$$

$$M_C := e^{(AF_{DSP} \times \lambda_{BER},\ t)}$$

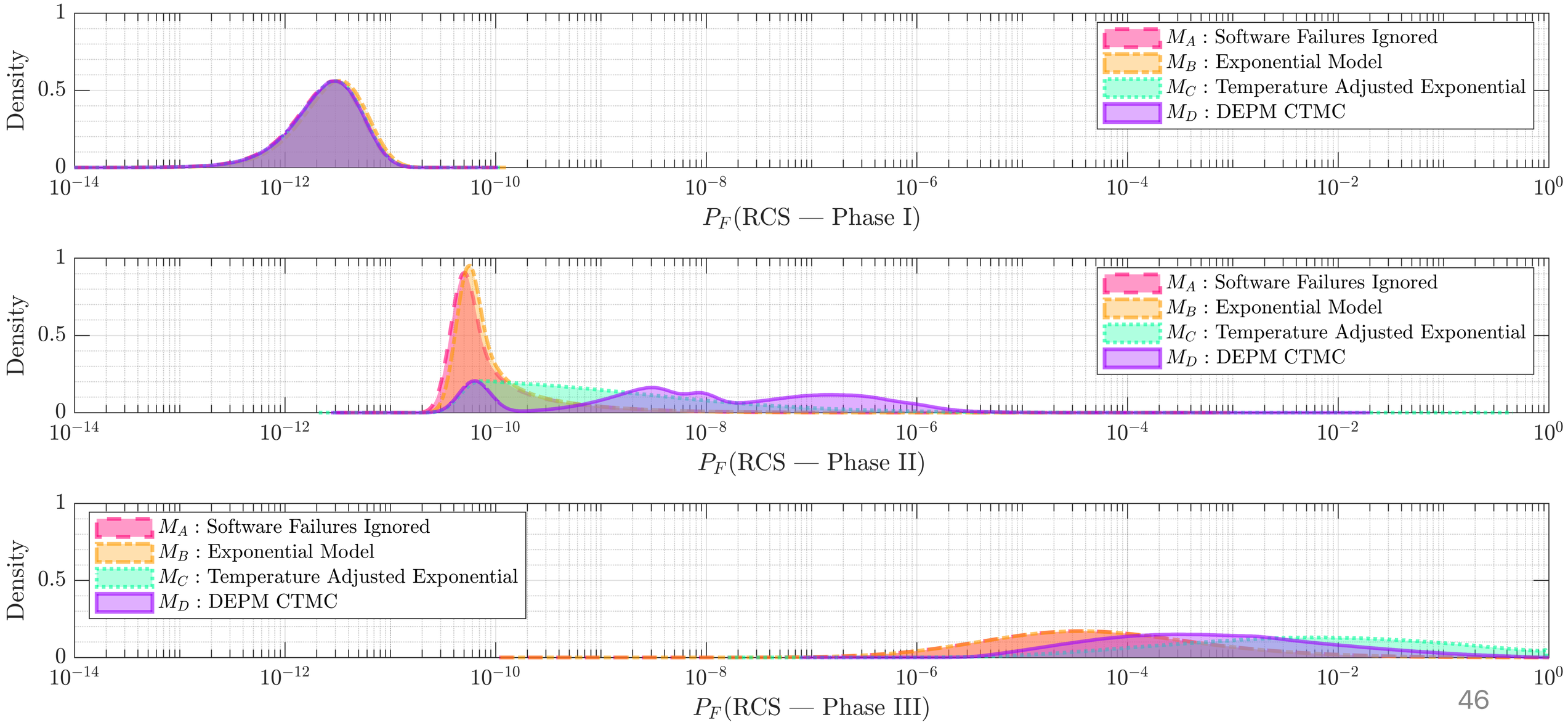
$$M_D := DEPM\ CTMC$$

Table 5.2 PLC PID software failure model contribution to Reactor Control System unavailability

Phase	Phase I	Phase II	Phase III
No Model	$\mathcal{LN}(\bar{m} \approx 3.09 \times 10^{-12}, EF \approx 3.65)$	$\mathcal{LN}(\bar{m} \approx 1.68 \times 10^{-10}, EF \approx 6.20)$	$\mathcal{LN}(\bar{m} \approx 8.07 \times 10^{-4}, EF \approx 44.9)$
$e^{(\lambda_{BER},\ t)}$	$\mathcal{LN}(\bar{m} \approx 3.48 \times 10^{-12}, EF \approx 3.63)$	$\mathcal{LN}(\bar{m} \approx 1.80 \times 10^{-10}, EF \approx 5.97)$	$\mathcal{LN}(\bar{m} \approx 8.07 \times 10^{-4}, EF \approx 44.9)$
$e^{(AF_{DSP} \times \lambda_{BER},t)}$	$\mathcal{LN}(\bar{m} \approx 3.18 \times 10^{-12}, EF \approx 3.65)$	$\mathcal{LN}(\bar{m} \approx 1.58 \times 10^{-8}, EF \approx 45.9)$	$\mathcal{LN}(\bar{m} \approx 1.99 \times 10^{-1}, EF \approx 89.3)$
DEPM CTMC	$\mathcal{LN}(\bar{m} \approx 3.14 \times 10^{-12}, EF \approx 3.56)$	$\mathcal{LN}(\bar{m} \approx 4.37 \times 10^{-7}, EF \approx 57.5)$	$\mathcal{LN}(\bar{m} \approx 1.92 \times 10^{-2}, EF \approx 38.4)$

DEPM Comparison Results

Figure 5.1 Reactor control system failure density estimates with alternative PID software failure model



Future Work

- Model Verification and Validation
- Automated Model Generation
- Incorporate Human Actions
- Expand the Case Studies
- Extend Applications

Thank You