Dynamic Reliability Assessment of the NIST NBSR Thermal Shield Cooling System

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CHRNS CENTER FOR HIGH RESOLUTION NEUTRON SCATTERING NIST

NIST Center for Neutron Research

Outline

- Overview
- Thermal Shield Cooling System Description
- Failure Modes
- Markov Methodology
- Cell-to-Cell Mapping Technique
- Dynamic Event Trees
- Future Goals

Overview

- Reliability assessments are used to quantify the likelihood of system failure.
- Why conduct a reliability assessment?
- Why conduct a *dynamic* reliability assessment?

The Thermal Shield Cooling System

- As the NBSR runs, waste heat is generated, then absorbed by the thermal shield.

- The thermal shield cooling system (TSCS) is a series of copper cooling lines embedded in the layer of lead.

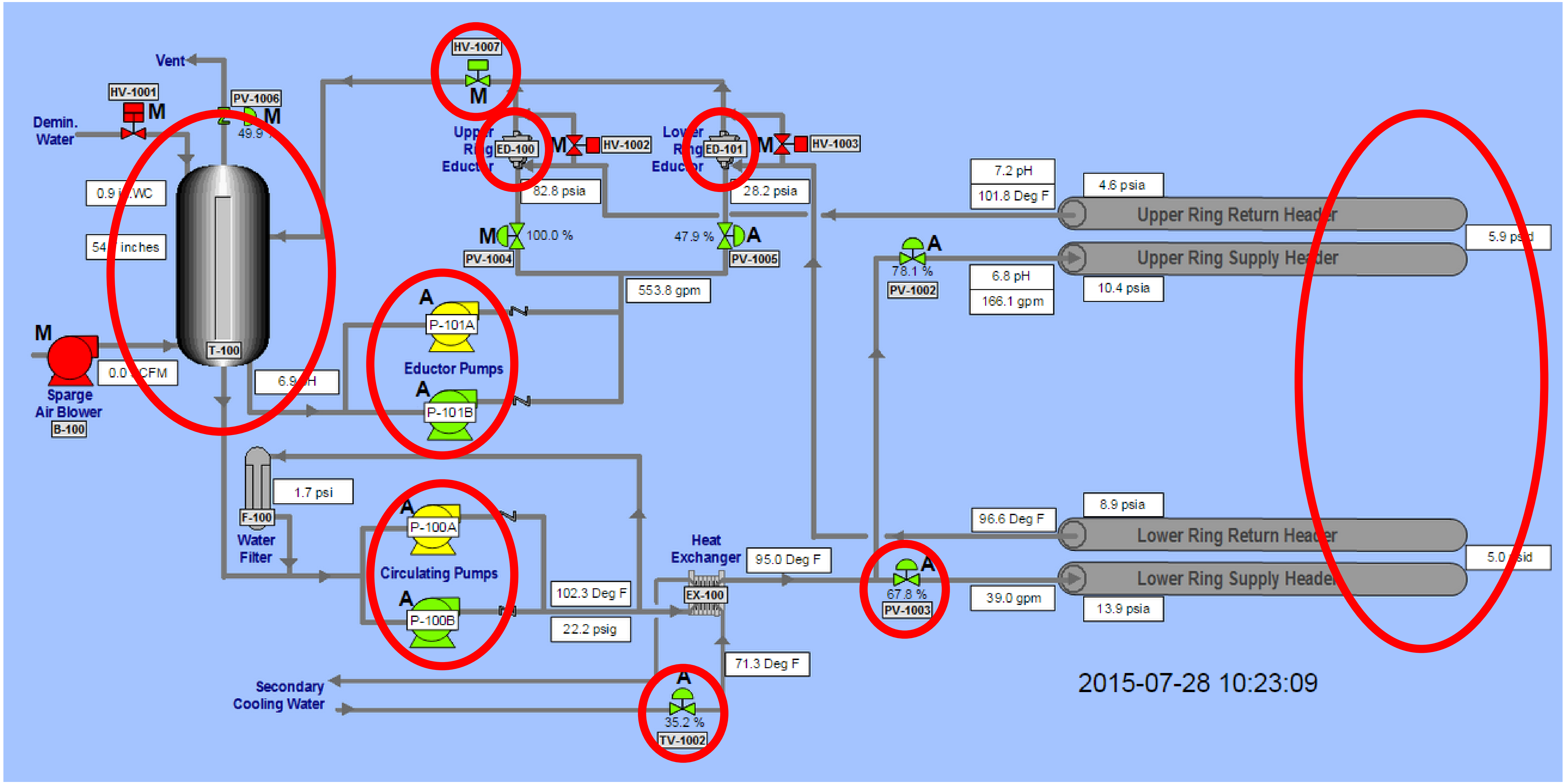
Major Components

Digital:

- PLCs (Programmable Logic Controllers)
- HMI (Human Machine Interface) and OIT (Operator Interface Terminal) Outputs

Mechanical:

- Cooling Water Storage Tank
- Flow Tubes
- Headers
- Pumps and Eductors



Vent
HV-1001
Demin. Water
PV-1006
49.9
0.9 in WC
54 inches
T-100
0.0 CFM
Sparge Air Blower
B-100
6.9 pH
HV-1007
Upper Ring Eductor
ED-100
HV-1002
82.8 psia
Lower Ring Eductor
ED-101
HV-1003
28.2 psia
100.0 %
PV-1004
47.9 %
PV-1005
553.8 gpm
P-101A
Eductor Pumps
P-101B
1.7 psi
F-100
Water Filter
P-100A
Circulating Pumps
P-100B
102.3 Deg F
22.2 psig
Heat Exchanger
EX-100
95.0 Deg F
71.3 Deg F
35.2 %
TV-1002
Secondary Cooling Water
7.2 pH
101.8 Deg F
4.6 psia
Upper Ring Return Header
5.9 psid
78.1 %
PV-1002
6.8 pH
166.1 gpm
Upper Ring Supply Header
10.4 psia
8.9 psia
96.6 Deg F
Lower Ring Return Header
5.0 psid
67.8 %
PV-1003
39.0 gpm
Lower Ring Supply Header
13.9 psia
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Monitored Quantities

- Pressure
- Flow
- Temperature
- pH
- Water Level

Definition of Failure

- Overall success is continued operation of reactor
- Malfunctions of the TSCS cause controlled rundown of reactor, which interrupts the reactor cycle
- Define failure as any event that compromises the TSCS and as a result will cause reactor rundown
- **FAILURE AS DEFINED HERE DOES NOT BRING ABOUT DANGEROUS FAILURE OF THE REACTOR IN AN UNSAFE WAY**

Failure Modes

- Built-in alarms at set point
  - Use these events to define main failure modes
  - Examples: High pressure in supply headers, low flow in cooling lines
- PLC failure
- Structural components (wires, pipes etc) fail much less

Failure Modes and Effects Analysis (FMEA)

- An FMEA lists effects and potential resolution of each failure mode

B3 Process Area

Failure	Detection	Effects
FT-1002: Low flow in upper ring supply header	Trip	Reactor rundown initiated.
FT-1003: Low flow in lower ring supply header	Trip	Reactor rundown initiated.

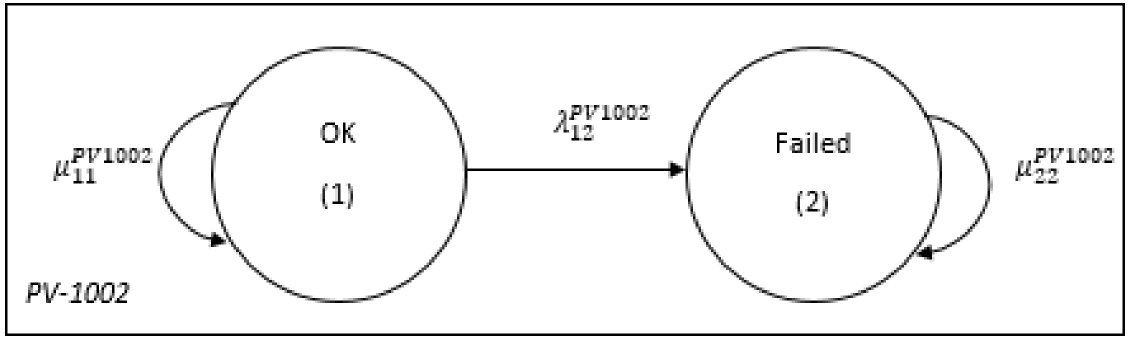
PLCs

Failure	Detection	Effects
One of C100 PLCs Fails	Alarm	None; PLCs are redundant
Both of C100 PLCs Fail	Rundown line to Control Room	Rundown

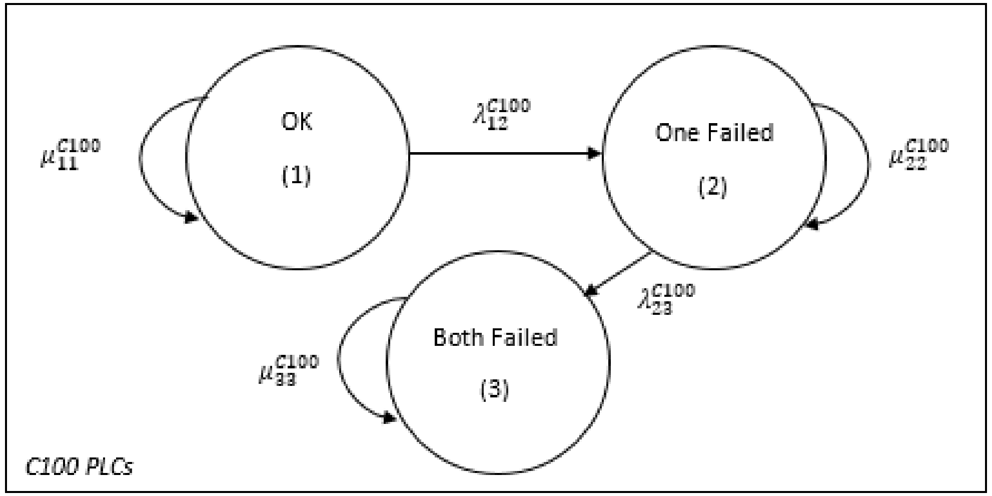
Portion of B3 Process Area and PLC FMEAs

Markov Diagrams

- A Markov diagram is made for each system component
- Nodes are possible states for the component
- Connections are transitions between states and have associated probabilities



Markov diagram for a pressure valve

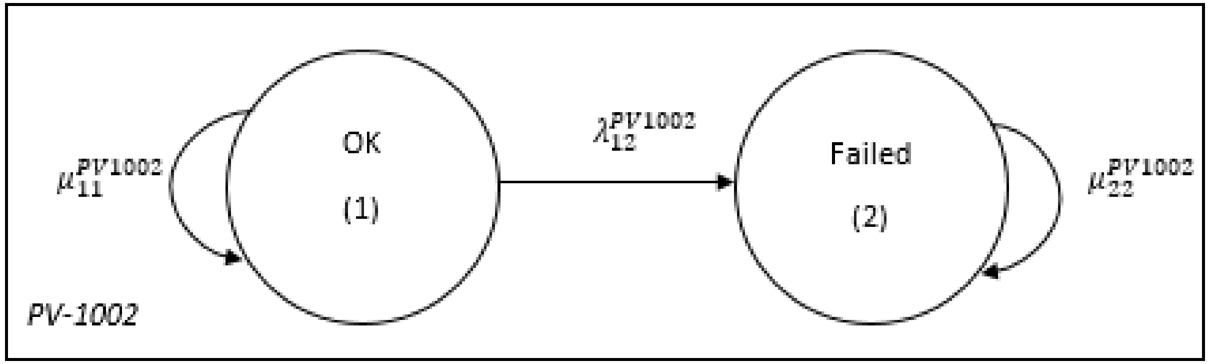


Markov diagram for C100 PLCs

Markov Diagrams (cont.)

- Time is divided into discrete steps of size Δt.
  - Δt = 1 day
  - Transitions can only occur at integer values of Δt
- The total number of component states is related to computation cost.
  - TSCS contains M = 19 components and N = 2^{17}*3*4 = 1,572,864 states
- The mean time between failures (MTBF) must be known for each component that is modeled

Transition Probabilities



Markov diagram for a pressure valve

- Sum of the probabilities leaving each node must be 1
- The probability that a component operates for time t is:

$$R(t) = e^{-\frac{t}{MTBF}}$$

- Therefore, the probability of a component failing within t is:

$$P(t) = 1 - R(t)$$
$$= 1 - e^{-\frac{t}{MTBF}}$$

Component Transition Probability Matrix

- Let n and n' be combinations of the states of all 19 components. For element h(n,n'):The transition probability is:

$$h(n, n') = \prod_{i=1}^{i=19} c_i(n_i \rightarrow n'_i)$$

which is the product of the probabilities of component i making the transition from n_i to n_i'

Cell-to-Cell Mapping Technique (CCMT)

- Model evolution of the system’s controlled variables
- System evolves in a controlled variable state space (CVSS) which is partitioned into cells. Each cell, V_j, is a unique combination of control variables
- Alarmed variables that are main failure modes are sink cells; when the system reaches a sink cell, it can no longer evolve
- Cell-to-cell transition probability matrix is made; this matrix is similar to the component transition probability matrix

The Controlled Variable State Space

- Each of alarmed variables is included in the CVSS
  - 18 controlled variables

Flow at LR SH	Value (gpm)
0	$P_{LR\,SH} < 45$
1	$45 \leq P_{LR\,SH} < 50$
2	$50 \leq P_{LR\,SH} < 64$
3	$P_{LR\,SH} \geq 64$

pH at T-100 Outlet	Value
0	$pH_{T100} < 7.0$
1	$7.0 \leq pH_{T100} < 7.3$
2	$7.3 \leq pH_{T100} < 7.5$
3	$pH_{T100} \geq 7.5$

Partitions of CVSS for lower supply header flow and T-100 pH

Cell-to-Cell Transition Probabilities

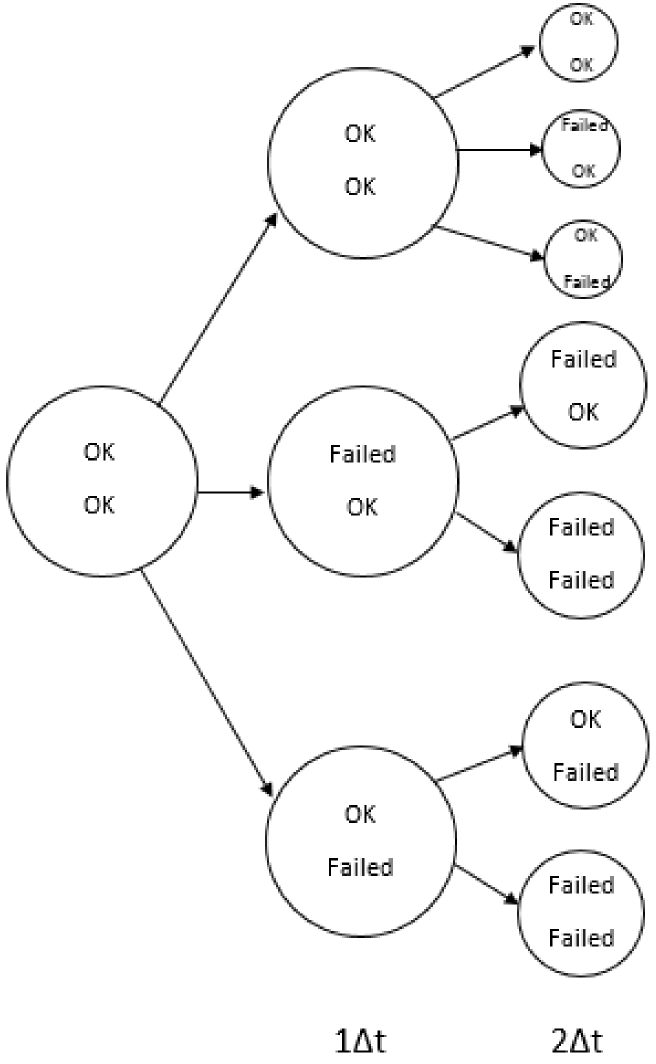
- Transition probabilities between cells V_j and $V_{j'}$ will be made into a cell-to-cell transition matrix with elements g(j,j’)
- Program will be written to implement a quadrature scheme
  - Stochastic evolution occurs in accordance to the control laws of the system which can be taken from the reactor’s control algorithm

Overall Transition Matrix

- Each element represents a transition between both component states and controlled variable states (n, n’, j, and j’)
  - $q(n,n',j,j') = h(n,n')g(j,j')$
- Matrix can be time dependent if any of the control laws introduce time dependence

Dynamic Event Trees (DETs)

- Choose to start in a state where all components are operational and controlled variables are in an acceptable range
- Tree steps through time and at each time step all possible states are considered using overall transition matrix probabilities
- Use DET generation software (ADAPT, RAVEN) and the transition matrix



Example DET for simplified system over two time steps

Future Goals

- Generate DETs
- Determine the CDF and PDF functions for the top events from the DET software

- OVERALL GOAL: have a working reliability model of the whole system so that individual parts can be switched out to examine the effects of potential system upgrades on reliability

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