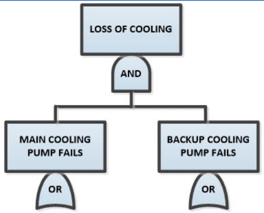
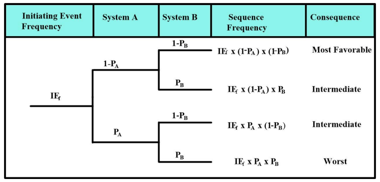
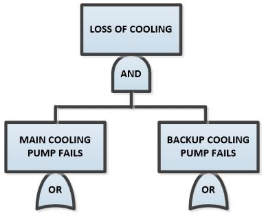


Session 4 Case Study
Chlorine Vaporizer and Salt Process Cell

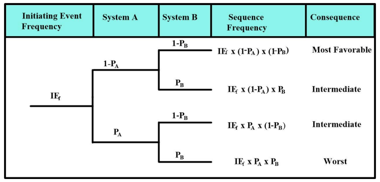


Fault Tree Analysis of Process Systems using Digraph Analysis

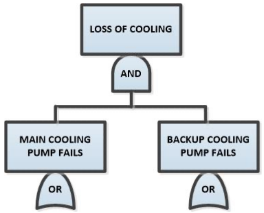
Howard Lambert
FTA Associates
2022



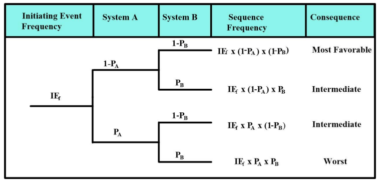
CHLORINE VAPORIZER DU PONT STUDY



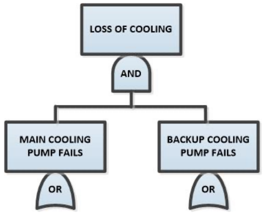
- Purpose -- Modify an existing system to improve safety without comprising reliability
- Top Event -- Overflow of liquid chlorine (Top Level Scenario considered in study)
- Used Fault Tree Analysis (FTA) to conduct design tradeoffs
- Design Goal -- MTTF 1000 Years (For high hazard facility)
- Chlorine Vaporizer study served as a case study to illustrate FTA protocol for major FTA effort at Savannah River plant (SRP) -- FTA studies at SRP were eight years in duration
- Study conducted by Colin Dunglinson a senior process engineer at DuPont



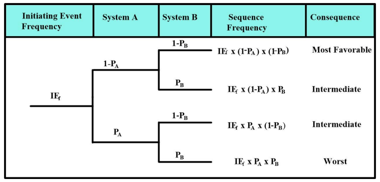
REFERENCE DOCUMENT



- Reference Document -- "Interval Reliability for Initiating and Enabling Events" IEEE Transactions on Reliability, June 1983
  - AUTHORS
    - COLIN DUNLINSON (Senior Process Engineer at DuPont)
    - HOWARD LAMBERT



Accident Sequence From Initiating Event to Accidental Event



IMPACT

casualties
property damage
business interruption losses
environmental damage

(CONSEQUENCE ANALYSIS)

MITIGATION SYSTEMS

- *Emergency response*
- *Fire protection*
- *Secondary containment*
- *Blast shielding*
- *Water/steam curtain*

ACCIDENTAL EVENT

fire, explosion,
hazardous material release
(loss of containment of process material and/or process energy)

(FAULT TREE TOP EVENTS)

PROTECTION SYSTEMS

- *Ignition source control*
- *Emergency relief*
- *Interlocks/trips*
- *Operator alarms*
- *Charts/indicators*

PROCESS DEVIATION

no flow
high pressure
low level
loss of agitation, etc.

(FAULT TREE INTERMEDIATE EVENTS)

STANDARD OPERATING LIMITS

INITIATING EVENT

control system failures, e.g., sensor, controller and actuator; mechanical failure, human error fouling, etc.

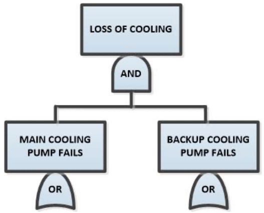
(BASIC EVENTS)

PREVENTION SYSTEMS

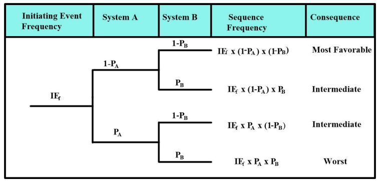
- *Process integrity*
- *Equipment integrity*
- *Operator training*
- *Site security*

PROCESS HAZARD

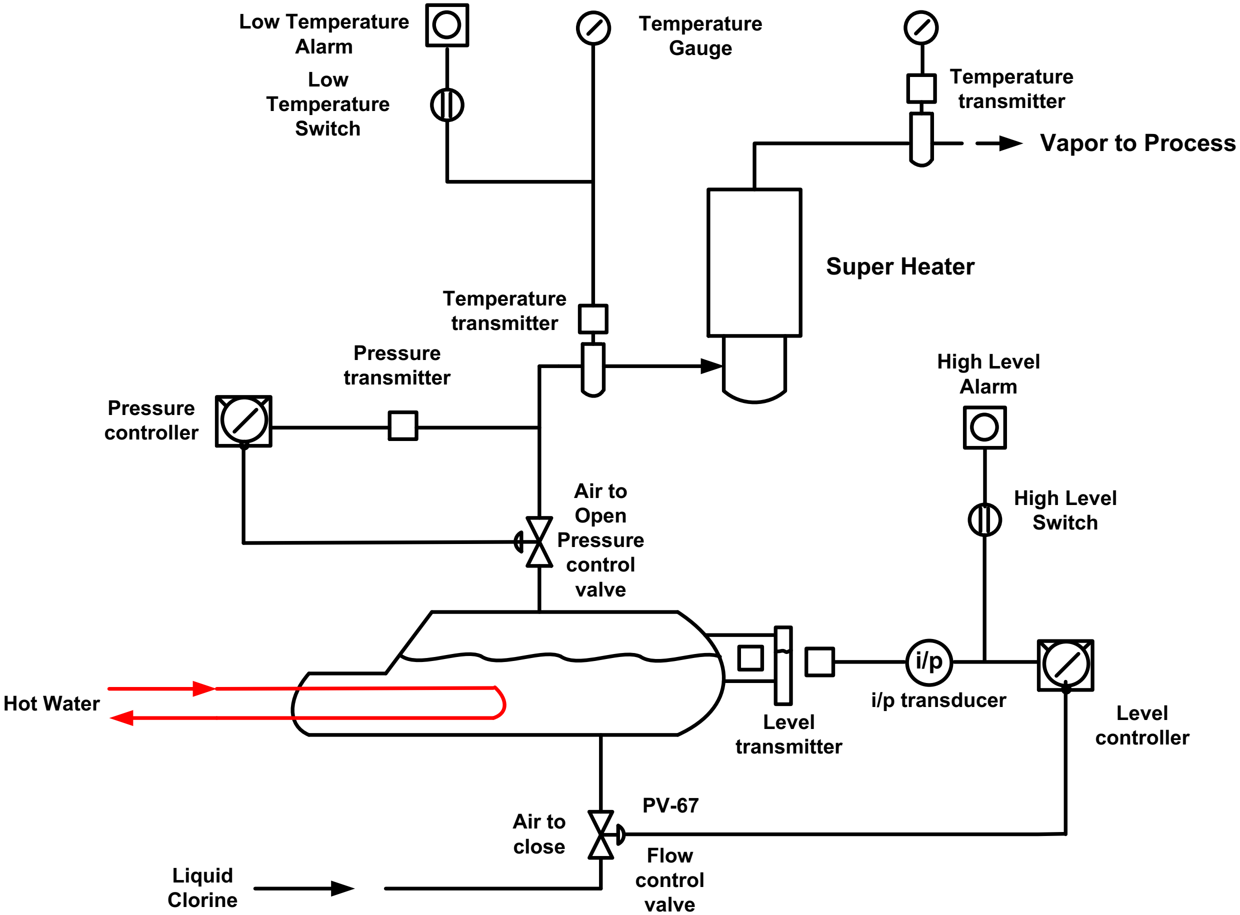
instability, flammability, toxicity, elevated pressure, tendency to polymerize, etc.

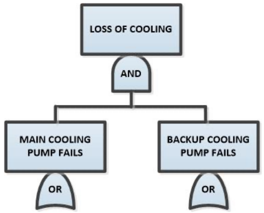


CHLORINE VAPORIZER – ORIGINAL SYSTEM

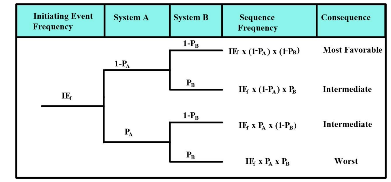


Notes: Original System is a Manual System – Liquid chlorine flow is shut off by the operator when the operator receives anyone of two alarms – (1) High chlorine level in the vaporizer and (2) Low chlorine temperature in the overheads

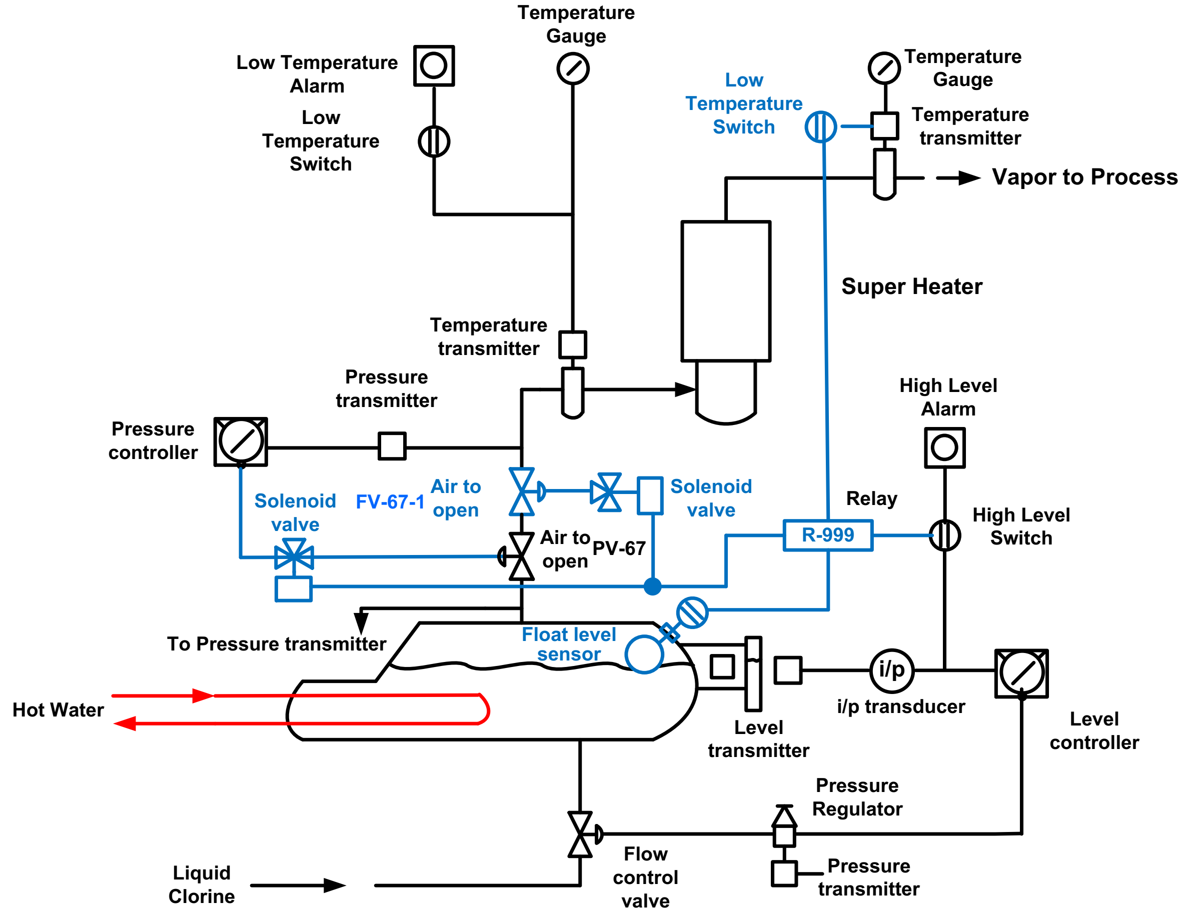


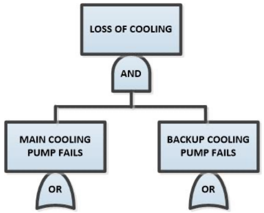


CHLORINE VAPORIZER –SYSTEM A

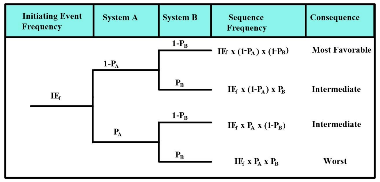


Notes: System A adds interlocks to automatically shut chlorine flow in the event of overflow – Two valves are used to shut off chlorine flow – three trip conditions close these valves – 1. high chlorine level or 2. low temperature – 3. a separate level float sensor is added. In addition, the operator can manually shut off chlorine flow as described for the original system.





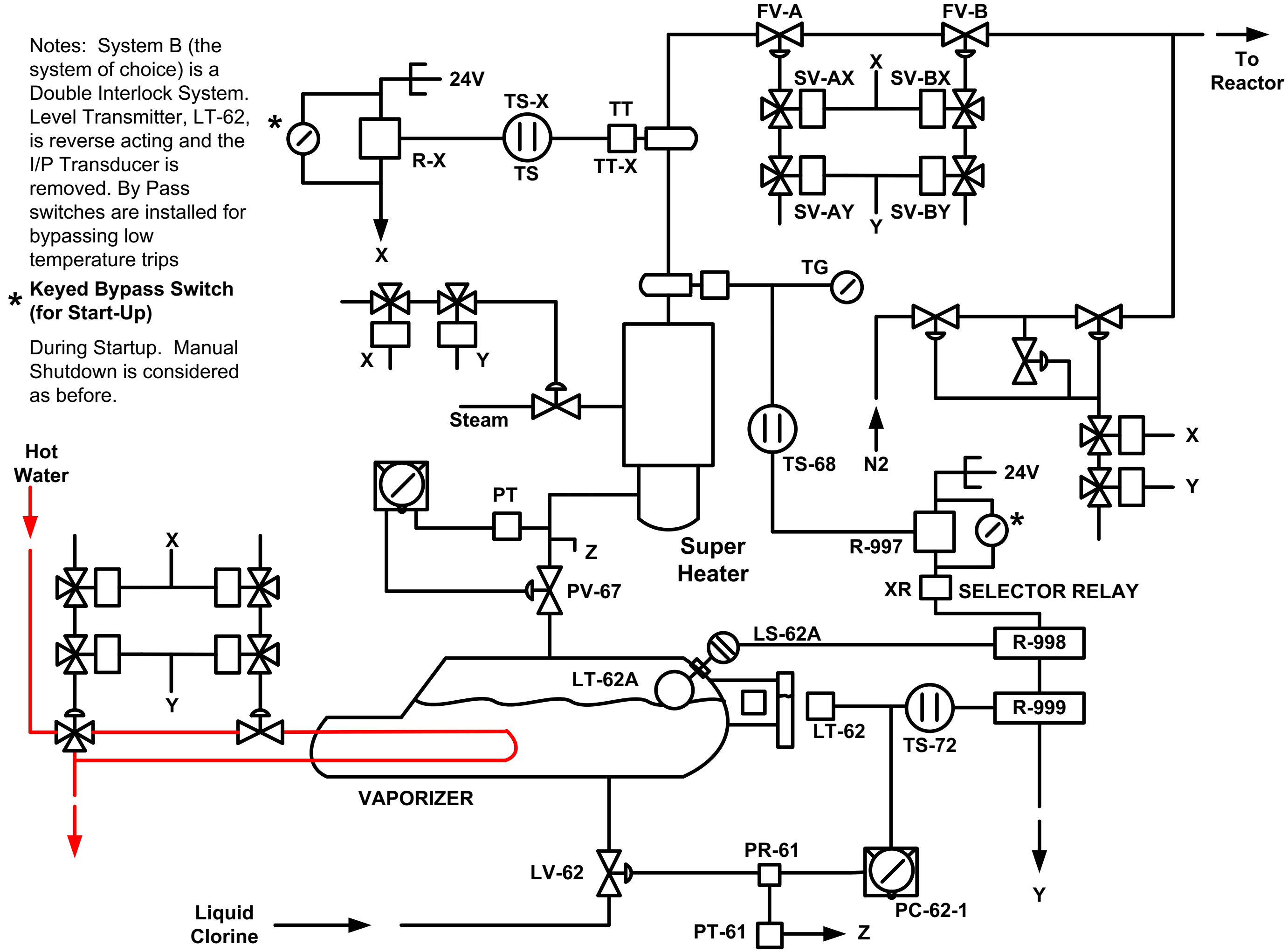
SYSTEM B – DOUBLE INTERLOCK SYSTEM

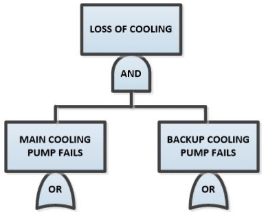


Notes: System B (the system of choice) is a Double Interlock System. Level Transmitter, LT-62, is reverse acting and the I/P Transducer is removed. By Pass switches are installed for bypassing low temperature trips

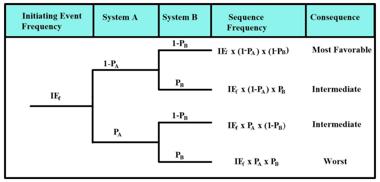
* **Keyed Bypass Switch (for Start-Up)**

During Startup. Manual Shutdown is considered as before.

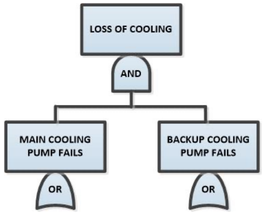




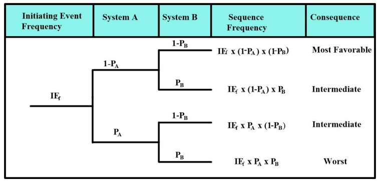
FAULT TREE ANALYSIS STEPS FOR CONTROL SYSTEMS



- STEP 1 -- top event definition (from PHR)
- Step 2 -- system understanding, assumptions
- Step 3 -- directed graph (digraph) construction
- STEP 4 -- fault tree construction (synthesis algorithm)
- Step 5 -- find min cut sets
- Step 6 -- reliability data
- Step 7 -- probabilistic analysis
- STEP 8 -- Importance analysis (summary fault trees)
- Step 9 -- conclusions, recommendations and results



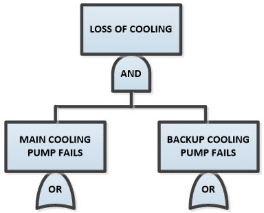
STEPS IN FAILURE MODE ANALYSIS



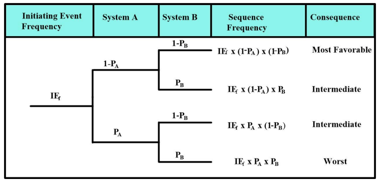
1. **top event definition -- overflow of liquid chlorine to down stream chemical reactor – potential consequence is rupture of a downstream chemical reactor due to an exothermic reaction**

2. **initiating events that can cause increased chlorine flow**

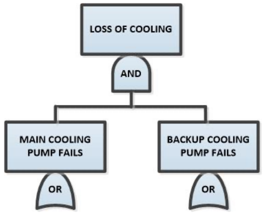
3. **control system failures -- level control**
   1. **control devices failing high or low/fully closed or open**
   2. **external disturbances -- large or fast disturbances**
   3. **reversal events -- wired backwards or computer programmed incorrectly**



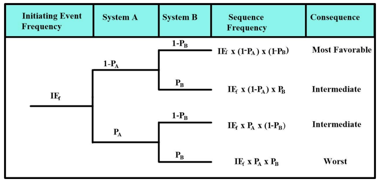
STEPS IN
FAILURE MODE ANALYSIS Cont'd



3. **mitigation -- interlocks (safe shutdown paths)**
4. **mitigation failures (all safe shutdown paths fail)**
5. **common-cause initiating events -- e.g., sensors used for control and protection**



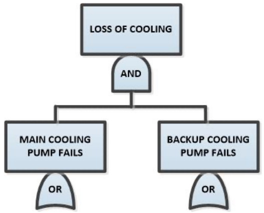
INITIATING EVENTS (DEVIATION EVENTS)



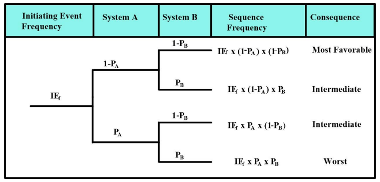
System A -- Single Interlock System As An Example

Liquid Chlorine Level Control Loop Causes Or Passes Disturbance(s)

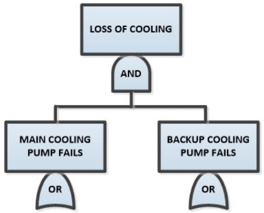
1. **Control Elements -- (Failure Modes That Cause High Chlorine Level In Vaporizer)**
2. **External Disturbances**



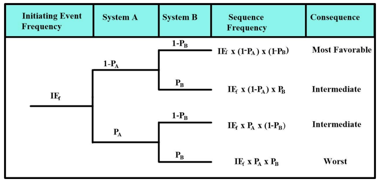
Control Elements – Failure Modes That Cause High Chlorine Level



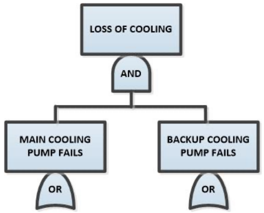
- **Level Transmitter -- LT-62 (Generates False Low Signal, Lose Power, Grounded, Reverse Polarity)**
- **Pneumatic To Current Transducer -- L-62-2 (Generates False Low Signal, Lose Air -- Local, Lose Air System, Lose Input, Reverse Polarity, Output Leak, Lose 24v -- Local Or System, Short Input)**
- **Level Controller -- LC-62-1 (Generates False Low Signal, Lose Air Local Or System, Output Leak, Set Point Low, Manual Set Low)**
- **Pressure Regulator -- PR-61 (Fails High Output)**
- **Air To Close Control Valve -- LV-62 (Reversed, Fail Open)**



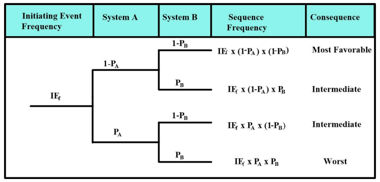
EXTERNAL DISTURBANCES



- **Heat input hot water -- hot water low flow or low temperature**
- **Input flow liquid chlorine -- flow rate too high**



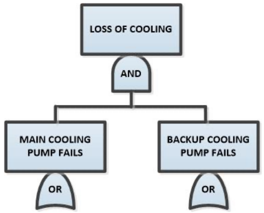
INTERLOCKS



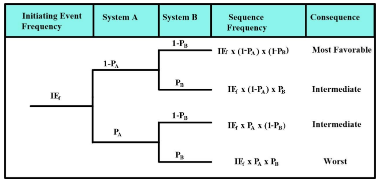
Three Types of Trips

1. **Low Temperature Trip**
2. **High Chlorine Level Trip (Level Transmitter)**
3. **High Chlorine Level Trip (Float Level)**

- **One Set Of Trips Initiated By Relay R999**
- **Another Set Of Trips Initiated By Operator**
- **Interlocks Close Either One Of Two Valves (FV-67-1 And PV-67)**



INTERLOCKS CONTINUED

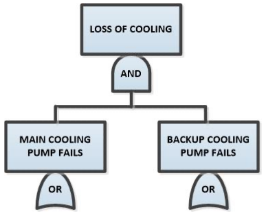


TOTAL OF 9 SHUTDOWN PATHS (PATHS 1-6 RELAYS, PATHS 7-9 OPERATOR)

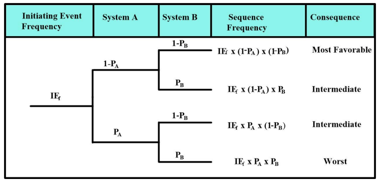
1. LT-62, L-62-2, LS-62, R-999, SV-A, FV-67-1
2. LT-62, L-62-2, LS-62, R-999, SV-B, PV-67
3. LT-62A, LS-62A, R-999, SV-A, FV-67-1
4. LT-62A, LS-62A, R-999, SV-B, PV-67
5. TT-68, TS-68, R-999, SV-A, FV-67-1
6. TT-68, TS-68, R-999, SV-B, PV-67
7. LT-62, L-62-2, GAUGE, OPR, PV-67
8. LT-62, L-62-2, LS-72, LA-62, OPR, PV-67
9. TT-68, TG-68, OPR, PV-67

WHERE:

LT-62 is level transmitter 62
L-62-2 is I/P transducer 62
LS-62 is level switch for transmitter LT-62
LT-62A is float level sensor
LS-62A is level switch for float level
R-999 is relay 999
SV-A is solenoid A
SV-B is solenoid B
FV-67-1 is block valve 67
PV-67 is pressure control valve 67
OPR is operator
GAUGE is level gauge
LA-62 is high level alarm
TG-68 is chlorine vapor temperature gauge
TS-68 is low temp switch
TT-68 is temperature transmitter



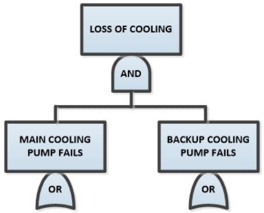
MITIGATION FAILURES



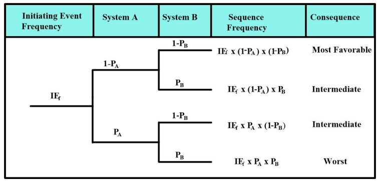
(For overflow of liquid chlorine --all mitigation shutdown paths must fail)

Dominant failure events

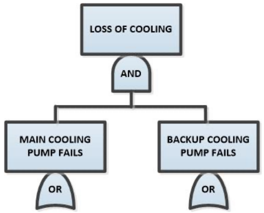
1. **Relay R-999 (fails first six shutdown paths)**
2. **Operator (fails last three shutdown paths)**



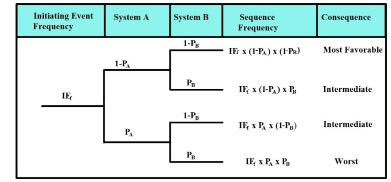
DIGRAPH FOR SYSTEM A

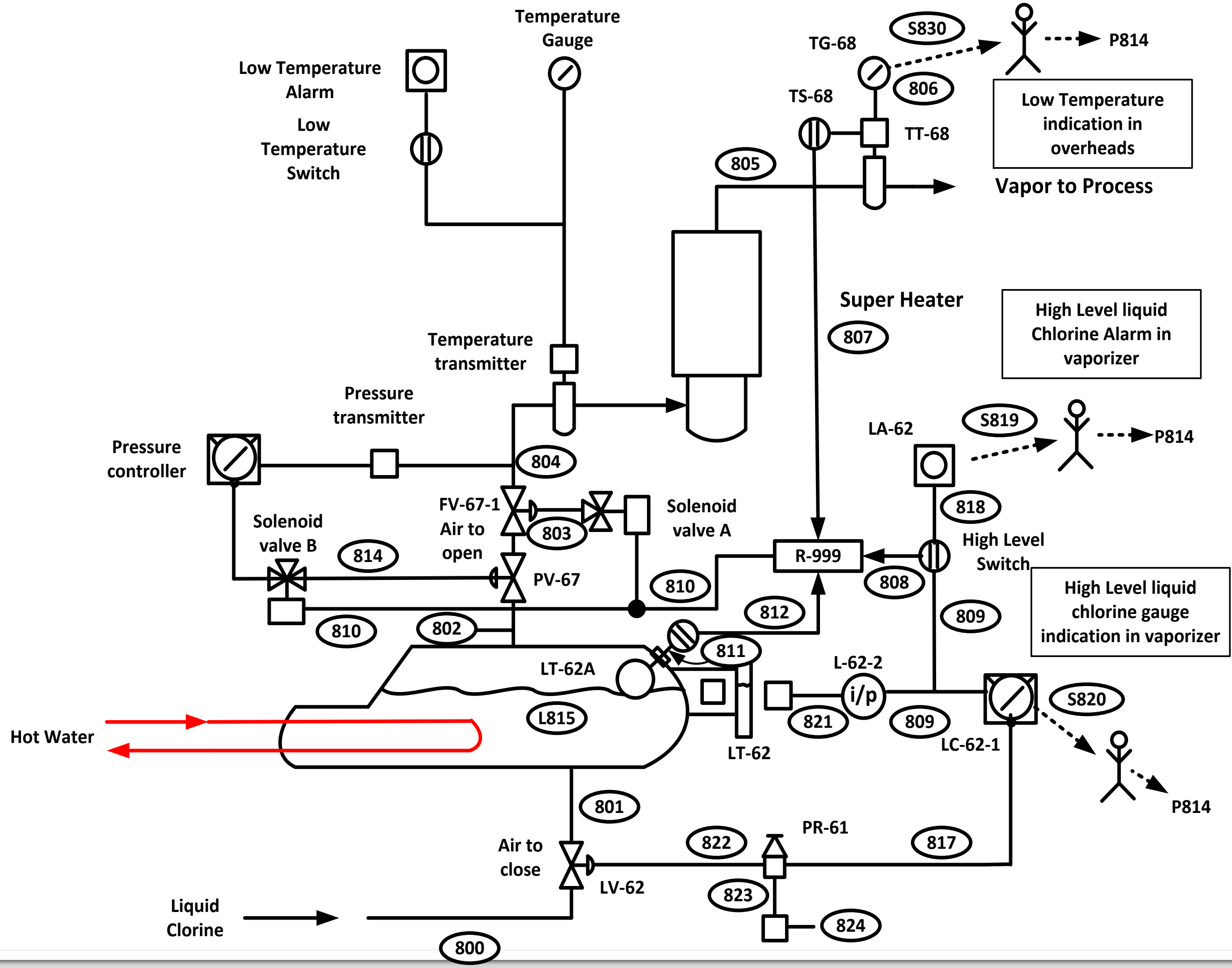


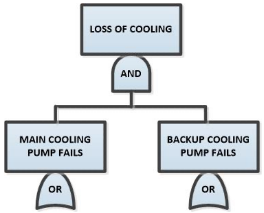
- Location specific nodes for the system A are displayed on the next page
- Following page displays digraph for system A
- “Normal information flow" is shown
- Trace interlocks and operator shutdown paths
- Identify initiating events that can cause high chlorine level
- Identify events that can fail interlocks and operator shutdown paths



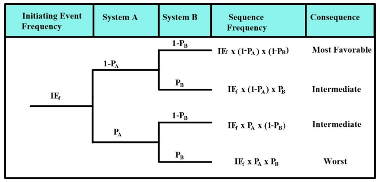
CHLORINE VAPORIZER –SYSTEM A WITH LOCATION NODES





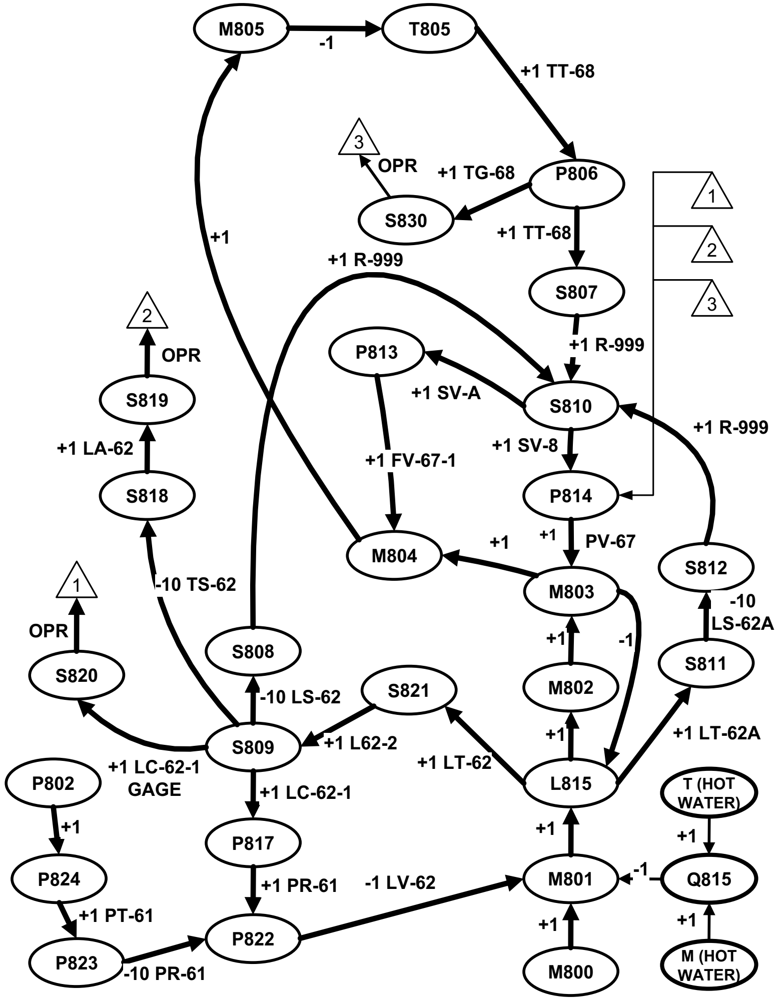


Basic Digraph System A



Show

1. Negative Feedback Loop
2. External Inputs and Disturbances
3. Show interlocks and shutdown paths by operator



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SV-A is solenoid A
SV-B is solenoid B
FV-67-1 is block valve 67
PV-67 is pressure control valve 67
OPR is operator
GAUGE is level gauge
LA-62 is high level alarm
TG-68 is chlorine vapor temperature gauge
TS-68 is low temp switch
TT-68 is temperature transmitter

Legend
Path information

External disturbance

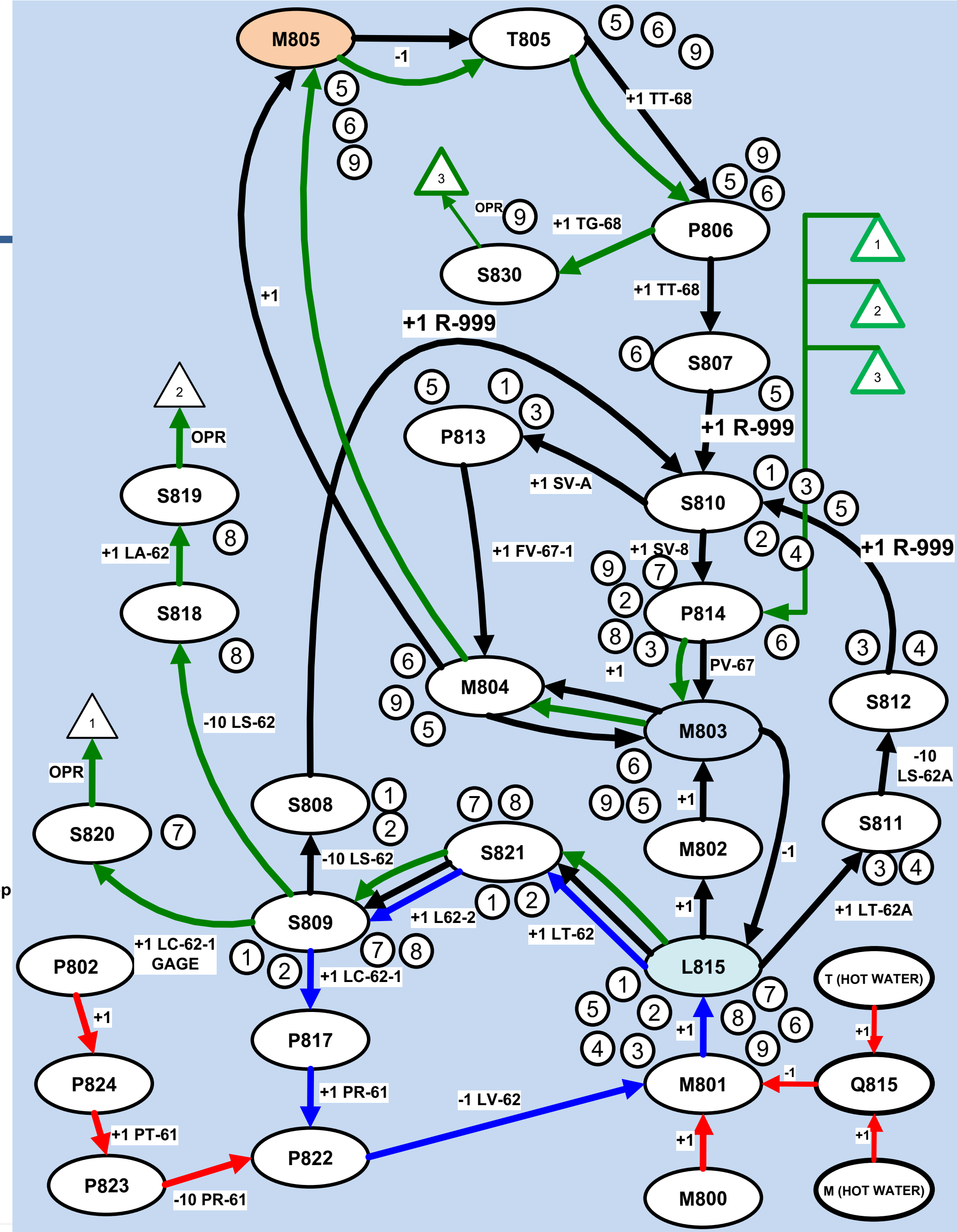
Negative Feed Back Loop

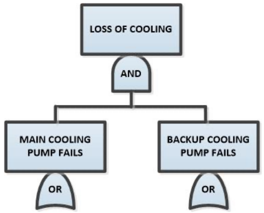
Operator Shutdown

Interlock

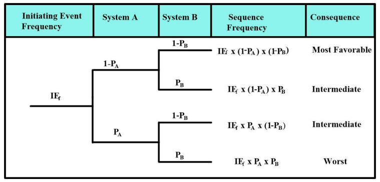
L815 Starting and ending node

M805 Top event node





FAILURE MODES AND RELIABILITY DATA PNEUMATIC FLOW TRANSMITTER



INSTRUMENT FT (P)   P= PNEUMATIC, E= ELECTRONIC

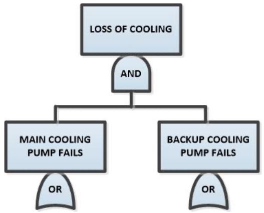
ZERO GAIN	λ	FAIL HI	λ	FAIL LO	λ
STUCK	1/20	MISC	1/20	SIGNAL LINE OUT	1/40
		PLUG IMPULSE LINES	1/3	CAPSULE FAILS	1/10
		VALVE OUT IMPULSE LINES	1/15	LOCAL AIR LOSS	1/10
				VALVED OUT	1/15
				OUTPUT LEAK	1/40
				IMPULSE LINE VALVED OUT	1/15
				IMPULSE LINE PLUGGED	1/3 ①

① SPECIFIC

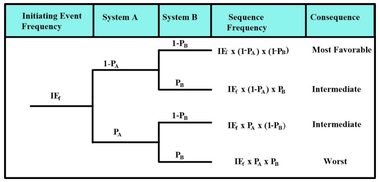
NOTES:

ENGINEERING COMPUTATION SHEET

SUBJECT — TITLE OF PROJ. OR STUDY — WORKS — PROJ. OR STUDY NO. — SHEET NO. — COMPUTER — DATE — G-46 REV. 5-77



FAILURE MODES AND RELIABILITY DATA SWITCH



ENGINEERING COMPUTATION SHEET

SUBJECT

TITLE OF PROJ. OR STUDY

PROJ. OR STUDY NO.

WORKS

SHEET NO.

COMPUTER

DATE

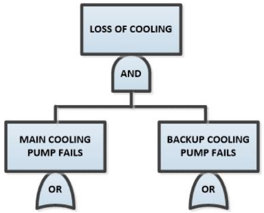
INSTRUMENT X S (P)

P= PNEUMATIC, E= ELECTRONIC

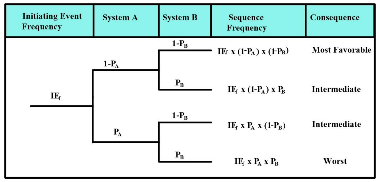
ZERO GAIN	λ	FAIL HI	λ	FAIL LO	λ
FAILS-MISC	1/35				
MISSET	1/35				
SHORTED	1/40				
OPEN INPUT (HI TRIP ONLY)	1/20				
3 WAY IN TEST	1/20				

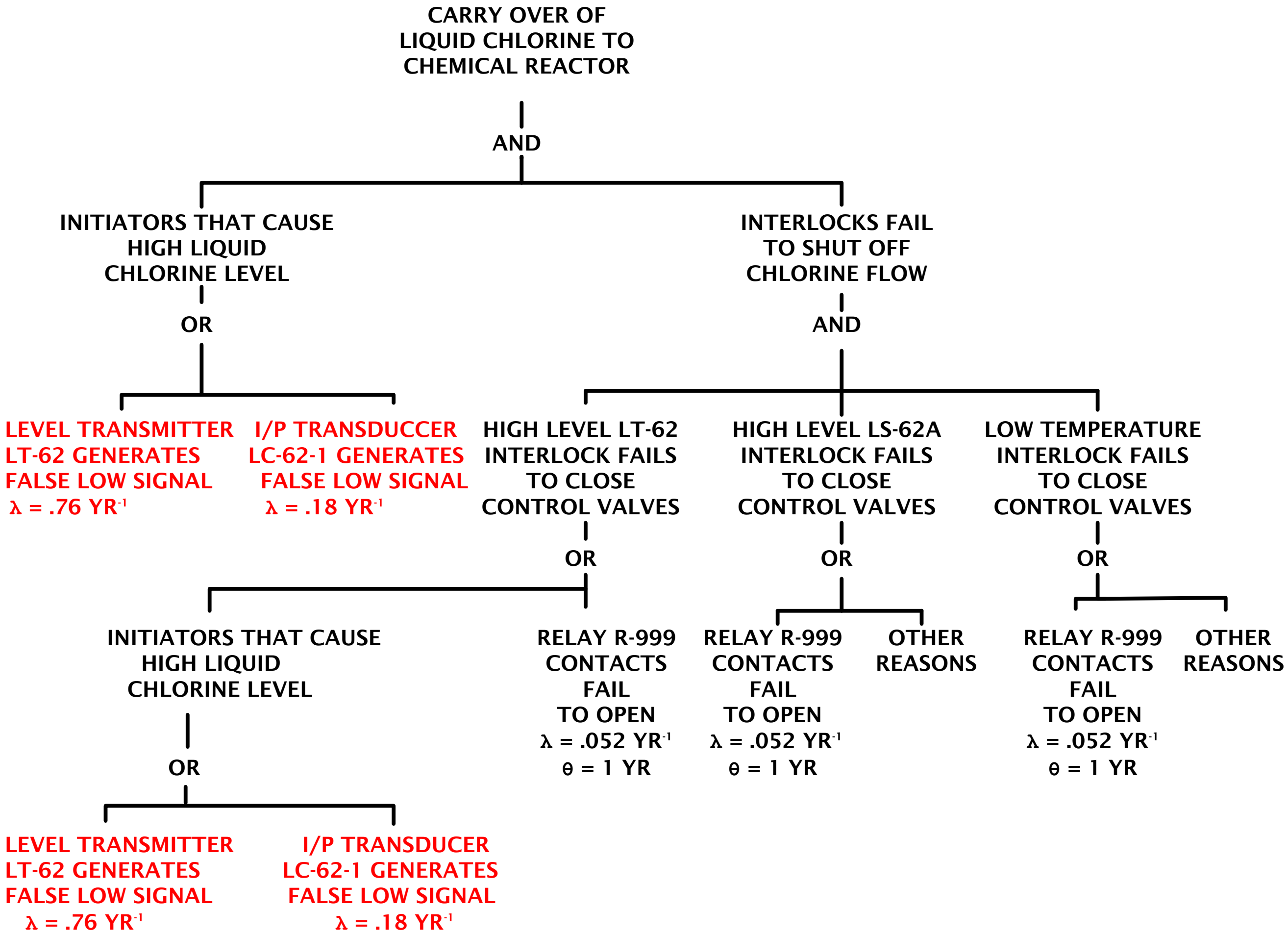
NOTES:

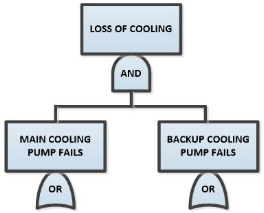
22



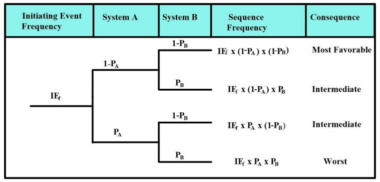
FAULT TREE FOR SYSTEM A (Common Cause Initiating Events)







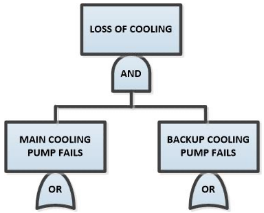
TWO MIN CUT SETS OF ORDER TWO – SYSTEM A



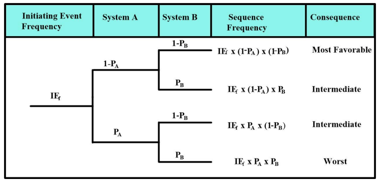
MIN CUT SET NO.	DESCRIPTION
1	1. LEVEL TRANSMITTER GENERATES FALSE LOW SIGNAL (i) 2. RELAY R-999 CONTACTS FAIL TO OPEN (e)
2	1. I/P TRANSDUCER GENERATES FALSE LOW SIGNAL (i) 2. RELAY R-999 CONTACTS FAIL TO OPEN (e)

(i) denotes initiating event

(e) denotes enabling event



BASIC EVENT DATA



1. **INITIATING EVENT FAILURE FREQUENCY, λ**

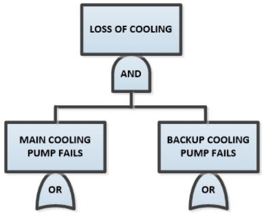
   LEVEL TRANSMITTER = .76 yr^{-1}

   I/P TRANSDUCER = .18 yr^{-1}

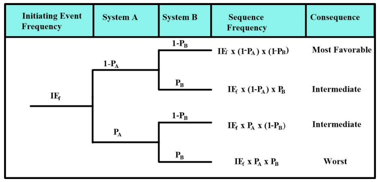
2. **AVERAGE ENABLING EVENT UNAVAILABILITY, $q = \lambda\, \theta/2$**

   RELAY = .052 yr^{-1} x 1 yr x 1/2 = .026

   θ = INSPECTION INTERVAL = 1 YEAR



MIN CUT SET / TOP EVENT OCCURRENCE FREQUENCIES



MIN CUT SET 1 $\lambda_{LT}\, q_R = .76 \times .026 = 1.98 \times 10^{-2}\ yr^{-1}$

MIN CUT SET 2 $\lambda_{I/P}\, q_R = .18 \times .026 = 4.68 \times 10^{-3}\ yr^{-1}$

TOP EVENT OCCURRENCE FREQUENCY $= 2.44 \times 10^{-2}\ yr^{-1}$

MEAN OCCURRENCE TIME = 40.9 years

IMPORTANCE

MIN CUT SET 1 $1.98 \times 10^{-2} / 2.44 \times 10^{-2} = .81$

MIN CUT SET 2 $4.68 \times 10^{-3} / 2.44 \times 10^{-2} = .19$

ORIGINAL SYSTEM -- IMPORTANCE RANKINGS
INITIATING EVENTS

MEAN TIME TO FAILURE = 1.51 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 13.0

RANK	IMPORTANCE	FTAP ID	COMPONENT	FAILURE MODE
1	0.148E 00	LT-62	LEVEL TRANSMITTER	MISC FAILS LOW
1	0.148E 00	L-62-2	i/p TRANSDUCER	LOSE AIR-LOCAL
2	0.742E-01	L-62-2	i/p TRANSDUCER	LOSE INPUT
2	0.742E-01	L-62-2	i/p TRANSDUCER	REV POLARITY
3	0.524E-01	LC-62-1	CONTROLLER	LOSE AIR-LOCAL
4	0.495E-01	LT-62	LEVEL TRANSMITTER	REV POLARITY
5	0.495E-01	LOSE 24V	DC POWER	SYSTEM
6	0.371E-01	L-62-2	i/p TRANSDUCER	OUTPUT LEAK
7	0.371E-01	LT-62	LEVEL TRANSMITTER	LOSE POWER
7	0.371E-01	L-62-2	i/p TRANSDUCER	MISC FAIL LO
7	0.371E-01	LT-62	LEVEL TRANSMITTER	GROUNDED
7	0.371E-01	L-62-2	i/p TRANSDUCER	LOSE 24V – LOCAL
8	0.297E-01	LOSE AIR	PNUEMATICS	SYSTEM
9	0.262E-01	LC-62-1	CONTROLLER	OUTPUT LEAK
9	0.262E-01	PT-780	PRESSURE TRANS	FAILS HI
9	0.262E-01	LC-62-1	CONTROLLER	MISC FAILS LO
10	0.247E-01	L-62-2	i/p TRANSDUCER	SHORT INPUT
11	0.175E-01	PR-61	PRESS REGULATOR	FAILS HI
11	0.175E-01	LC-62-1	CONTROLLER	SET POINT (+10)
11	0.175E-01	LC-62-1	CONTROLLER	MANUAL SET (+10)
12	0.175E-01	LV-62	CONTROL VALVE	REVERSED
13	0.131E-01	LV-62	CONTROL VALVE	FAILS OPEN
14	0.156E-02	P800 (+10)	LIQUID CHLORINE SUPPLY	CL_2 SUPPLY PRESS VERY HI

ORIGINAL SYSTEM -- IMPORTANCE RANKINGS
ENABLING EVENTS

MEAN TIME TO FAILURE = 1.51 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 13.0

RANK	IMPORTANCE	COMPONENT	FAILURE MODE
1	0.820E 00	OPERATOR	NO OPR RESP TO S830 & S820
2	0.816E 00	OPERATOR	NO OPR RESP TO S830
3	0.143E 00	OPERATOR	OPR BUSY
3	0.143E 00	OPERATOR	OPR NOT PRESENT
3	0.143E 00	OPERATOR	WRONG OPR RESPONSE
4	0.989E-01	OPERATOR	NO OPR RESP TO S830 & S819
5	0.715E-01	OPERATOR	OPR – MISC NO RESPONSE
6	0.419E-01	OPERATOR	NO OPR RESP TO S820
7	0.201E-01	OPERATOR	NO OPR RESP TO S820 & S819
8	0.136E-01	HI LEVEL SWITCH	LS-62 OPEN INPUT
9	0.777E-02	HI LEVEL SWITCH	LS-62 MISSET
9	0.777E-02	HI LEVEL SWITCH	LS-62 MISC FAILS
10	0.680E-02	HI LEVEL SWITCH	LS-62 SHORTED
11	0.131E-02	CONTROLLER	LC-62-1 ON MANUAL
12	0.286E-03	TEMP TRANSMITTER	TT-68 STUCK
12	0.286E-03	TEMP GAUGE	TG-68 STUCK
13	0.124E-03	LEVEL TRANSMITTER STUCK	LT-62 STUCK
14	0.111E-03	i/p TRANSDUCER	L-62-2 STUCK

SYSTEM A -- SINGLE RELAY -- IMPORTANCE RANKINGS -- INITIATING EVENTS

MEAN TIME TO FAILURE = 26.7 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 0.71

RANK	IMPORTANCE	FTAP ID	COMPONENT	FAILURE MODE
1	0.161E 00	L-62-2	i/p TRANSDUCER	LOSE AIR – LOCAL
1	0.161E 00	LT-62	LEVEL TRANSMITTER	MISC FAILS LO
2	0.803E-01	L-62-2	i/p TRANSDUCER	LOST INPUT
2	0.803E-01	L-62-2	i/p TRANSDUCER	REV POLARITY
3	0.535E-01	LT-62	LEVEL TRANSMITTER	REV POLARITY
4	0.525E-01	LOSE 24V	DC POWER	SYSTEM
5	0.402E-01	L-62-2	i/p TRANSDUCER	OUTPUT LEAK
6	0.401E-01	L-62-2	i/p TRANSDUCER	MISC FAILS LO
6	0.401E-01	LT-62	LEVEL TRANSMITTER	GROUND
6	0.401E-01	LT-62	LEVEL TRANSMITTER	LOSE LOCAL POWER
6	0.401E-01	L-62-2	i/p TRANSDUCER	LOSE 24V – LOCAL
7	0.373E-01	LC-62-1	CONTROLLER	LOSE AIR – LOCAL
8	0.320E-01	LOSE AIR	PNUEMATICS	SYSTEM
9	0.267E-01	L-62-2	i/p TRANSDUCER	SHORT INPUT
10	0.186E-01	LC-62-1	CONTROLLER	OUTPUT LEAK
10	0.186E-01	PT-780	PRESS TRANSMITTER	FAILS HI
10	0.186E-01	LC-62-1	CONTROLLER	MISC FAILS LO
11	0.124E-01	LV-62	CONTROL VALVE	REVERSED
12	0.124E-01	PR-61	PRESS REGULATOR	FAILS HI
12	0.124E-01	LC-62-1	CONTROLLER	SET POINT (+10)
12	0.124E-01	LC-62-1	CONTROLLER	MANUAL SET (+10)
13	0.931E-02	LV-62	CONTROL VALVE	FAILS OPEN
14	0.676E-03	P800 (+10)		CL_2 SUPPLY PRESS V HI

SYSTEM A -- SINGLE RELAY --
IMPORTANCE RANKINGS -- ENABLING EVENTS

MEAN TIME TO FAILURE = 26.7 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 0.71

RANK	IMPORTANCE	COMPONENT	FAILURE MODE
1	0.863E 00	OPERATOR	NO OPR RESP TO S830 & S820
2	0.739E 00	OPERATOR	NO OPR RESP TO S830
3	0.160E 00	OPERATOR	OPR NOT PRESENT
3	0.160E 00	OPERATOR	WRONG OPR RESPONSE
4	0.160E 00	OPERATOR	OPR – MISC NO RESPONSE
5	0.154E 00	RELAY R-999	R-999 JUMPERED
6	0.132E 00	RELAY R-999	R-999 SHORTED
7	0.118E 00	OPERATOR	NO OPR RESP TO S830 & S819
8	0.116E 00	RELAY R-999	R-999 MISC FAILS SHUT
9	0.813E-01	OPERATOR	OPR – MISC NO RESPONSE
10	0.770E-01	RELAY R-999	R-999 CONTACTS WELDED SHUT
11	0.764E-01	SOLENOID VALVE B	SV-B VENT BLOCKED
12	0.468E-01	FLOW CONTROL VALVE	FV-67-1 STUCK
12	0.468E-01	SOLENOID VALVE A	SV-A VENT BLOCKED
13	0.340E-01	SOLENOID VALVE B	SV-B STUCK

THREE RELAYS --
IMPORTANCE RANKINGS -- INITIATING EVENTS

MEAN TIME TO FAILURE = 150 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 0.037

RANK	IMPORTANCE	FTAP ID	COMPONENT	FAILURE MODE
1	0.173E 00	L-62-2	i/p TRANSDUCER	LOST AIR – LOCAL
1	0.173E 00	LT-62	LEVEL TRANSMITTER	MISC FAILS LO
2	0.856E-01	L-62-2	i/p TRANSDUCER	LOSE INPUT
2	0.856E-01	L-62-2	i/p TRANSDUCER	REV POLARITY
3	0.564E-01	LT-62	LEVEL TRANSMITTER	REV POLARITY
4	0.435E-01	L-62-2	i/p TRANSDUCER	OUTPUT LEAK
5	0.414E-01	L-62-2	i/p TRANSDUCER	MISC FAILS LO
5	0.414E-01	LT-62	LEVEL TRANSMITTER	GROUND
5	0.414E-01	L-62-2	i/p TRANSDUCER	LOSE 24V – LOCAL
5	0.414E-01	LT-62	LEVEL TRANSMITTER	LOSE LOCAL POWER
6	0.331E-01	LC-62-1	CONTROLLER	LOSE AIR – LOCAL
7	0.298E-01	LOSE AIR	PNEUMATICS	SYSTEM
8	0.269E-01	L-62-2	i/p TRANSDUCER	SHORT INPUT
9	0.245E-01	LOSE 24V	DC POWER	SYSTEM
10	0.166E-01	LC-62-1	CONTROLLER	OUTPUT LEAK
10	0.166E-01	PT-780	PRESS TRANSMITTER	FAILS HI
10	0.166E-01	LC-62-1	CONTROLLER	MISC FAILS LO
11	0.110E-01	LV-62	CONTROL VALVE	REVERSED
12	0.110E-01	PR-61	PRESS REGULATOR	FAILS HI
12	0.110E-01	LC-62-1	CONTROLLER	SET POINT (+10)
12	0.110E-01	LC-62-1	CONTROLLER	MANUAL SET (+10)
13	0.829E-02	LV-62	CONTROL VALVE	FAILS OPEN
14	0.470E-03	P800 (+10)	CHLORINE SUPPLY	CL_2 FEED PRESS V HI

THREE RELAYS --
IMPORTANCE RANKINGS -- ENABLING EVENTS

MEAN TIME TO FAILURE = 150 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 0.037

RANK	IMPORTANCE	COMPONENT	FAILURE MODE
1	0.746E 00	OPERATOR	NO OPR RESP TO S830
2	0.746E 00	OPERATOR	NO OPR RESP TO S830 & S820
3	0.234E 00	SOLENIOD VALVE B	SV-B VENT BLOCKED
4	0.152E 00	LEVEL SWITCH	LS-62A MISSET
5	0.152E 00	LEVEL SWITCH	LS-62A MISC FAILS CLOSED
6	0.151E 00	TEMP SWITCH	TS-68 MISSET
7	0.151E 00	TEMP SWITCH	TS-68 MISC FAILS CLOSED
8	0.147E 00	FLOW CONTROL VALVE	FV-67-1 STUCK
8	0.147E 00	SOLENIOD VALVE A	SV-A VENT BLOCKED
9	0.132E 00	LEVEL SWITCH	LS-62A SHORTED
10	0.131E 00	LOW TEMP SWITCH	TS-68 SHORTED
11	0.112E 00	OPERATOR	NO OPR RESP TO S830 & S819
11	0.112E 00	OPERATOR	OPR NOT PRESENT
11	0.112E 00	OPERATOR	OPR BUSY
12	0.112E 00	OPERATOR	WRONG OPR RESPONSE
13	0.104E 00	SOLENIOD VALVE B	SV-B STUCK
14	0.843E-01	RELAY 998	R-998 JUMPERED
15	0.840E-01	RELAY 997	R-997 JUMPERED
16	0.718E-01	RELAY 998	R-998 SHORTED
17	0.716E-01	RELAY 997	R-997 SHORTED
18	0.662E-01	SOLENIOD VALVE B	SV-A STUCK
19	0.622E-01	RELAY 998	R-998 MISC FLS SHUT
20	0.620E-01	RELAY 997	R-997 MISC FLS SHUT
21	0.527E-01	OPERATOR	OPR – MISC NO RESPONSE

CC: J. V. Woodrick
G. R. Ehrman
C. A. Thayer
File 1-5-8

July 2, 1979

TO: PLANT PROCESS HAZARDS COMMITTEE

FROM: C. DUNGLINSON

INTERLOCK SYSTEM DESIGN

Interlock reliability can be significantly improved by providing each branch with a separate relay. Victoria Plant interlock systems often have all branches activating a single relay. (Figures 1 and 2 illustrate the difference.) We recently calculated a 5X reduction in top event rate upon substitution of the multiple relay system.

Details

Fault tree analysis of the DCB Area chlorine vaporizers showed that installing an interlock system with a relay for each sensing branch (Figure 2) would reduce the failure rate from 1/28 years to 1/150 years when compared to a common-relay system, (Figure 1) an over 5X reduction. A "failure" is defined as liquid chlorine carry-over, of any magnitude, into the chlorine header.

Figure 3 is the fault tree for interlock failure--the 1 relay and 3 relay sub-trees are alternates for the "signal to SVs holds" sub-tree. If each branch (i.e., XT and XS) have the same combined unavailability (q_B) and all relays have unavailability q_R, the unavailability for the failure mode "signal to SVs holds" (q_S) is:

for the 1 relay system (Figure 1)

$$q_S \doteq q_R + q_B^3 \qquad (1)$$

for the 3 relay system (Figure 2)

$$q_S \doteq (q_R + q_B)^3 \qquad (2)$$

Since most q's are much less than one, (2) is significantly lower than (1).

"Critical" Interlocks should be considered for conversion to multiple relays. New design should specify multiple relays.

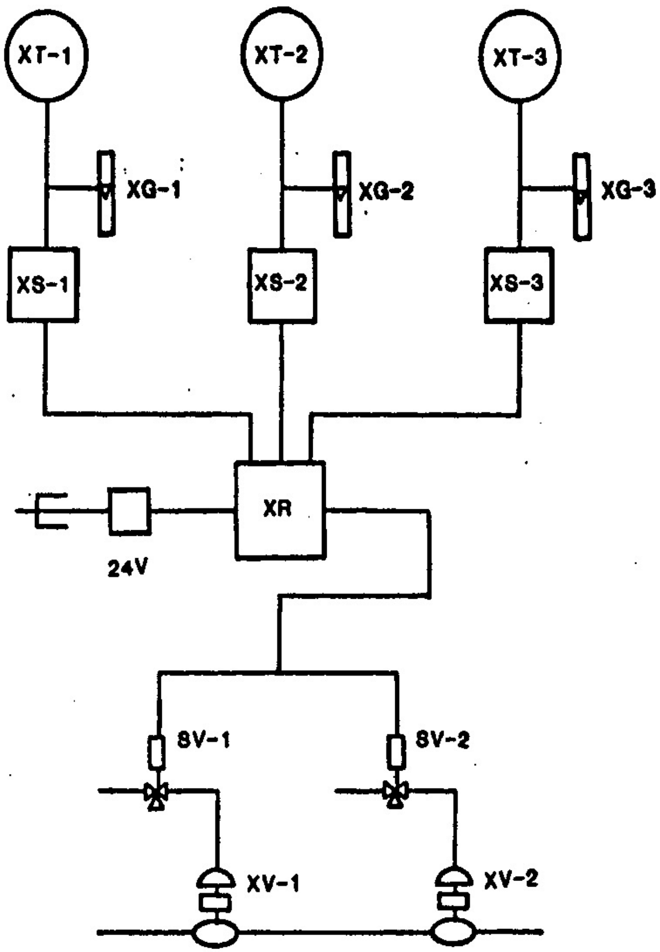


FIG 1 Single Relay Interlock

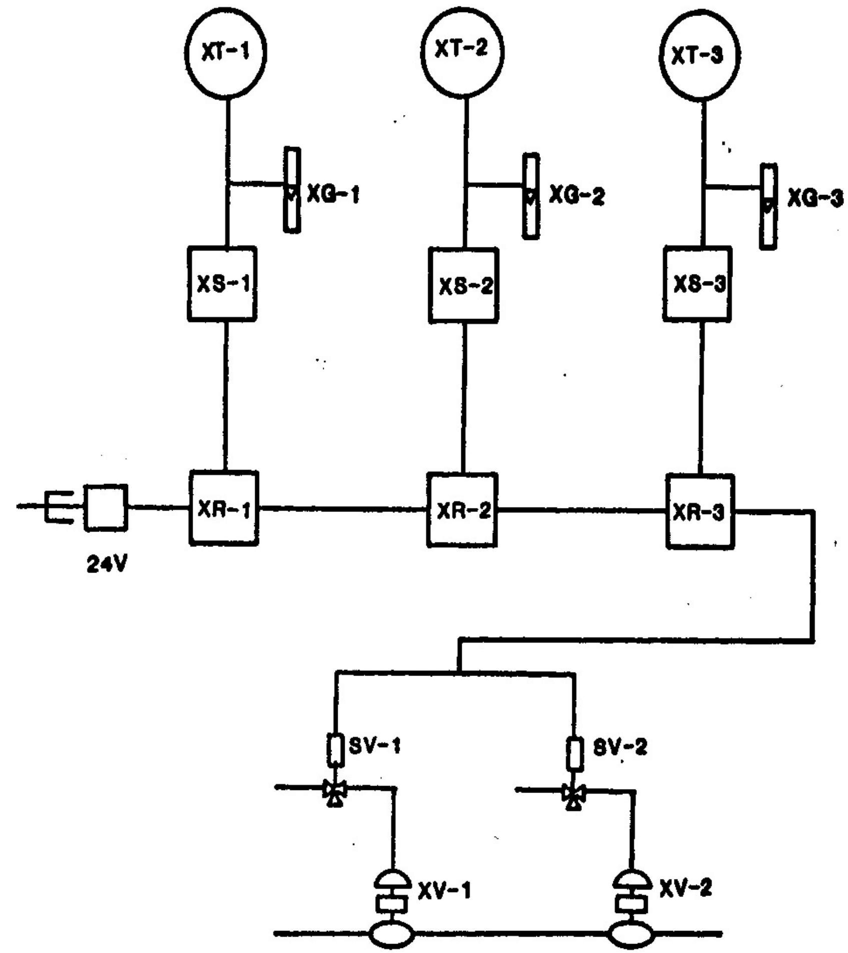
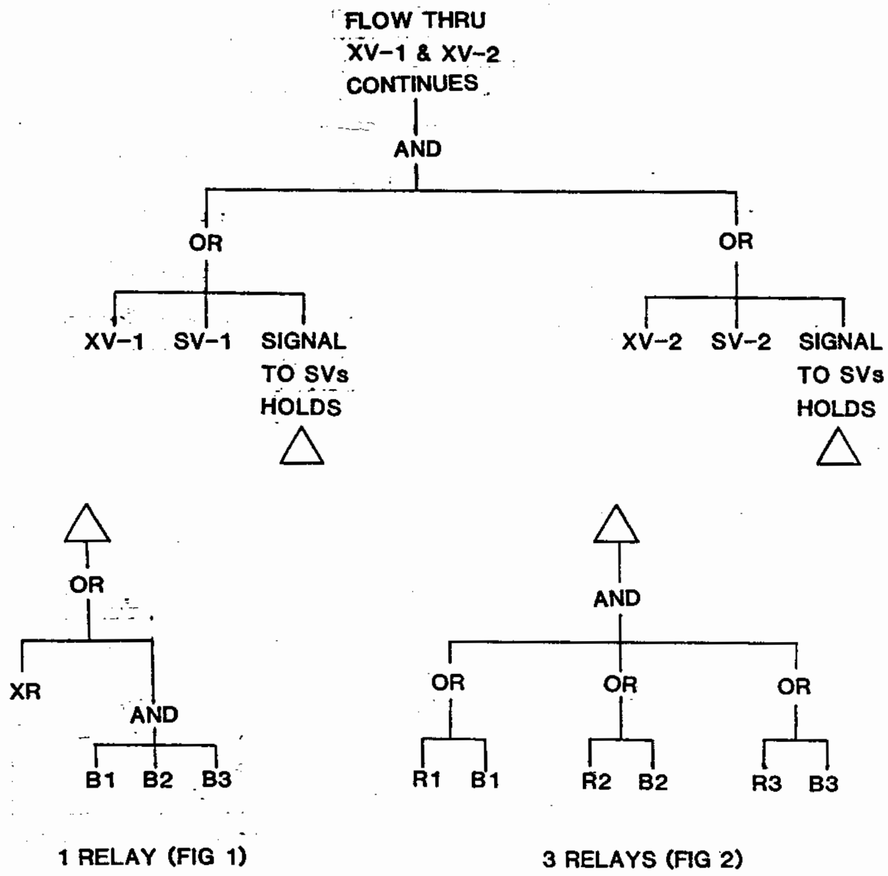


FIG 2 Multiple Relay Interlock

ENGINEERING COMPUTATION SHEET



B1 ⟹ branch 1 (ie XT-1 & XS-1) fails

XR ⟹ XR fails

FIG 3 Fault Tree for Interlock Failure

THREE RELAYS -- REVERSE ACTING TRANSMITTER -- IMPORTANCE RANKINGS -- INITIATING EVENTS

MEAN TIME TO FAILURE = 526 YEARS
EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS = 0.037

RANK	IMPORTANCE	FTAP ID	COMPONENT	FAILURE MODE
1	0.261E 00	LT-62	LEVEL TRANSMITTER	FAILS HI
2	0.160E 00	LT-62	LEVEL TRANSMITTER	LEG BREAK
3	0.116E 00	LC-62-1	LEVEL CONTROLLER	LOSE AIR – LOCAL
4	0.104E 00	LOSE AIR	PNUEMATICS	SYSTEM
5	0.580E-01	LC-62-1	LEVEL CONTROLLER	OUTPUT LEAK
5	0.580E-01	PT-61	PRESSURE TRANSMITTER	FAILS HI
5	0.580E-01	LC-62-1	LEVEL CONTROLLER	MISC FAILS LO
6	0.386E-01	LV-62	CONTROL VALVE	REVERSED
7	0.386E-01	PR-61	PRESSURE REGULATOR	FAILS HI
7	0.386E-01	LC-62-1	LEVEL CONTROLLER	SET POINT (+10)
7	0.386E-01	LC-62-1	LEVEL CONTROLLER	MANUAL SET (+10)
8	0.290E-01	LV-62	CONTROL VALVE	FAILS OPEN
9	0.164E-02	P800 (+10)	CHLORINE SUPPLY	CL_2 SUPPLY PRESS V HI

THREE RELAYS -- REVERSE ACTING TRANSMITTER -- IMPORTANCE RANKINGS -- ENABLING EVENTS

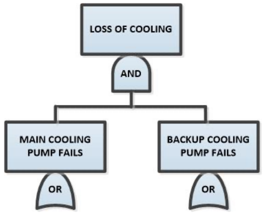
MEAN TIME TO FAILURE
= 526 YEARS

EXPECTED NUMBER OF SYSTEM FAILURES IN 20 YEARS
= 0.037

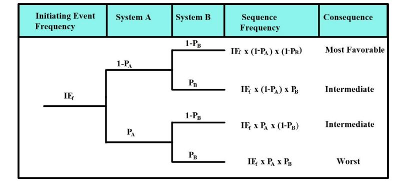
RANK	IMPORTANCE	COMPONENT	FAILURE MODE
1	0.458E 00	OPERATOR	NO OPR RESPONSE TO S830 & S820
2	0.458E 00	OPERATOR	NO OPR RESPONSE
3	0.419E 00	SOLENOID VALVE B	SV-B VENT BLOCKED
4	0.260E 00	FLOW CONTROL VALVE	FV-67-1 STUCK
5	0.260E 00	SOLENOID VALVE A	SV-A VENT BLOCKED
6	0.188E 00	SOLENOID VALVE B	SV-B STUCK
7	0.117E 00	SOLENOID VALVE A	SV-A STUCK
8	0.924E-01	LOW TEMP SWITCH	TS-68 MISSET
9	0.924E-01	LOW TEMP SWITCH	TS-68 MISC FAILS CLOSED
10	0.924E-01	LOW LEVEL SWITCH	LS-62A MISSET
11	0.924E-01	LOW LEVEL SWITCH	LS-62A MISC FAILS CLOSED
12	0.790E-01	LOW LEVEL SWITCH	LS-62A SHORTED
13	0.790E-01	LOW TEMP SWITCH	TS-68 SHORTED
14	0.498E-01	RELAY R-999	R-998 JUMPERED
15	0.498E-01	RELAY R-997	R-997 JUMPERED
16	0.420E-01	RELAY R-998	R-998 SHORTED
17	0.420E-01	RELAY R-997	R-997 SHORTED
18	0.415E-01	OPERATOR	OPR BUSY
19	0.415E-01	OPERATOR	NO OPR RESP TO S830 & S819
19	0.415E-01	OPERATOR	OPR NOT PRESENT
19	0.415E-01	OPERATOR	WRONG OPR RESPONSE
20	0.367E-01	RELAY R-998	R-998 MISC FAILS CLOSED
21	0.367E-01	RELAY R-997	R-997 MISC FAILS CLOSED
22	0.222E-01	RELAY R-998	R-998 CONTACTS WELDED
23	0.222E-01	RELAY R-997	R-997 CONTACTS WELDED
24	0.164E-01	LEVEL CONTROLLER	LC-62-1 ON MANUAL

EFFECT OF SYSTEM DESIGN CHANGES

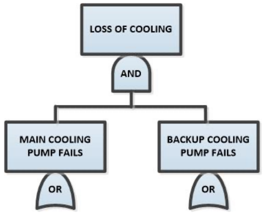
SYSTEM	MEAN TIME TO FAILURE (YR)	EXPECTED NUMBER OF FAILURES (20YR)	LEVEL TRANSMITTER FAILURE RATE (1/YR)
• ORIGINAL	1.5	13	1/1.5
• INTERLOCK 1 RELAY	26.7	0.70	1/1.5
• INTERLOCK 3 RELAYS	59.5	0.34	1/1.5
• INTERLOCK 3 RELAYS	308	0.06	1/17
• INTERLOCK 3 RELAYS + SEL SW & BYPASS	273	0.07	1/17
• INTERLOCK 3 RELAYS + SEL SW & BYPASS	4250 796	.0046 .024	1/17 1/1.5



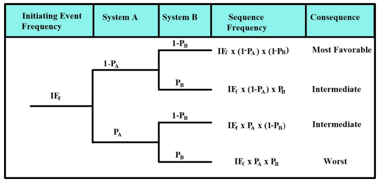
Salt Process Cell
Fault Tree Analysis Study



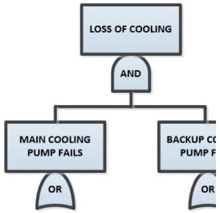
- Study Conducted 1986-1993
- Salt process cell part of the Defense Waste Processing Facility (DWPF) at the Savannah River Site
- Concerned with Benzene Air Deflagrations
- Title of Study
  - "Fault Tree Analysis for Fire Explosion within the Salt Process Cell," Howard Lambert, FTA Associates. February 1993.

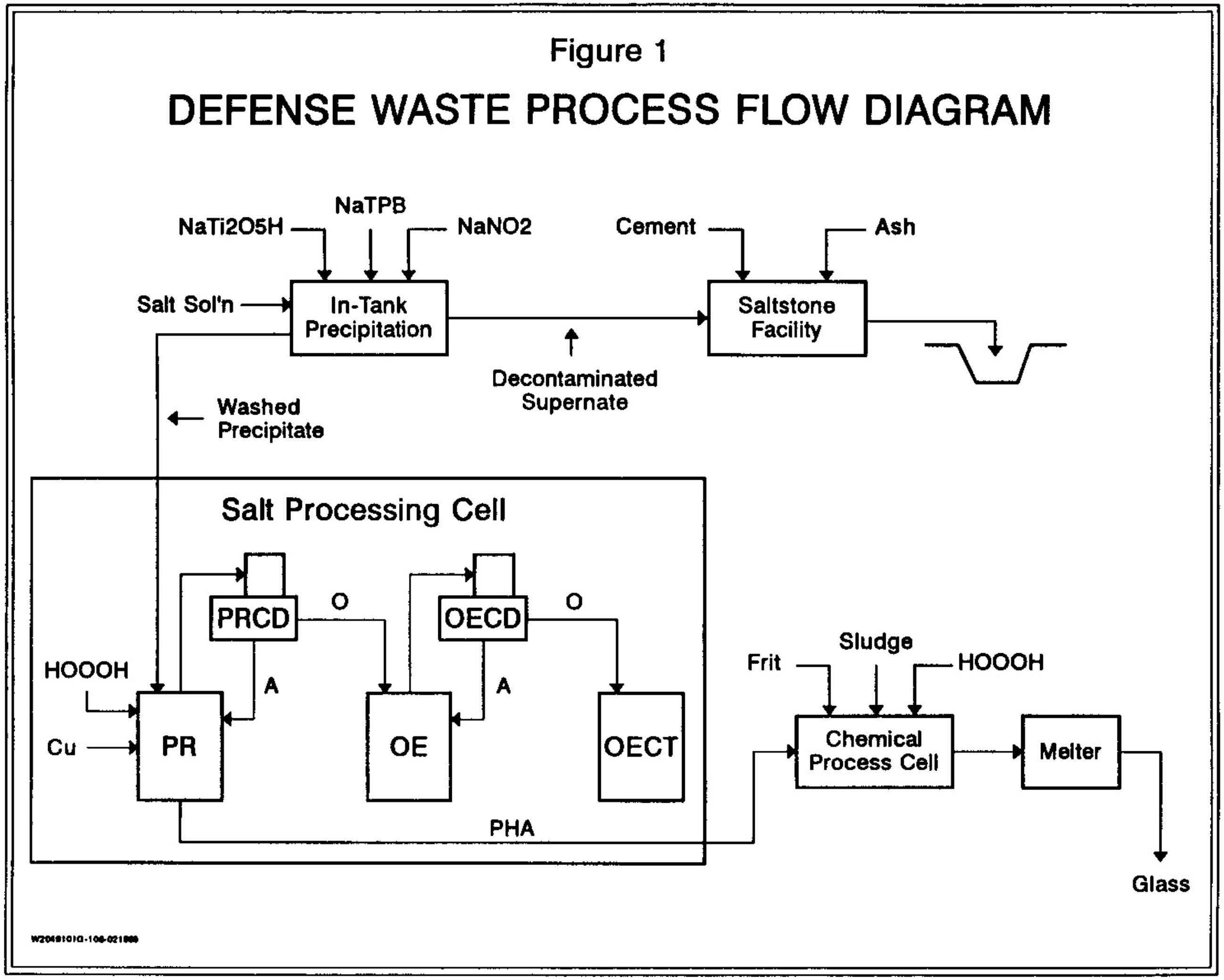


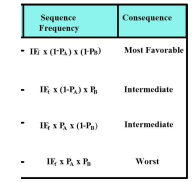
Acronyms for Salt Process Cell (SPC) study



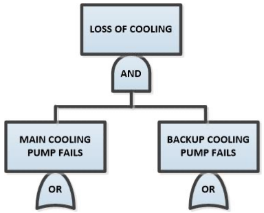
- PR Precipitate Reactor
- PRFT Precipitate Reactor Feed Tank
- PRBT Precipitate Reactor Bottoms Tank
- PVVH Process Vessel Vent Header
- OE Organic Evaporator
- OECT Organic Evaporator Condensate Tank
- SCVC Salt Cell Vent Condenser
- DCS Distributed Control System
- FAVC Formic Acid Vent Condenser
- SME Subject Matter Expert
- SRAT Sludge Receipt Adjustment Tank
- LEL Lower Explosive Limit
- WSRC – Westinghouse Savanah River Company
- HAN – Hydroxyl Amine Nitrate



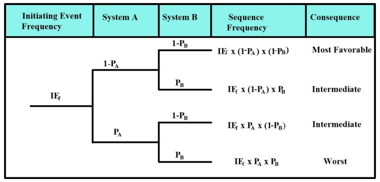


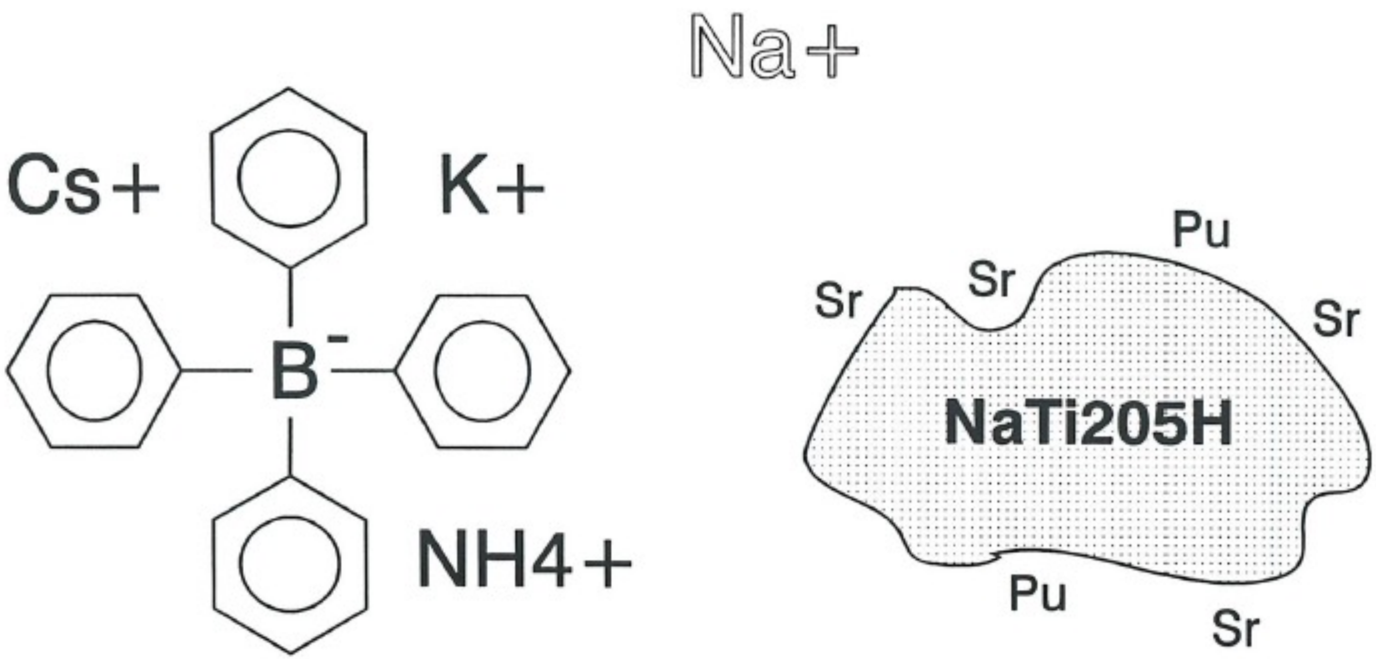


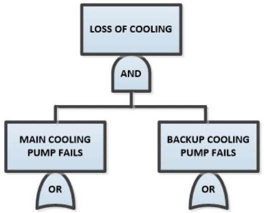
Legend:
PR Precipitate Reactor
PRCD Precipitate Reactor Condenser Decanter
OE Organic Evaporator
OECD Organic Evaporator Condenser Decanter
PRBT Precipitate Reactor Bottoms Tank
PHA Process Hazards Analysis



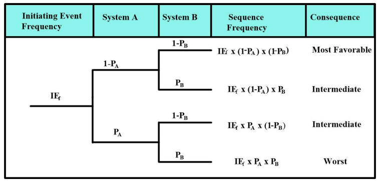
IN-Tank Precipitation





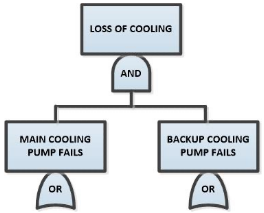


Ideal Precipitate Hydrolysis Reaction

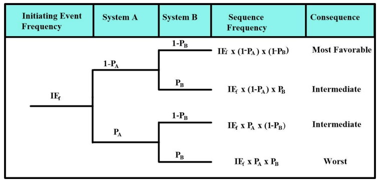


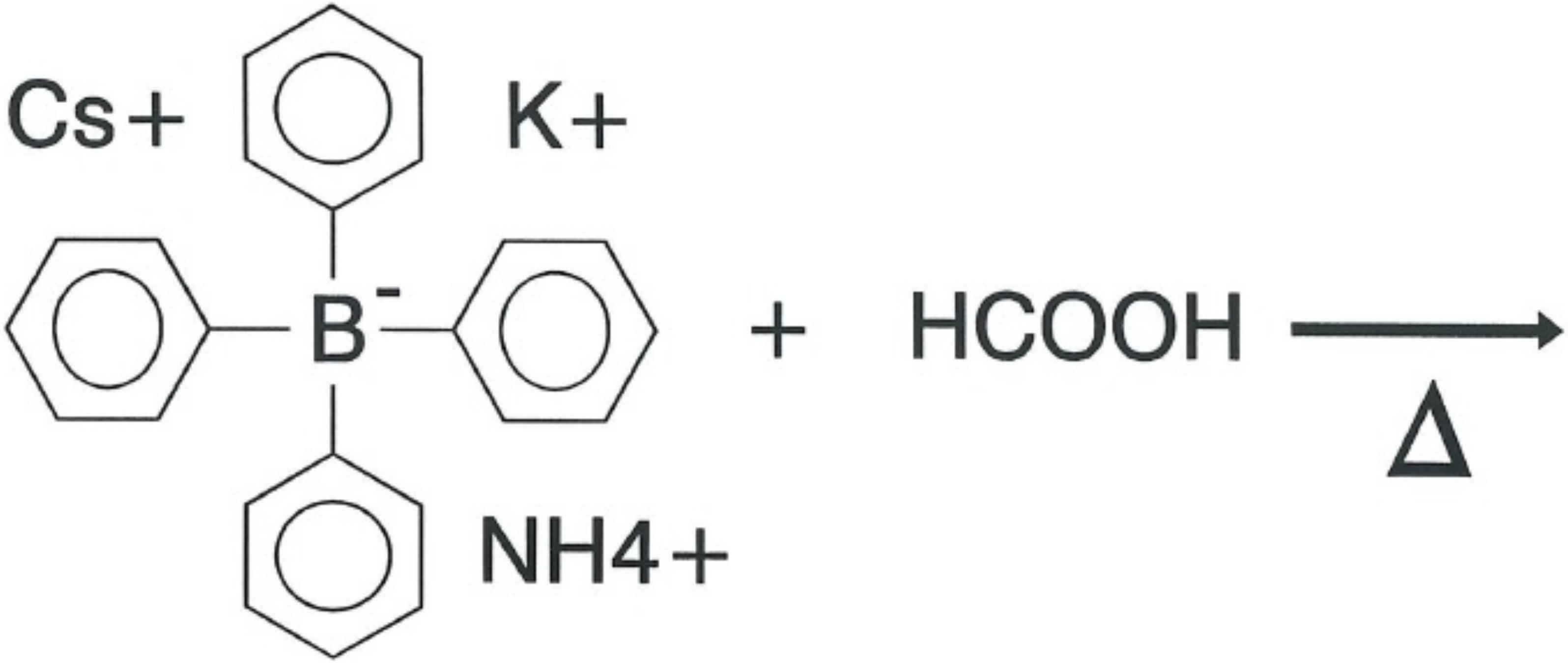
$$Cs(C_6H_5)_4 + HCOOH + 3\,H_2O \xrightarrow{Cu\,(II)} 4\,C_6H_6 + B(OH)_3 + CsOOH$$

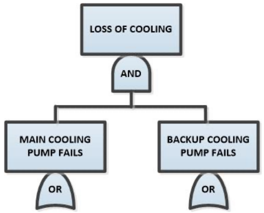
Cesium TPB • Formic Acid • Water —Copper→ Benzene • Boric Acid • Cesium Formate



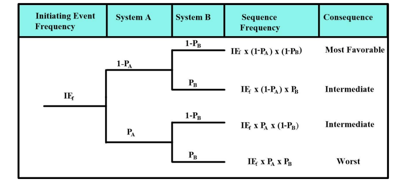
Tetraphenylborate Reaction

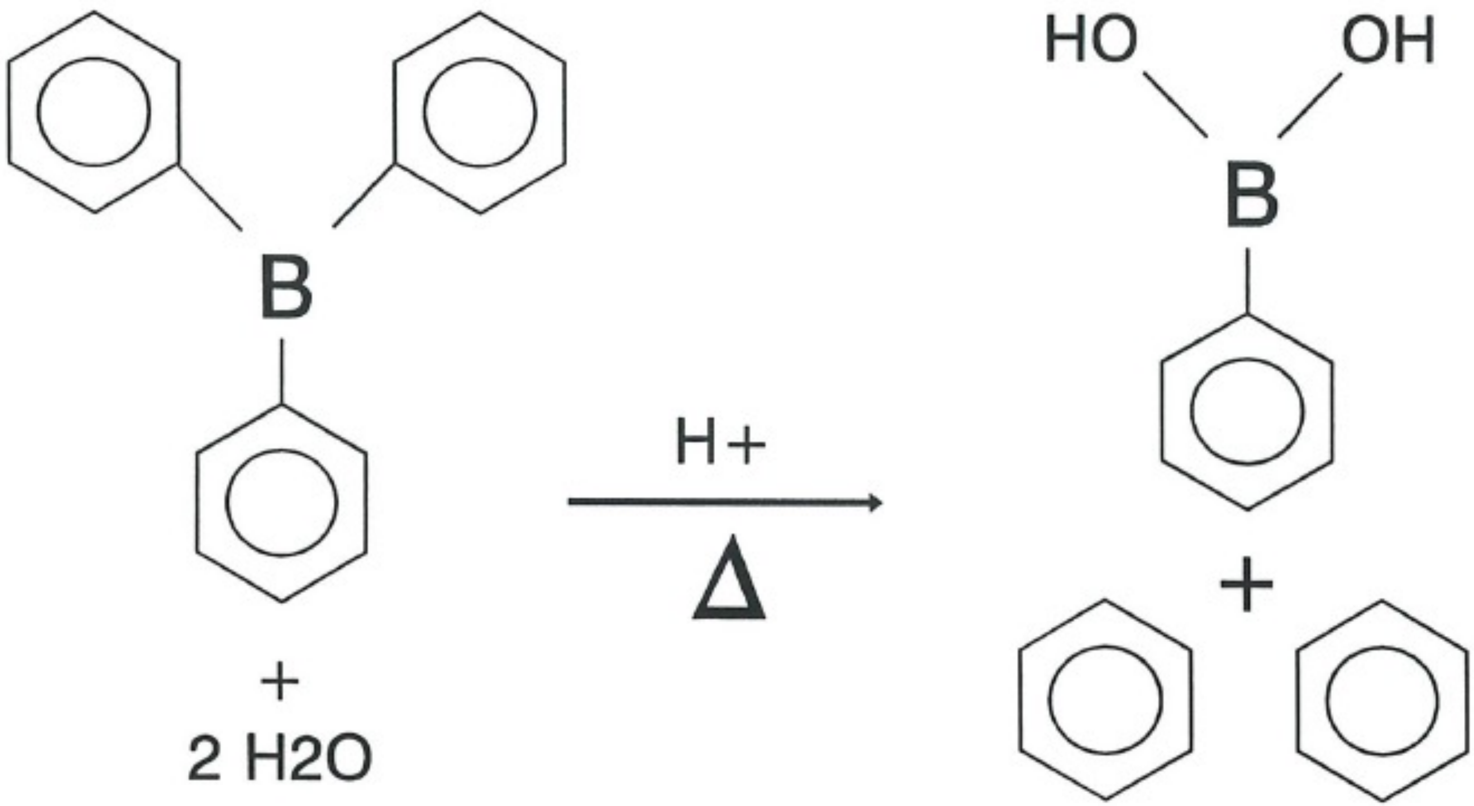


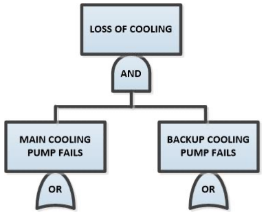




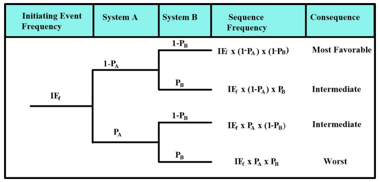
Tetraphenylborate Reaction

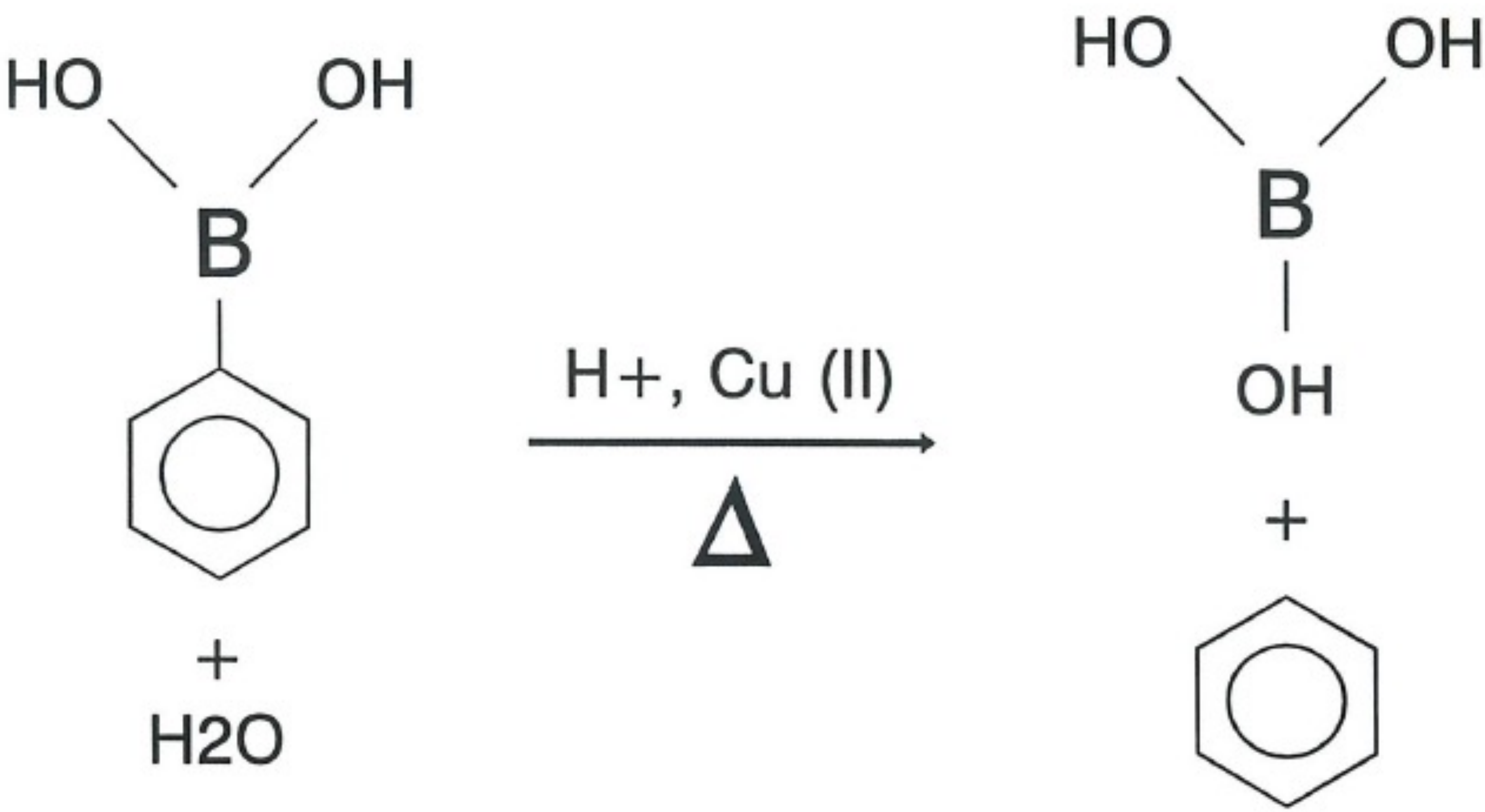






Tetraphenylborate Reaction





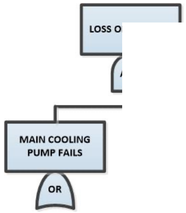
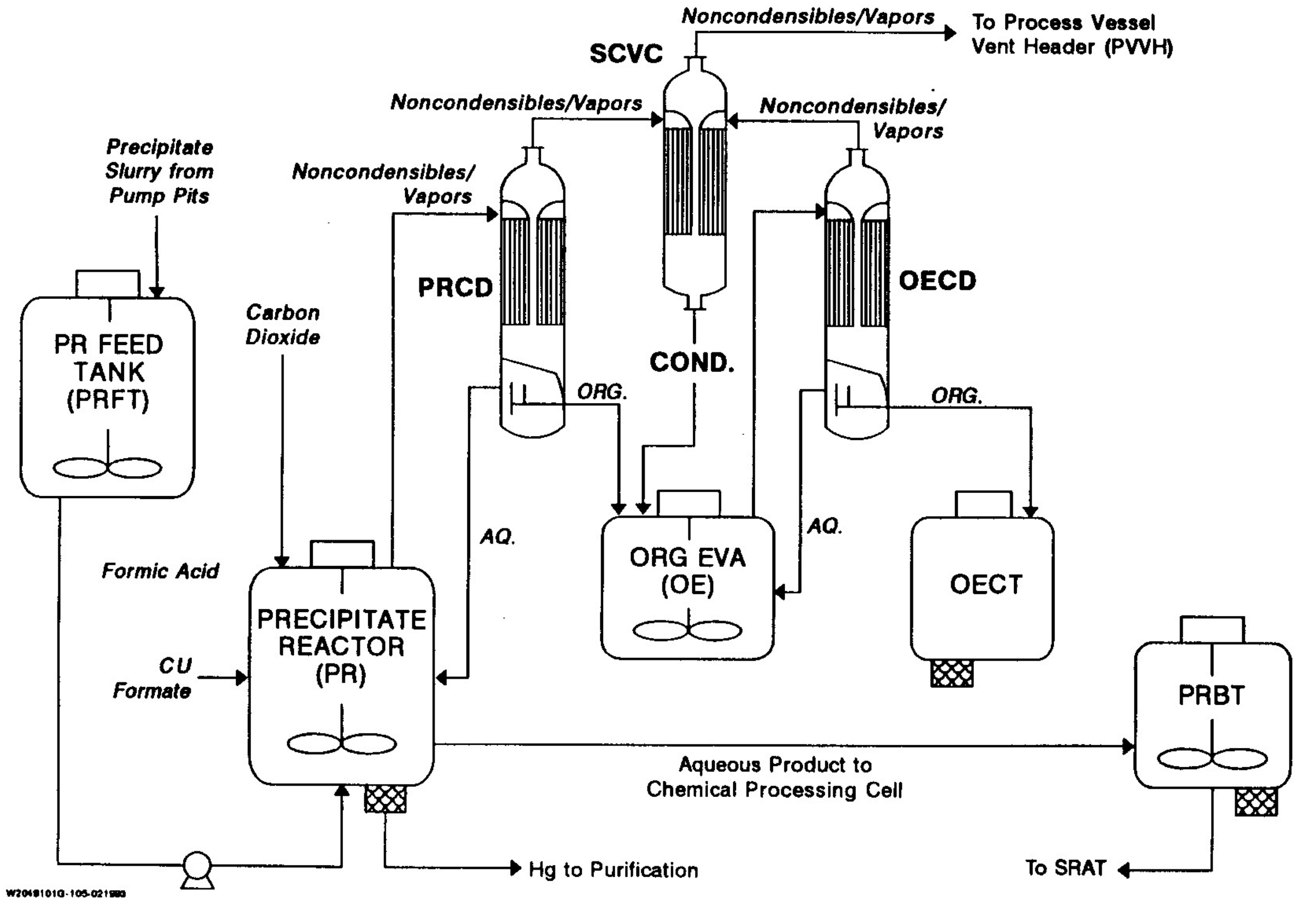
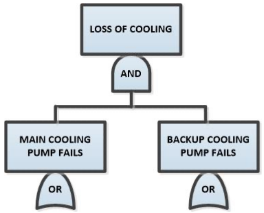


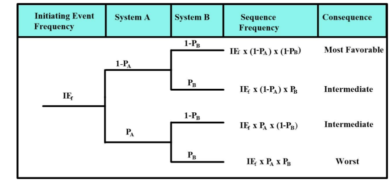
Figure 3

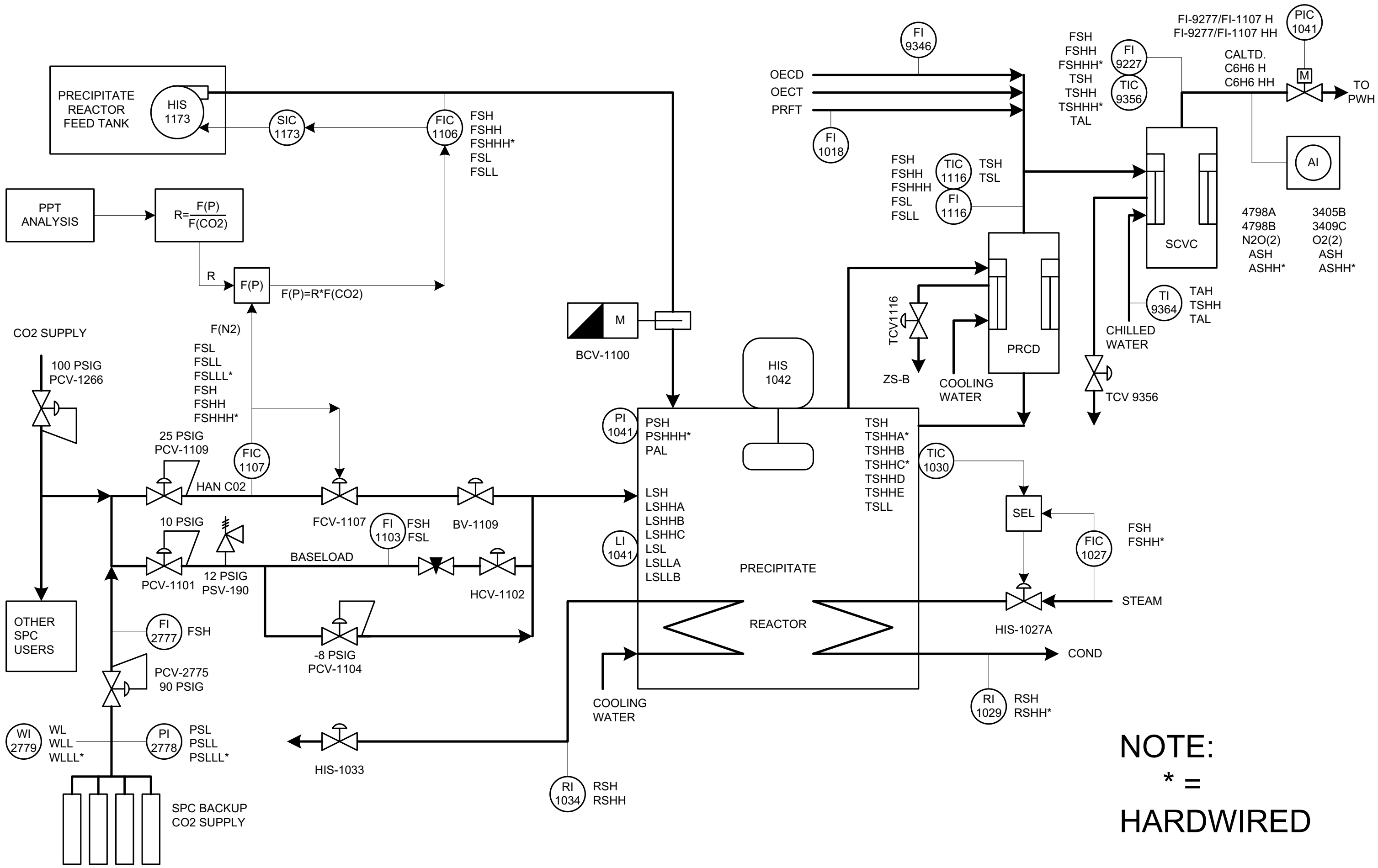
PRECIPITATE HYDROLYSIS PROCESS OVERVIEW



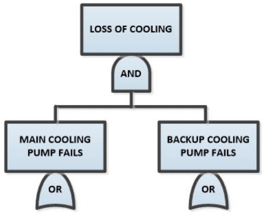


Precipitate Reactor Control System

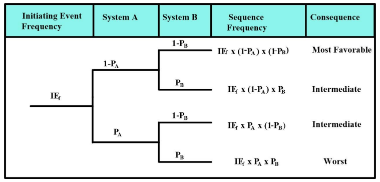


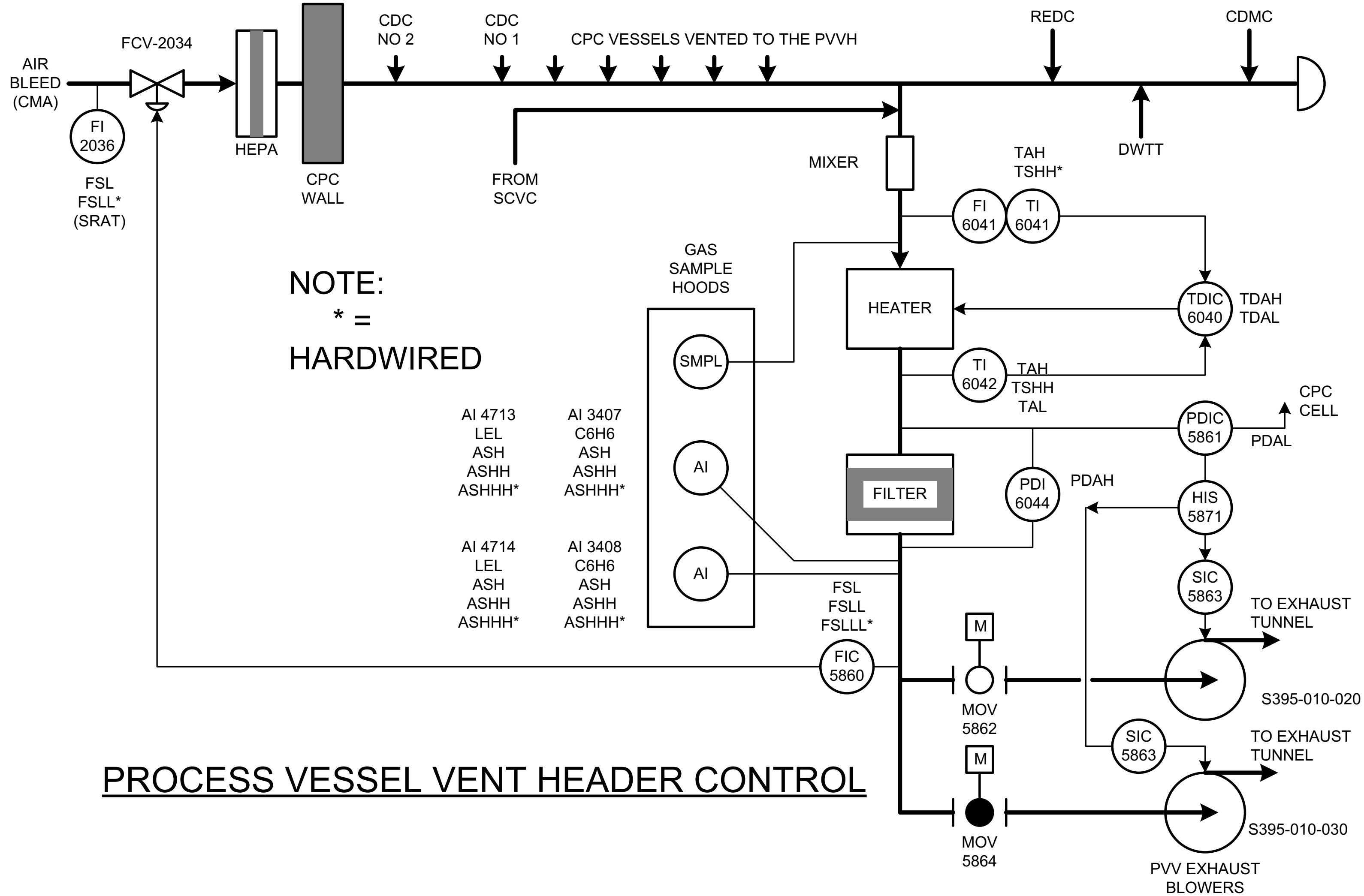


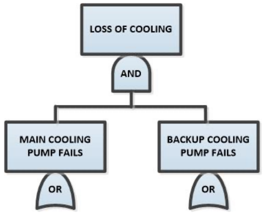
PRECIPITATE REACTOR CONTROL SYSTEM



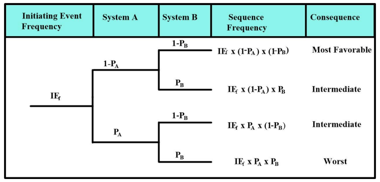
Process Vessel Vent Header Control

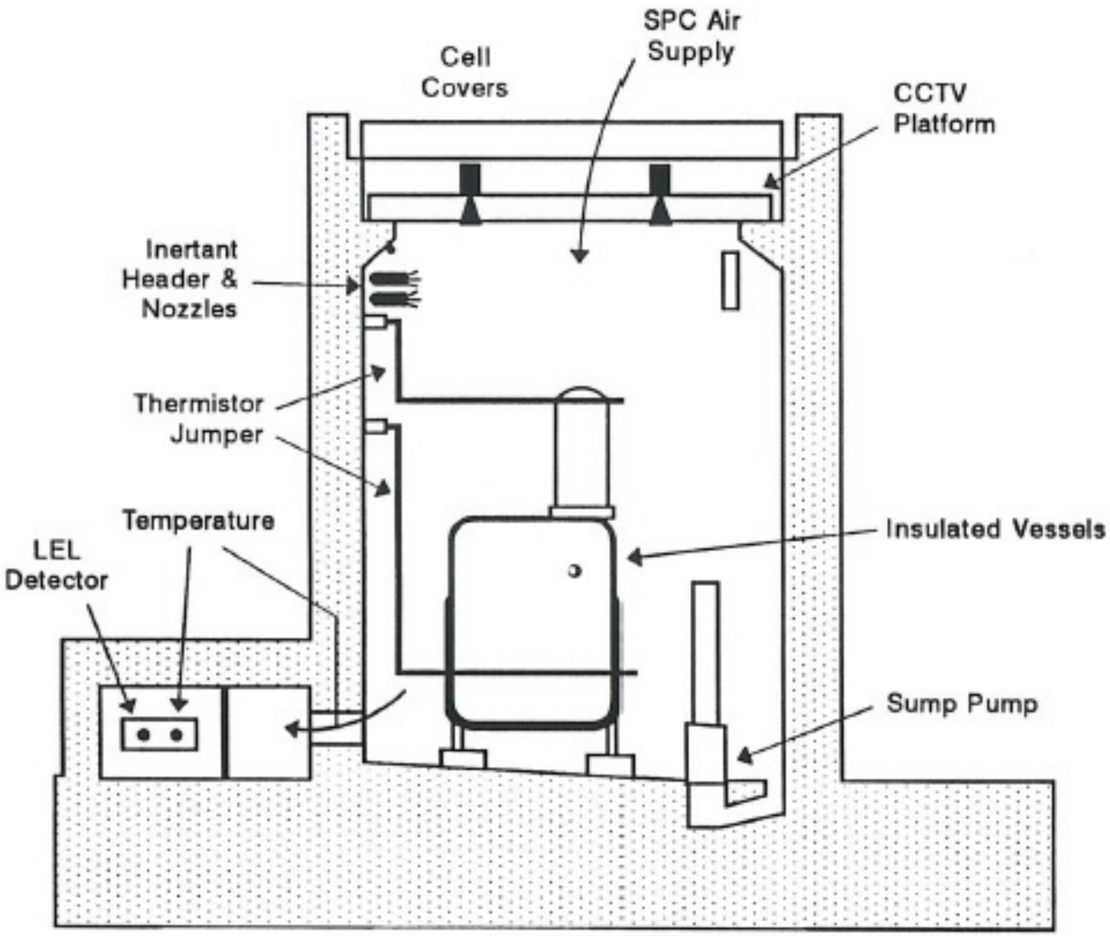




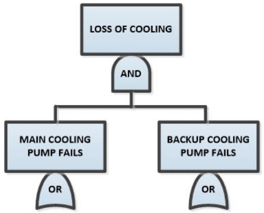


SPC FIRE SUPRESSION

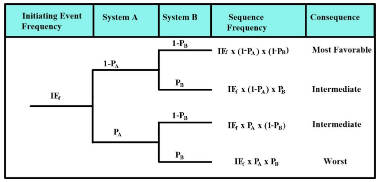




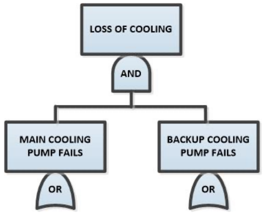
Elevation View



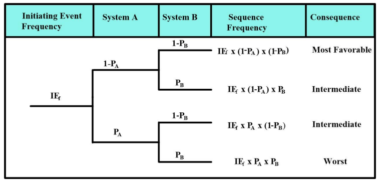
PHR IDENTIFIED THE FOLLOWING EVENTS THAT REQUIRED FTA



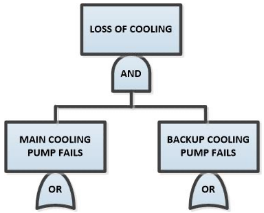
1. Benzene – Air Fire/Explosion in the Precipitate Process (PRFT, PR, OE and OECT)
2. Benzene – Air/Explosion in the Process Vessel Vent System
3. Benzene – Fire/Explosion in the Salt Process Cell or Exhaust System



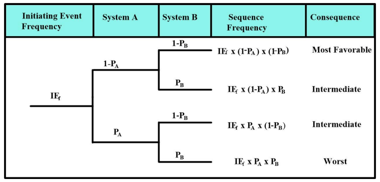
SYSTEM DESIGN/OPERATION PHILOSOPHY



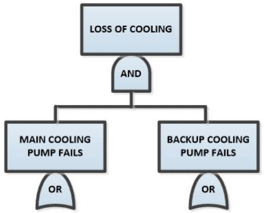
1. Prevent Air/Benzene Deflagration in Process Vessels by Ensuring that O_2 Concentration is Below 60% of the MOC
2. Prevent Air/Benzene Deflagration in PVVH by Ensuring that Benzene Concentration is Below 60% of the LEL
3. Prevent System Over pressurization and Benzene Vapor Release to the SPC
4. Prevent Leaks in Transfer Lines by Shutting Off Pumps in the Event of High Sump Level
5. Shut off Ignition Sources when Sump Level is High or Exhaust Tunnel LEL is Above Noise Level



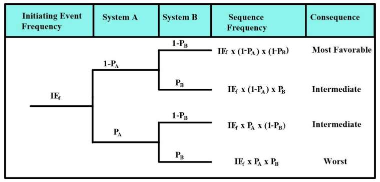
Hazard Severity

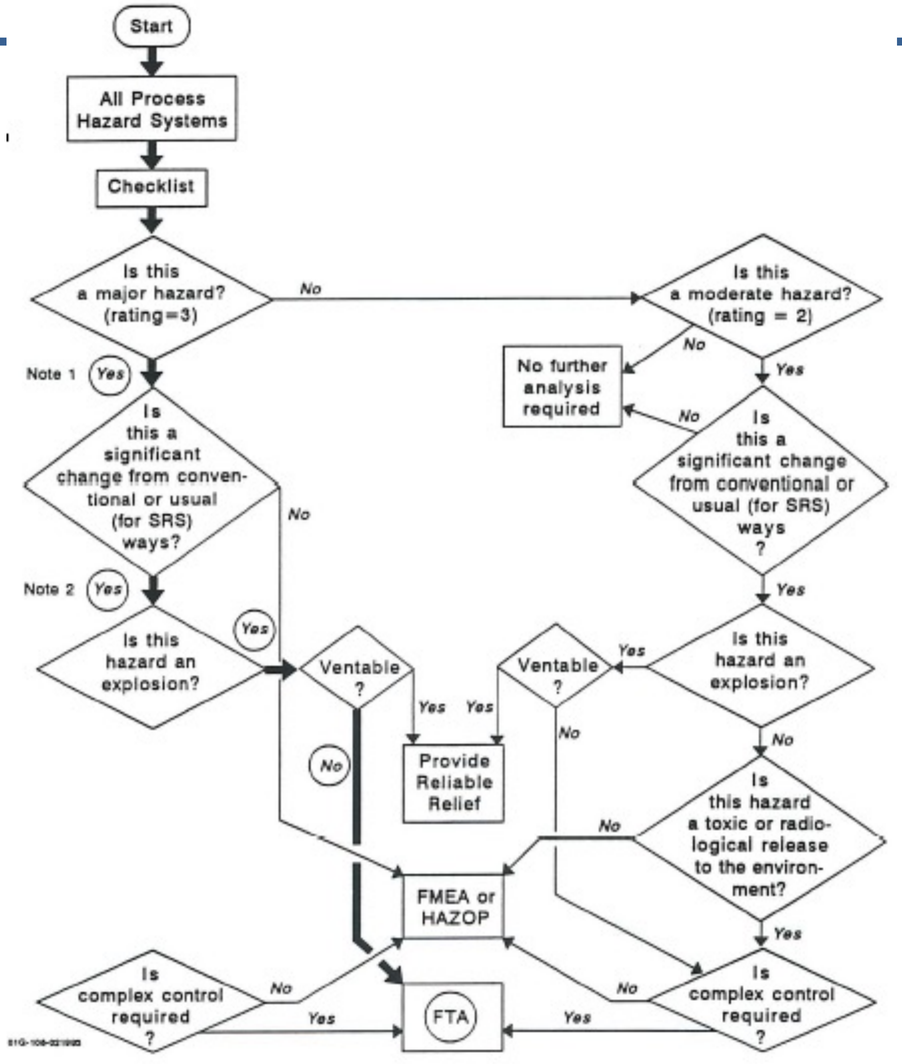


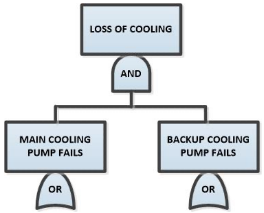
HAZARD RATING	FATALITY/INJURY	INVESTMENT ($ MILLIONS)	DURATION (DOWN TIME)
3	Multiple fatalities	> 10	> 6 months
2	Single fatality or multiple injuries	1 - 10	1-6 months
1	Serious injury	0.1 - 1	1 week-1 month
0	No injury	< 0.1	< 1 week



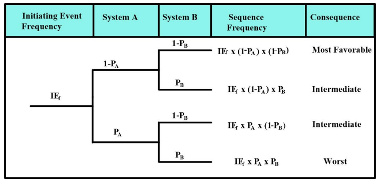
Decision Tree for Review Method Selection



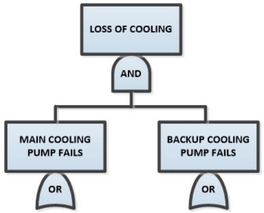




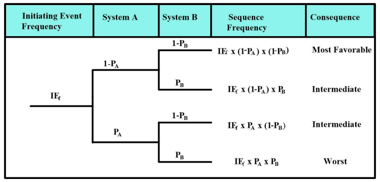
SYSTEM DESCRIPTION

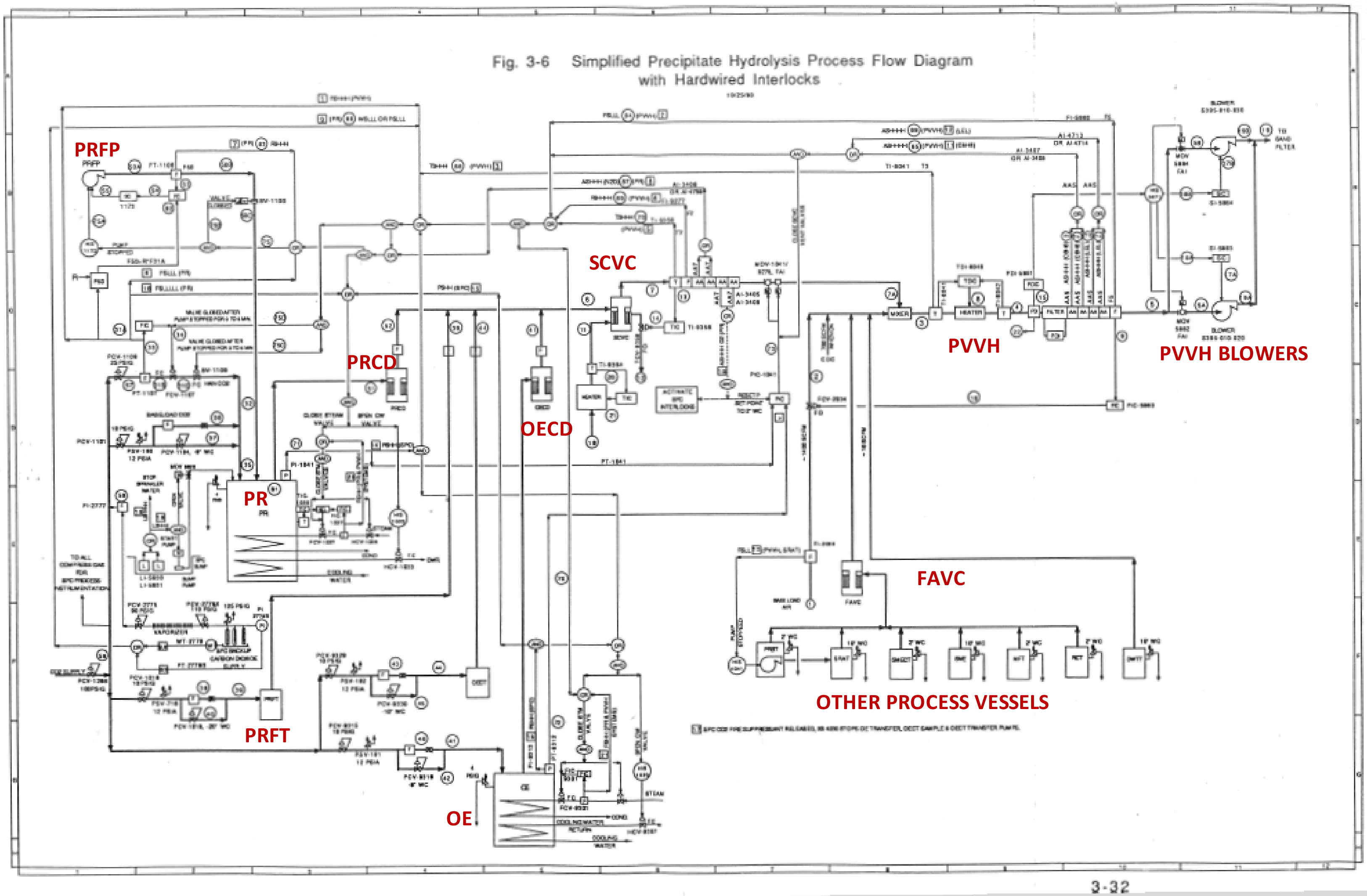


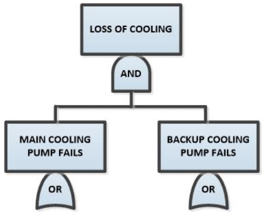
1. Generate Simplified Flow Diagram with Zone Index
2. Identify Sequence of Operations During 44 Hour Cycle Time
3. Identify Negative Feedback Loops/Control Elements
4. Interlock Strategy
5. Identify Interlocks/Control Elements



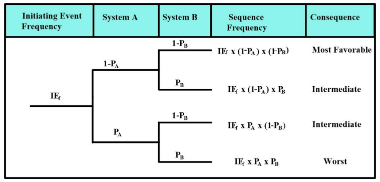
Simplified Precipitate Hydrolysis Process Flow Diagram with Hardwired Interlocks

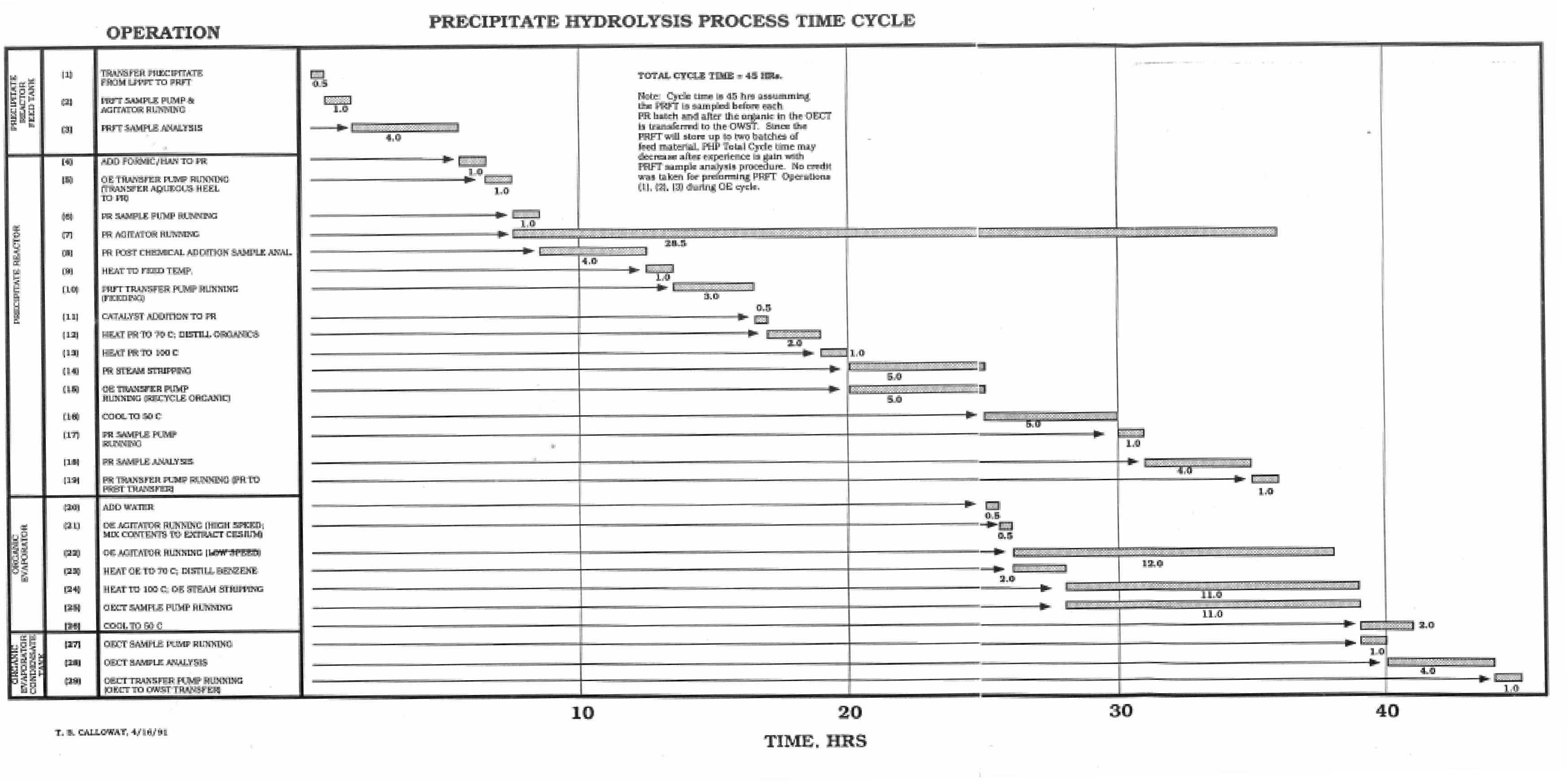


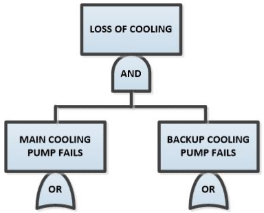




Bar Chart shows operations during batch process







Control Elements on Negative Feedback Loops

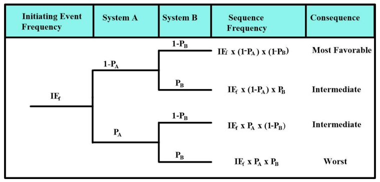
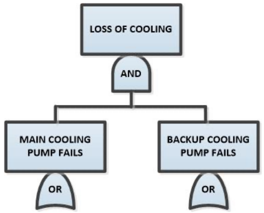


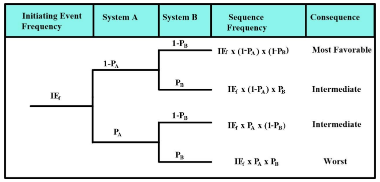
TABLE A-2

CONTROL ELEMENTS ON NEGATIVE FEEDBACK LOOPS

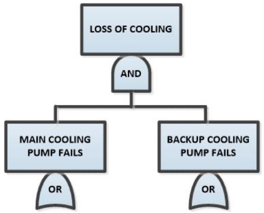
NFBL DESCRIPTION	SENSOR [LOCATION]	CONTROLLER [LOCATION]	OTHER CONTROL ELEMENTS [LOCATION]
CONTROL PUMP SPEED DURING FEEDING	FI-1106 [B-2]	FC-1106 [B-2]	SPEED CONTROLLER 1173 [B-1] FEED PUMP [B-1]
CONTROL HIGH FLOW CO_2 DURING FEEDING	FT-1107 [D-2]	FC-1107 [C-2]	FCV-1107 [D-2]
CONTROL STEAM FLOW TO PR DURING FEEDING/ BOILUP/ STEAM STRIPPING	FI-1027 [E-3]	FIC-1027 [E-3]	PR FLOW CONTROL VALVE 1027 [E-3] I/P TRANSFUCER FY 1027 [E-3]
CONTROL STEAM FLOW TO OE DURING DISTILLATION/ STEAM STRIPPING	FI-9301 [G-5]	FIC-9301 [G-5]	OE FLOW CONTROL VALVE 9301 [G-5] I/P TRANSDUCER 9301
CONTROL FLOW OF DILUTION AIR IN PVVH	FT-5860 [C-10]	FIC-5860 [D-10]	FLOW CONTROL VALVE 2034 [D-7]
CONTROL SCVC EXHAUST TEMPERATURE	TI-9356 [C-6]	TIC-9356 [C-6]	FLOW CONTROL VALVE 9356 [C-6]



INTERLOCK STRATEGY



- 3 LEVELS OF PROTECTION
  - HARD-WIRED INTERLOCKS – SAFETY
  - SOFTWARE INTERLOCKS – Control Logic Diagrams
  - PROCESS OPERATING PROCEDURES (POP’s)



HARDWIRED INTERLOCKS

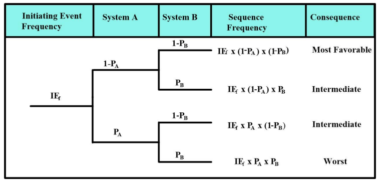
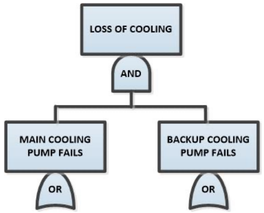


TABLE A-3

CONTROL ELEMENTS COMPRISING HARDWIRED INTERLOCKS THAT PREVENT BENZENE-N_20 FIRE/EXPLOSION IN PR

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
PR HI-FLOW $C0_2$ PURGE FLOW LLL (6, PR)	FI-1107* [D-2]	FSLL1107B	HR5	PRFT TRANSFER PUMP (HIS-1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2]
PRFT-PR PPT FEED FLOW HHH (7, PR)	FI-1106* [B-2]	FSHH1106B	HR2	SAME AS INTERLOCK 6 ABOVE
SCVC EXHAUST N_20 CONC HHH (8, PR)	AI-3406 [C-6] AI-4798 [C-6}	ASHH3406B ASHH4798B	CR3D CR6D	PRFT TRANSFER PUMP (HIS-1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2] PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4]
SPC BACKUP $C0_2$ WEIGHT LLL (9A, PR)	WI-2779 [F-2]	WSLL2779B	HR7	PRFT TRANSFER PUMP (HIS-1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2] PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4] PR HI-FLOW CO_2 VALVE (FCV-1107) CLOSED (5 MIN DELAY) [D-2] PR HI-FLOW BLOCK VALVE (HCV-1109) CLOSED (5 MIN DELAY) [D-2]



HARDWIRED INTERLOCKS

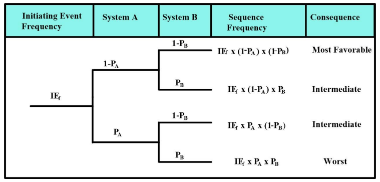
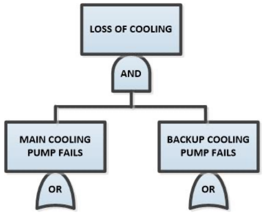


TABLE A-3 (Continued)

CONTROL ELEMENTS COMPRISING HARDWIRED INTERLOCKS THAT PREVENT BENZENE-N20 FIRE/EXPLOSION IN PR

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
SPC BACKUP CO_2 PRESSURE LLL (9B, PR)	PI-2779 [F-3]	PSLL2779B	HR7	SAME AS INTERLOCK 9A ABOVE
PR HI-FLOW CO_2 FLOW LLLLL (16, PR)	FI-1107* [D-2]	FSLL1107D	HR8	PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4]
SCVC EXHAUST FLOW HHHH (4, PVVH, PR)	FI-9277 [C-6]	FSHH9277C	HR9	PRFT TRANSFER PUMP (HIS-1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2] PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4] PR HI-FLOW CO_2 VALVE (FCV-1107) CLOSED (5 MIN DELAY) [D-2] PR HI-FLOW CO_2 BLOCK VALVE (HCV-1109) CLOSED (5 MIN DELAY) [D-2] OE STEAM FLOW VALVE (FCV-9301) CLOSED [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED [G-6]

*COMPONENT ON NFBL, FAIL HIGH OR LOW FAILURE MODE IS COMMON CAUSE INITIATING EVENT



HARDWIRED INTERLOCKS

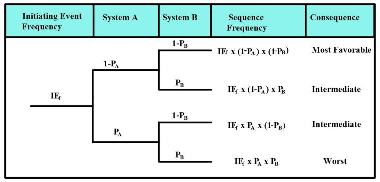


TABLE A-4

CONTROL ELEMENTS COMPRISING HARDWIRED AND DCS DEPENDENT INTERLOCKS FOR PREVENTION OF BENZENE-AIR FIRE/EXPLOSION IN PRECIPITATE PROCESS SYSTEM

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
SCVC OXYGEN CONCENTRATION HHH (10, ALL PROCESS VESSELS, ALL THE TIME)	AI-3405 AI-3409	ASHH3405B ASHH3409C	CR3C CR6C	RAISE SPC VESSEL SYSTEM PRESSURE TO POSITIVE (PC-1401 & 9278) ** [D-3], [G-4] AGITATORS STOPPED: PR (HIS-1140), PR (-1042), OE (-9317) *** [E-3], [G-5] CATALYST FEED TANK TRANSFER PUMP (HIS-1008) STOPPED *** FORMIC ACID FEED TANK TO PR BLOCK VALVE (HIS-2056) CLOSED *** HAN FEED TANK TO PR BLEED VALVE (HCV-8829) OPENED *** HAN FEED TANK TO PR DOWN STREAM TRANSFER VALVE (HCV-8830) CLOSED *** HAN FEED TANK TO PR UP STREAM TRANSFER VALVE (HCV-8828) CLOSED *** LPPT TRANSFER PUMP (HIS-7162A) STOPPED *** OE COOLING WATER VALVE (HCV-9301) OPENED *** [H-6] OE TRANSFER PUMP (HIS-9316) STOPPED *** [G-5] OECT SAMPLE PUMP (HIS-9333) STOPPED *** OECT TRANSFER PUMP (HIS-9337) STOPPED ***

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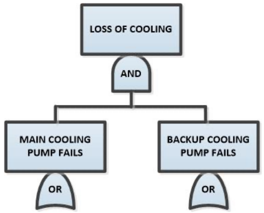


HARDWIRED INTERLOCKS

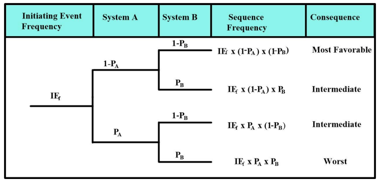
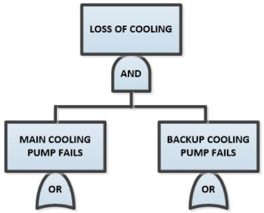


TABLE A-4 (Continued)

CONTROL ELEMENTS COMPRISING HARDWIRED AND DCS DEPENDENT INTERLOCKS FOR PREVENTION OF BENZENE-AIR FIRE/EXPLOSION IN PRECIPITATE PROCESS SYSTEM

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
SCVC OXYGEN CONCENTRATION HHH (10, ALL PROCESS VESSELS, ALL THE TIME) (Continued)	AI-3405 AI-3409	ASHH3405B ASHH3409C	CR3C CR6C	PR SAMPLE PUMP (HIS-1044) STOPPED *** PR TRANSFER PUMP (HIS-1057) STOPPED *** PRFT TRANSFER PUMP (HIS-1173) STOPPED *** [B-1] PRFT SAMPLE PUMP (HIS-1172) STOPPED *** PRFT-PR BLOCK VALVE (MOV-1100) CLOSED *** [B-3] PR STEAM FLOW VALVE (FCV-1027) CLOSED *** [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED *** [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN *** [E-4] PR HI-FLOW CO_2 VALVE (FCV-1107) CLOSED *** (5 MIN DELAY) [D-2] PR HI-FLOW CO_2 BLOCK VALVE (HCV-1109) CLOSED *** (5 MIN DELAY) [D-2] OE STEAM FLOW VALVE (FCV-9301) CLOSED *** [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED *** [G-5]

** HARDWIRED INTERLOCK
*** DCS INTERLOCK



HARDWIRED INTERLOCKS

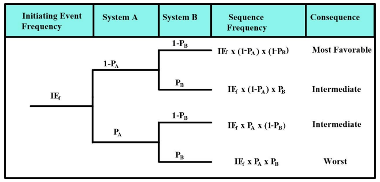
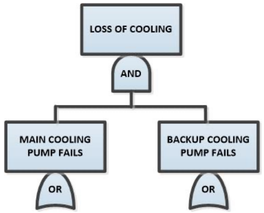


TABLE A-5

CONTROL ELEMENTS COMPRISING HARDWIRED INTERLOCKS FOR PREVENTION OF BENZENE-AIR FIRE/EXPLOSION IN PVVH SYSTEM

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
PR HI-FLOW CO_2 PURGE FLOW HHH (1, PVVH)	FI-1107 * [D-3]	FSHH1107B	HR4	PRFT TRANSFER PUMP (HIS- 1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2] PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4] PR HI-FLOW CO_2 VALVE (FCV-1107) CLOSED (5 MIN DELAY) [D-2] PR HI-FLOW CO_2 BLOCK VALVE (HCV-1109) CLOSED (5 MIN DELAY) [D-2] OE STEAM FLOW VALVE (FCV-9301) CLOSED [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED [G-6]
PVVH FLOW LLL (2, PVVH)	FI-5860 * [C-10]	FSLL5860B	HR3	SAME AS INTERLOCK 1 ABOVE
PVVH TEMPERATURE HHH (3, PVVH)	TI-6041 [C-9]	TSHH6041B	HR1	SAME AS INTERLOCK 1 ABOVE
SCVC EXHAUST FLOW HHHH (4, PVVH)	FI-9277 [C-6]	FSHH9277C	HR9	SAME AS INTERLOCK 1 ABOVE
SCVC EXHAUST TEMPERATURE HHHH (5, PVVH)	TI-9356 * [C-6]	TSHH9356C	HR6	SAME AS INTERLOCK 1 ABOVE

64



HARDWIRED INTERLOCKS

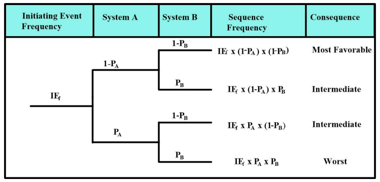
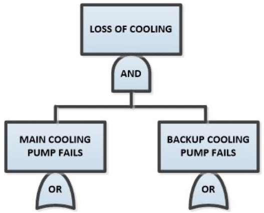


TABLE A-5 (Continued)

CONTROL ELEMENTS COMPRISING HARDWIRED INTERLOCKS FOR PREVENTION OF BENZENE-AIR FIRE/EXPLOSION IN PVVH SYSTEM

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
PVVH C6H6 CONCENTRATION HHHH (11, PVVH)	AI-3407 [C-10] AI-3408 [C-10]	ASHH3407C ASHH3408C	CR3A CR6A	PRFT TRANSFER PUMP (HIS- 1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2] PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4] PR HI-FLOW CO_2 VALVE (FCV-1107) CLOSED (5 MIN DELAY) [D-2] PR HI-FLOW CO_2 BLOCK VALVE (HCV-1109) CLOSED (5 MIN DELAY) [D-2] OE STEAM FLOW VALVE (FCV-9301) CLOSED [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED [G-6] SCVC MOV'S 1041 & 9278 CLOSED [C-7]
PVVH LEL HHHH (12, PVVH)	AI-4713 [C-10] AI-4714 [C-10]	ASHH4713C ASHH4714C	CR3B CR6B	SAME AS INTERLOCK 11 ABOVE

* COMPONENT ON NFBL, FAIL HIGH OR LOW FAILURE MODE IS COMMON CAUSE INITIATING EVENT



HARDWIRED INTERLOCKS

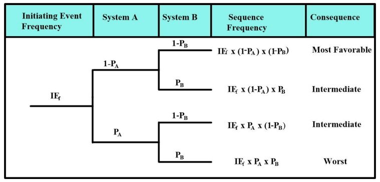
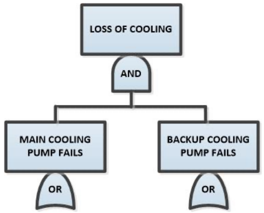


TABLE A-6

CONTROL ELEMENTS COMPRISING HARDWIRED INTERLOCKS FOR PREVENTION OF ORGANICS FIRE IN SPC

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
PR PRESSURE HH (14, SPC)	PI-1041 [D-3]	PSHH1041	PSHHX1041	PRFT TRANSFER PUMP (HIS-1173) STOPPED [B-1] PRFT-PR BLOCK VALVE (MOV-1100) CLOSED [B-2] PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-4] PR HI-FLOW CO_2 VALVE (FCV-1107) CLOSED (5 MIN DELAY) [D-2] PR HI-FLOW CO_2 BLOCK VALVE (HCV-1109) CLOSED (5 MIN DELAY) [D-2] OE STEAM FLOW VALVE (FCV-9301) CLOSED [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED [G-6] OE COOLING WATER VALVE (HCV-9307) OPENED [G-6]
OE PRESSURE HH (15, SPC)	PI-9313 [G-5]	PSHH9313	PSHHX9313	PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3] PR COOLING WATER VALVE (HCV-1033) OPEN [E-3] OE STEAM FLOW VALVE (FCV-9301) CLOSED [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED [G-6] OE COOLING WATER VALVE (HCV-9307) OPENED [G-6]



HARDWIRED INTERLOCKS

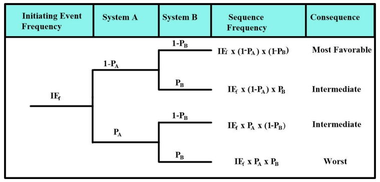
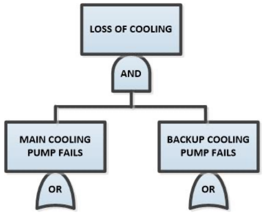


TABLE A-6 (Continued)

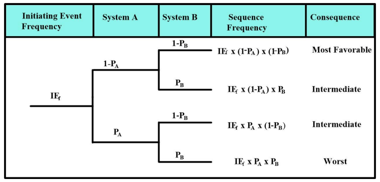
CONTROL ELEMENTS COMPRISING HARDWIRED INTERLOCKS FOR PREVENTION OF ORGANICS FIRE IN SPC

INTERLOCK TRIP CONDITION (INTERLOCK NUMBER, VESSEL OR SPC PROTECTION)	SENSOR/ ANALYZER [LOCATION]	SWITCH	RELAY	CONTROL ACTION [LOCATION]
SPC CO_2 FIRE SUPPRESSANT RELEASED (17, SPC)	XS-4030	X54030	X54030	OE TRANSFER PUMP (HIS-9316) STOPPED OECT TRANSFER PUMP (HIS-9337) STOPPED OECT SAMPLE PUMP (HIS-9333) STOPPED
SUMP PUMP LEVEL HHH (18, SPC)	LI-5925 [E-2] LI-5927 [E-2]	LSHH5925B LSHH5927B	LSHHX5925B LSHHX5927B	SPC SUMP PUMP (HIS-5925B) STARTED SUMP PUMP DISCHARGE VALVE (MOV-5928) OPENED [D-2]
SUMP PUMP LEVEL HHHH (19, SPC)	LI-5930 [E-2] LI-5931 [E-2]	LSH5930 LSH5931	LSHX5930 LSHX5931	SPC SPRAY WATER VALVE (SV-7276) CLOSED
PR STEAM FLOW HH (20, PR & PVV SYSTEMS)	FSH-1027 * [E-3]	FSHH1027	FSHHX1027	PR STEAM FLOW VALVE (FCV-1027) CLOSED [E-3] PR STEAM BLOCK VALVE (HCV-1038) CLOSED [E-3]
OE STEAM FLOW HH (21, PR & PVV SYSTEMS)	FSH-9301 * [G-5]	FSH9301	FSHX9301	OE STEAM FLOW VALVE (FCV09301 CLOSED [G-5] OE STEAM BLOCK VALVE (HCV-XXXX) CLOSED [G-6]

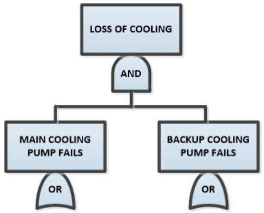
* COMPONENT ON NFBL, FAIL HIGH OR LOW FAILURE MODE IS COMMON CAUSE INITIATING EVENT



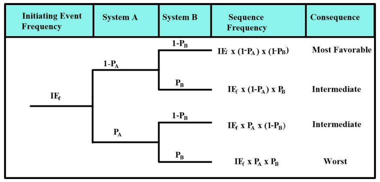
STEP 3 – FAULT TREE CONSTRUCTION

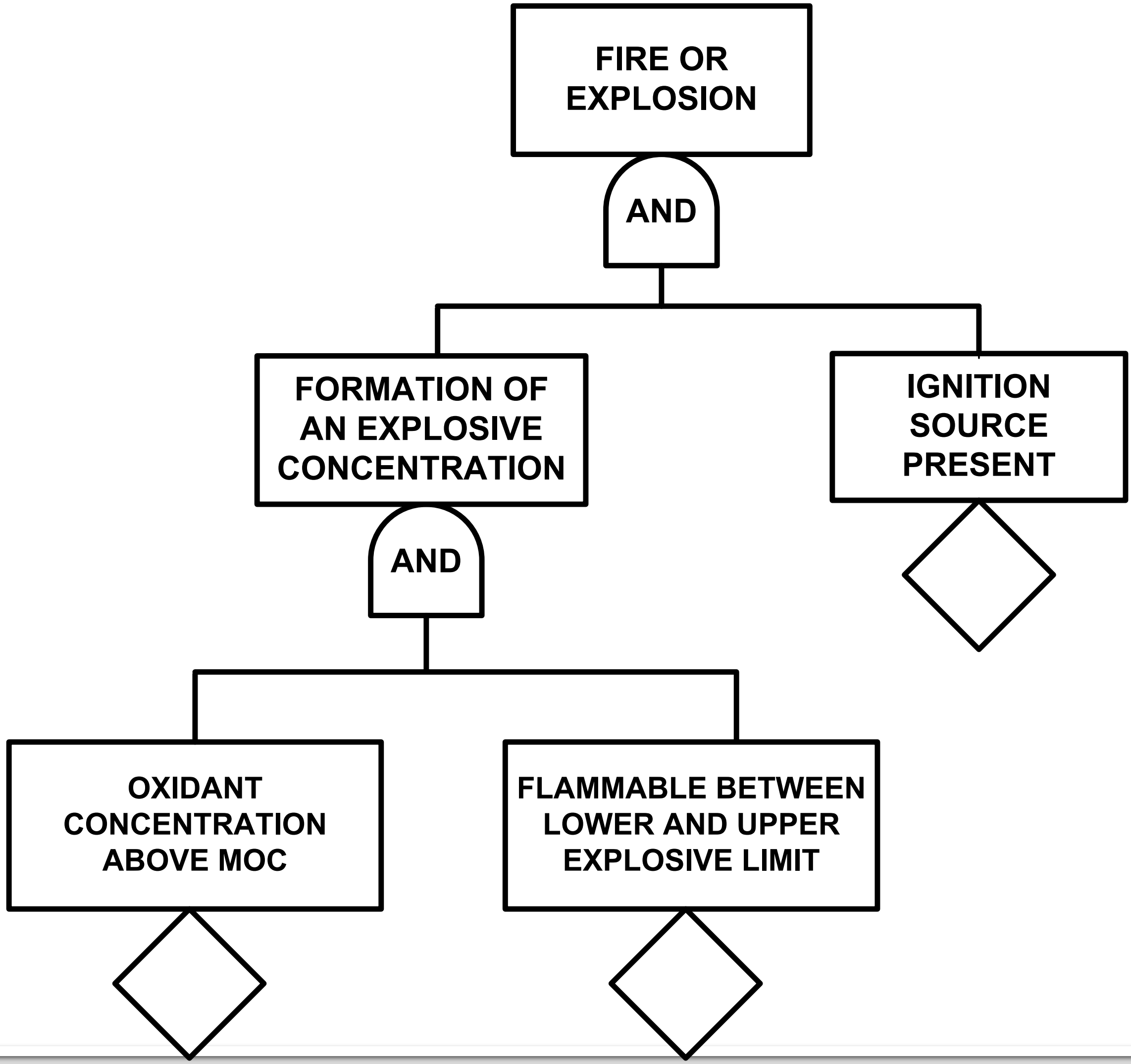


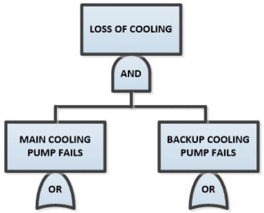
- Top Level Fault Tree
- Control System Failure Modes Dependent on Top Events
- Generation of AND Gates
  1. Conditions for Fire/Explosion
  2. Redundancy
  3. Mitigation by Interlocks
  4. Common Cause Initiating Events (also called special initiators)



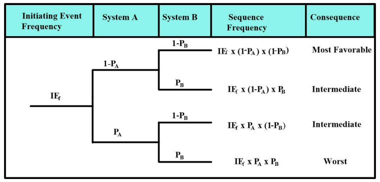
Generic Fault Tree for Fire and Explosion



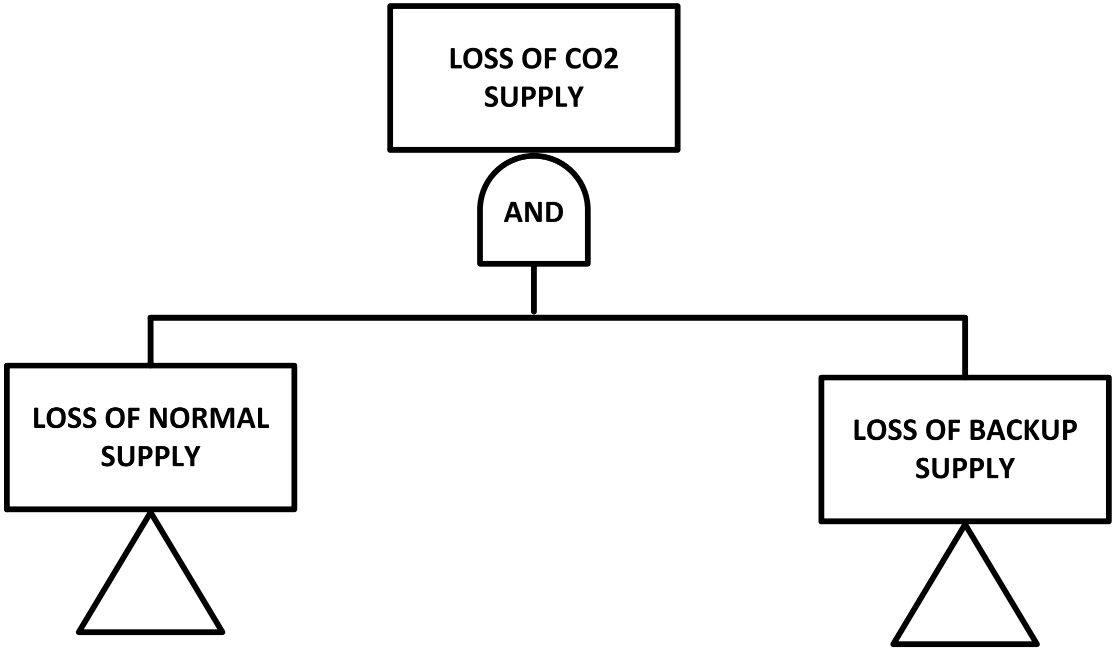


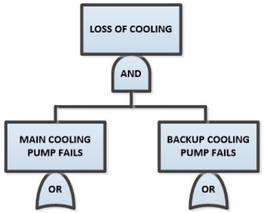


EXAMPLE OF STANDBY REDUNDANCY

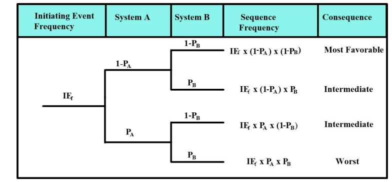


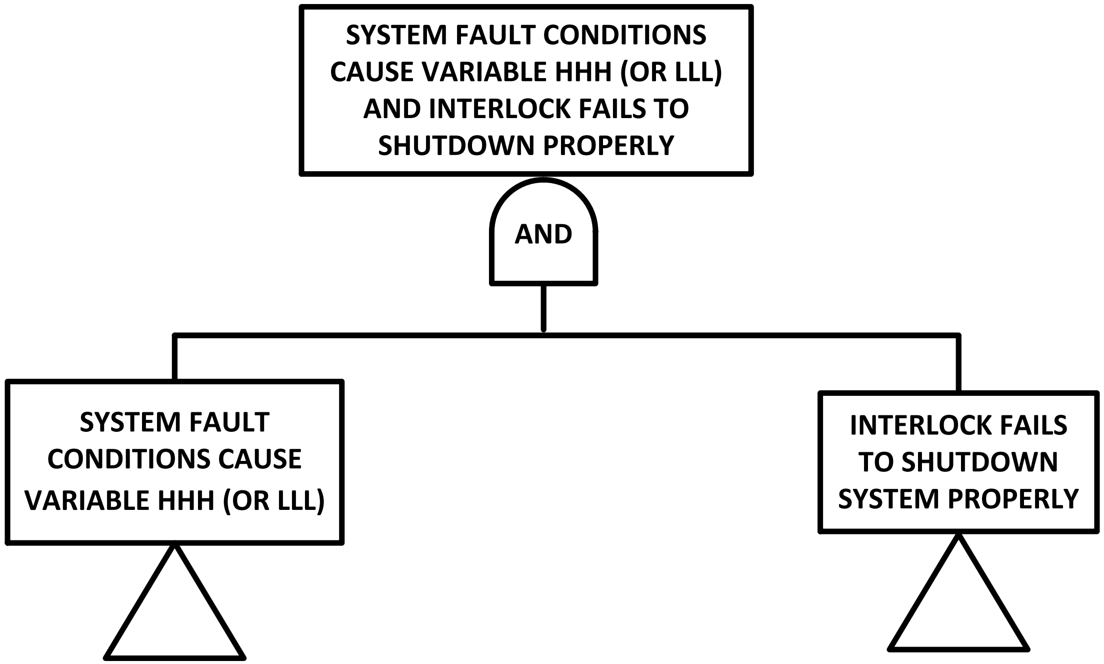
PREVENTS OCCURRENCE OF THE INITIATING EVENT





FAULT TREE LOGIC FOR INCLUSION OF INTERLOCKS

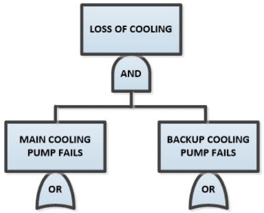




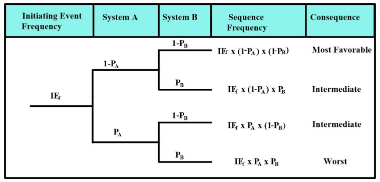
BASIC EVENTS WHICH CAUSE SYSTEM UPSET CONDITIONS ARE CALLED INITIATING EVENTS

BASIC EVENTS WHICH CAUSE INTERLOCK FAILURE ARE CALLED ENABLING EVENTS

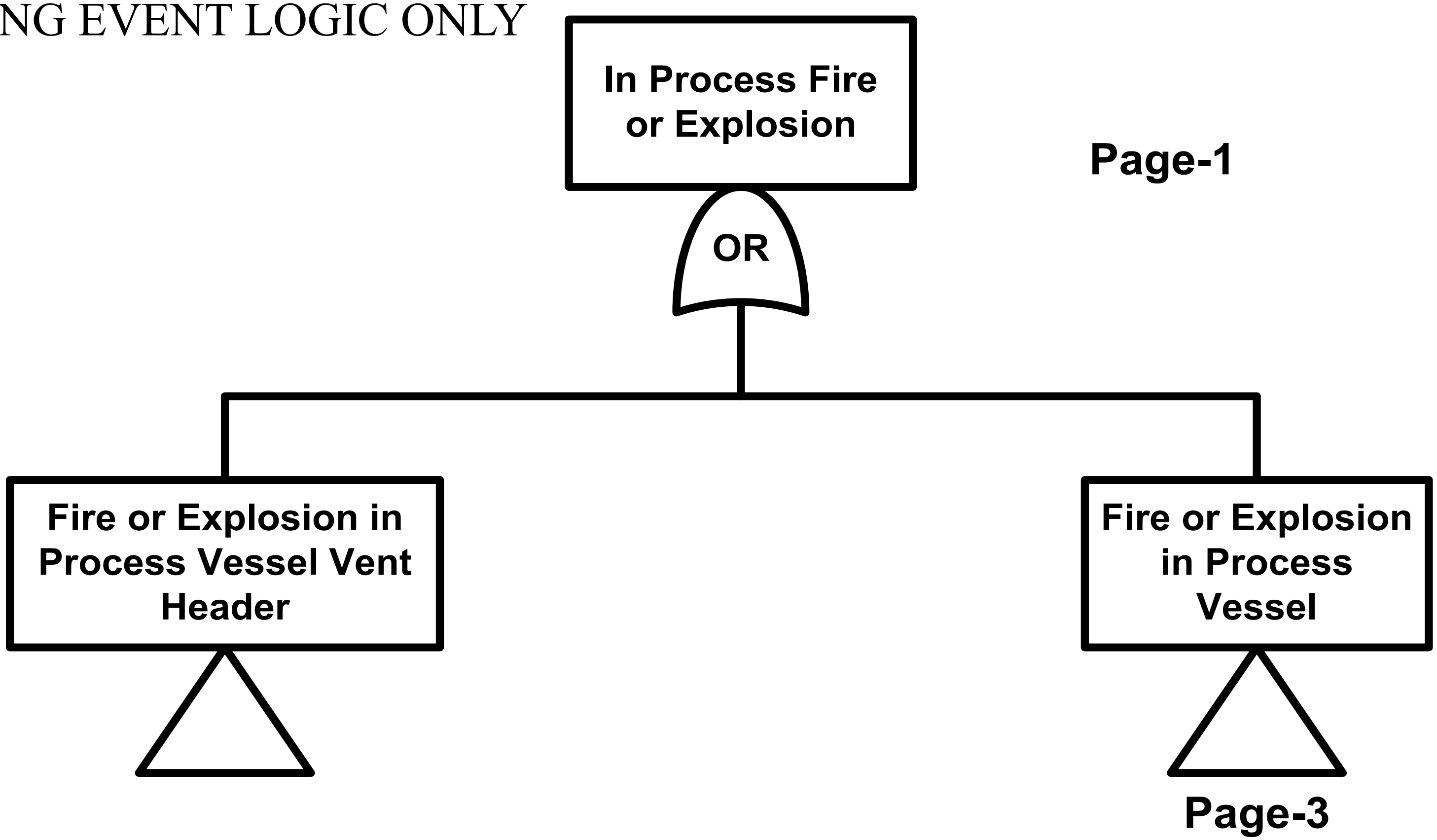
SOME BASIC EVENTS CAN BE EITHER INITIATING OR ENABLING -- FOR EXAMPLE FORMATION OF AN EXPLOSIVE CONCENRATION AND IGNITION SOURCE PRESENT

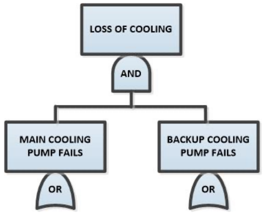


TOP LEVEL FAULT TREE FOR IN PROCESS FIRE OR EXPLOSION

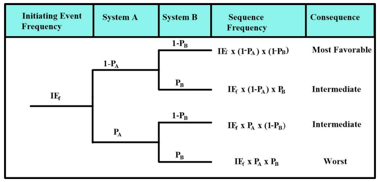


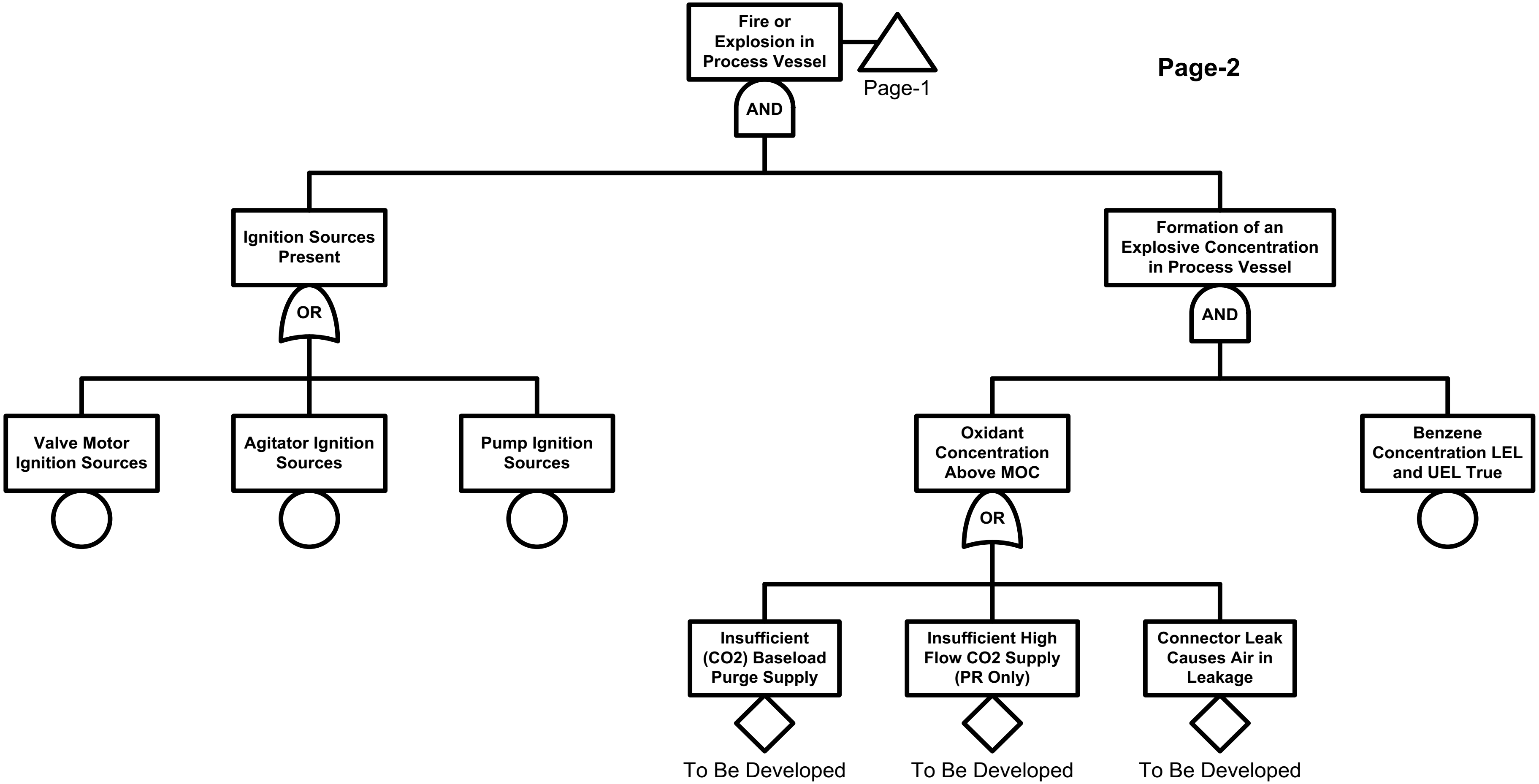
INITIATING EVENT LOGIC ONLY

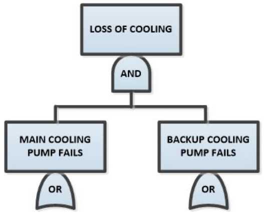




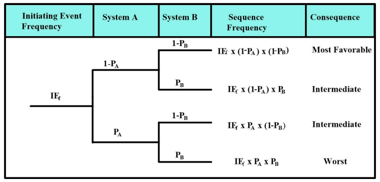
TOP LEVEL FAULT TREE FOR EXPLOSION IN PROCESS VESSEL

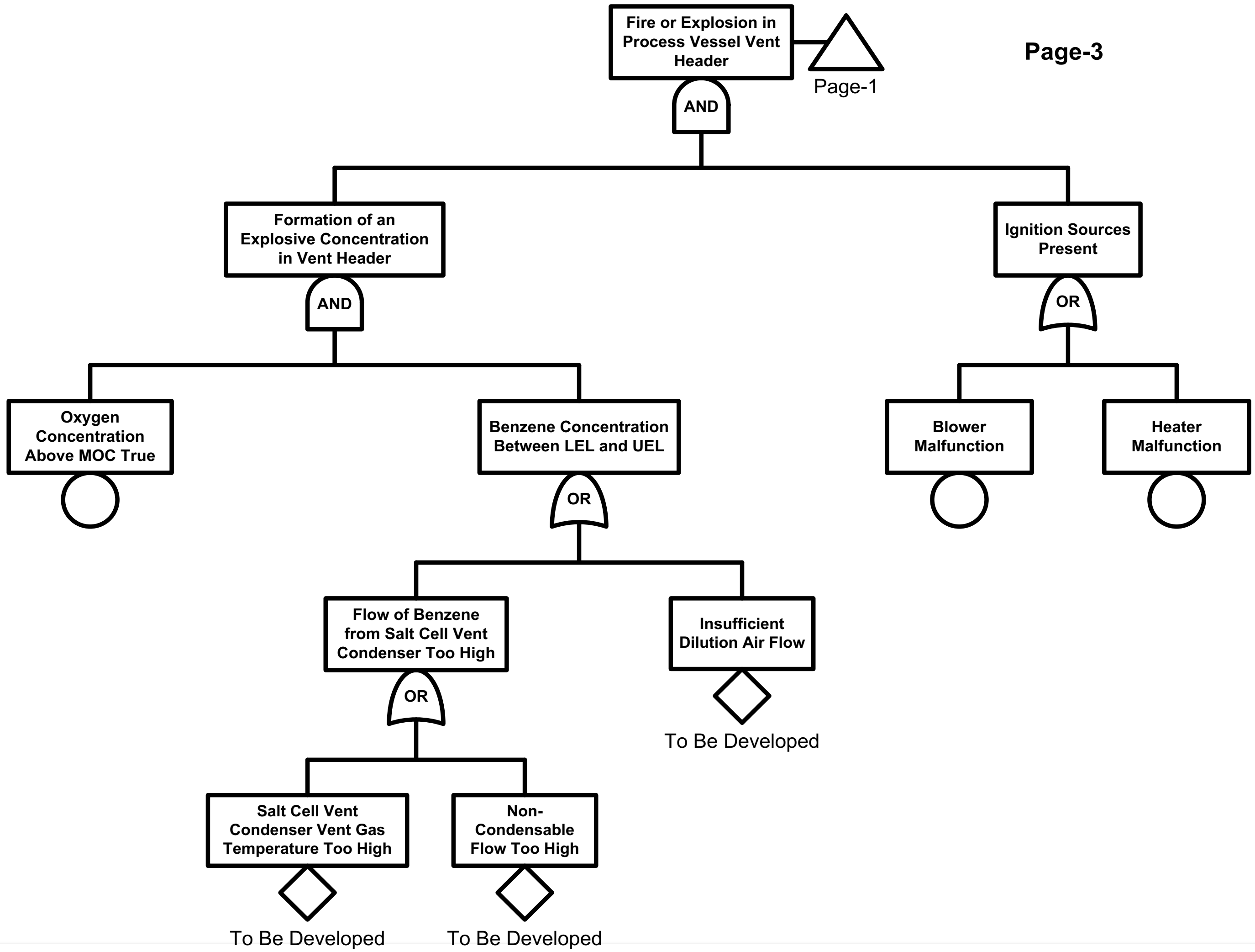


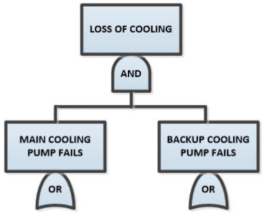




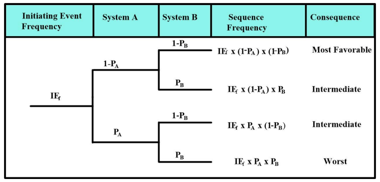
TOP LEVEL FAULT TREE FOR EXPLOSION IN PROCESS VESSEL VENT HEADER



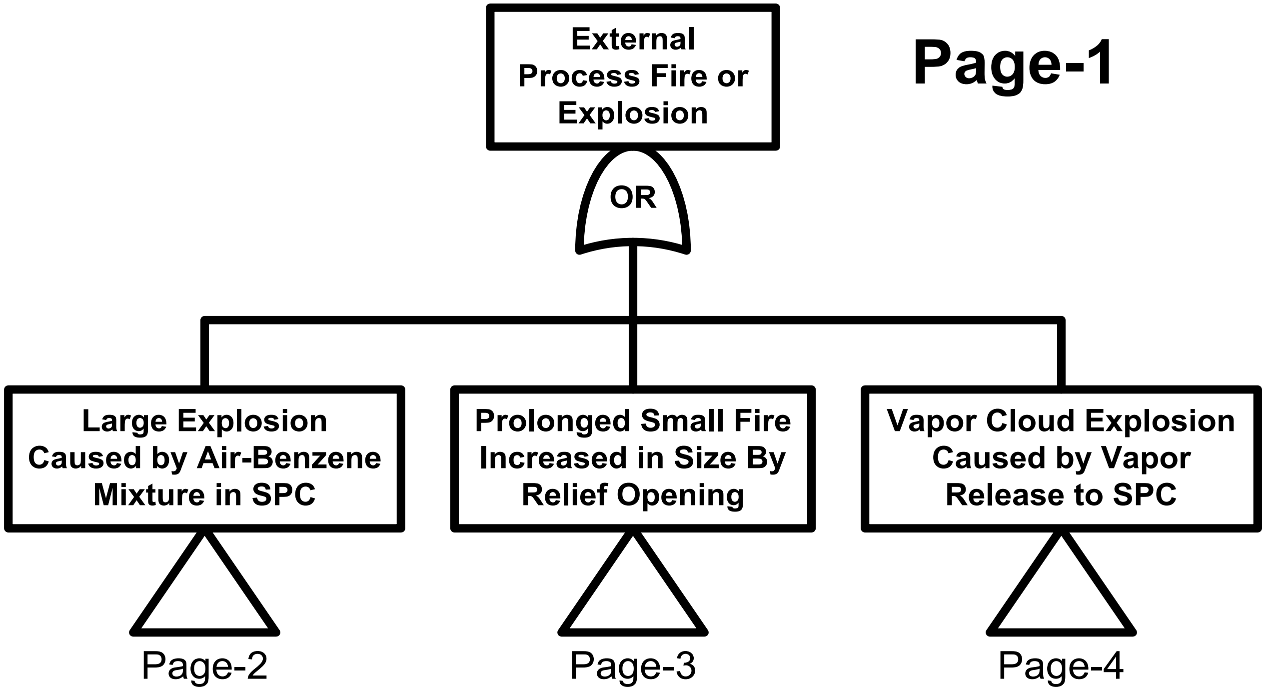


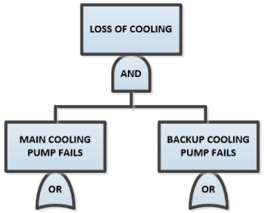


TOP LEVEL FAULT TREE CELL FIRE OR EXPLOSION – EXTERNAL TO SPC PROCESS BOUNDARY

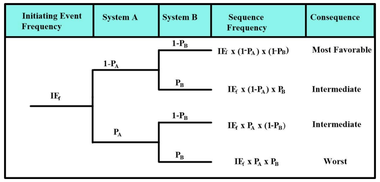


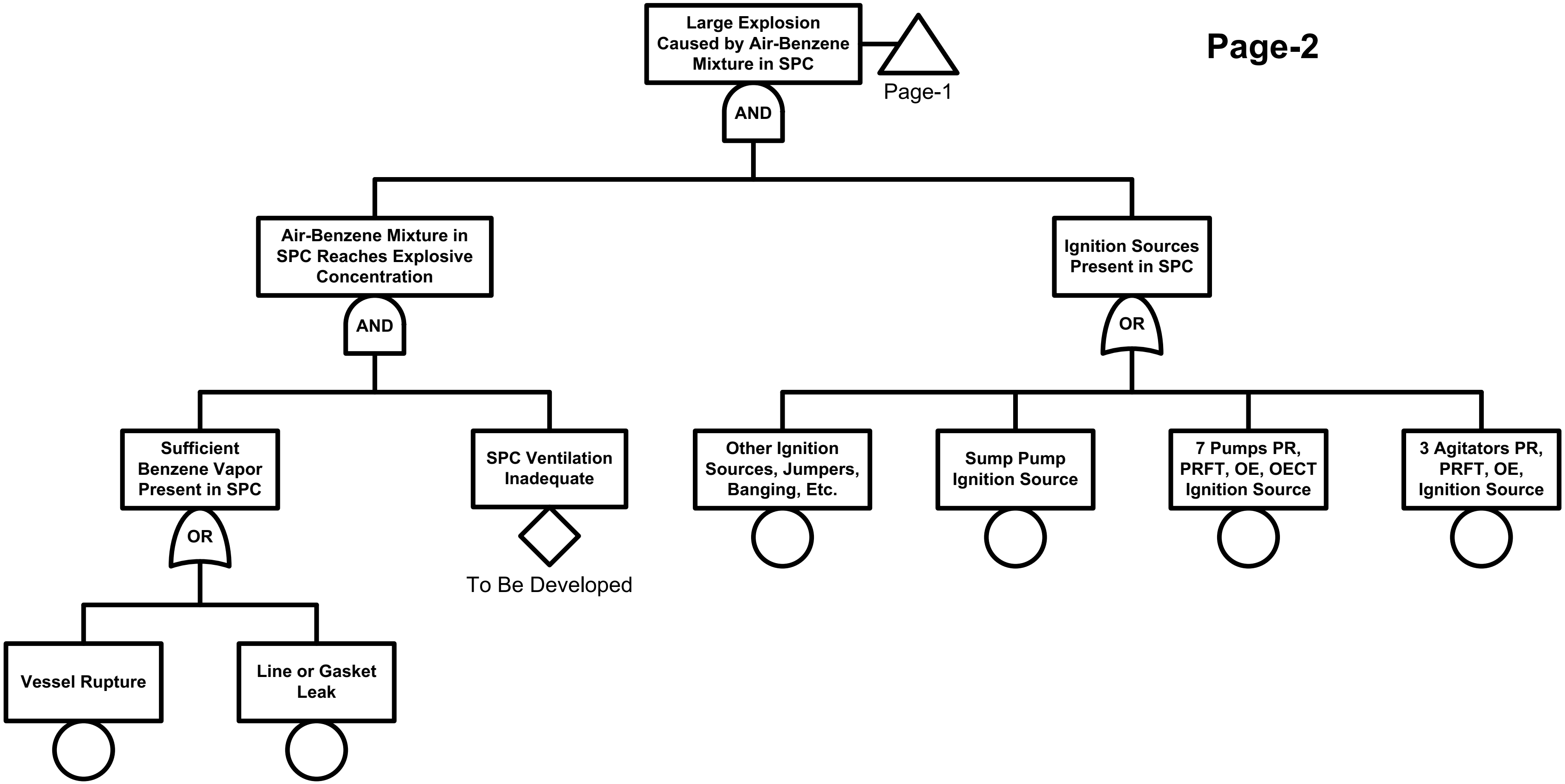
Page-1

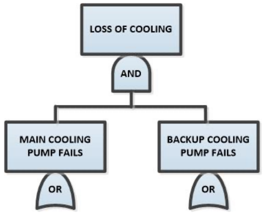




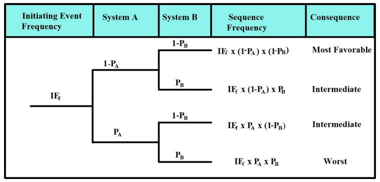
Large Explosion Caused by Air-Benzene Mixture in SPC (Salt Process Cell)

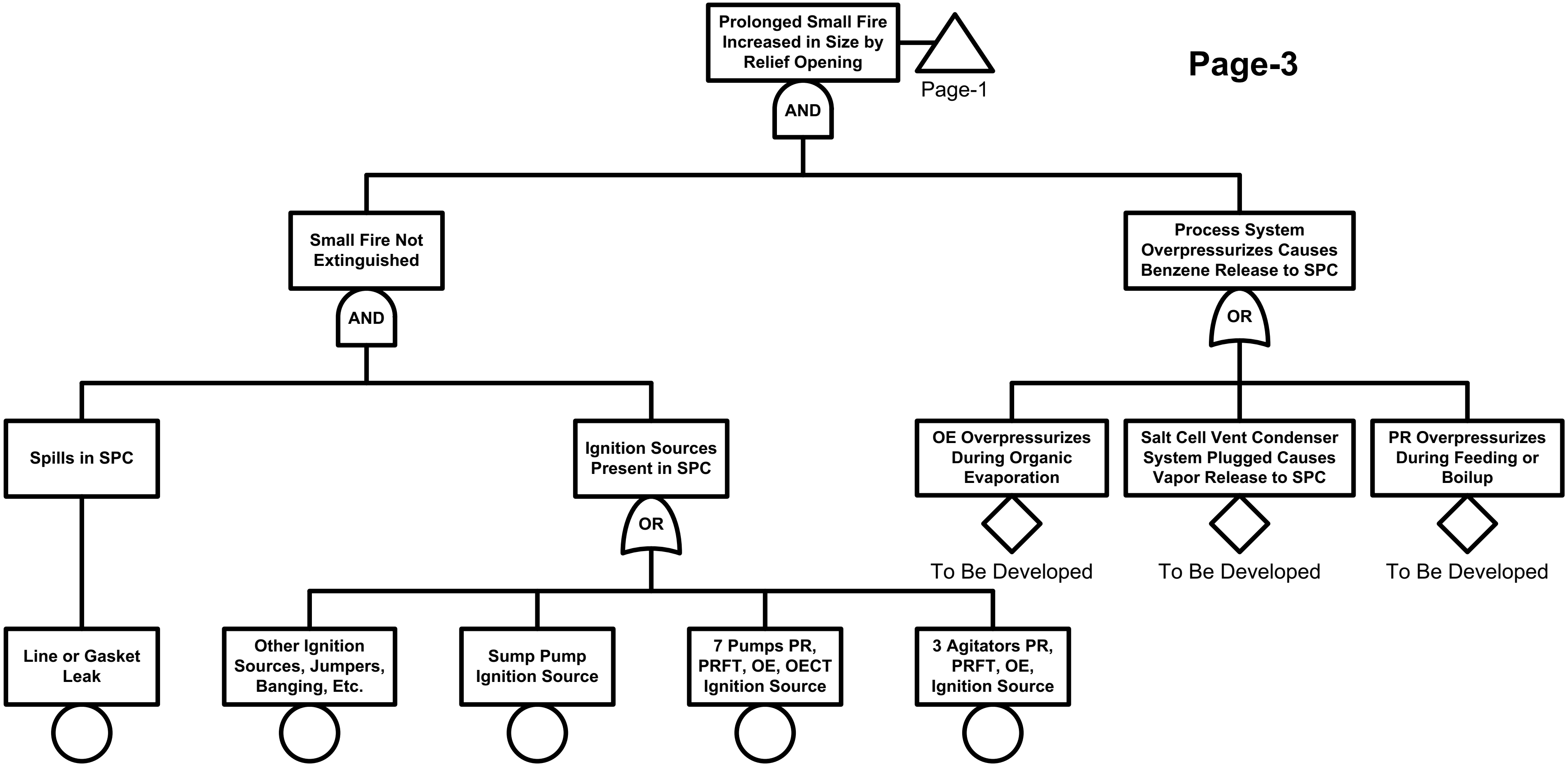


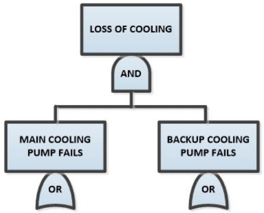




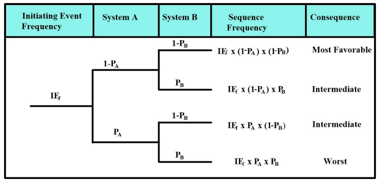
Prolonged Small Fire Increased in Size by Relief Opening

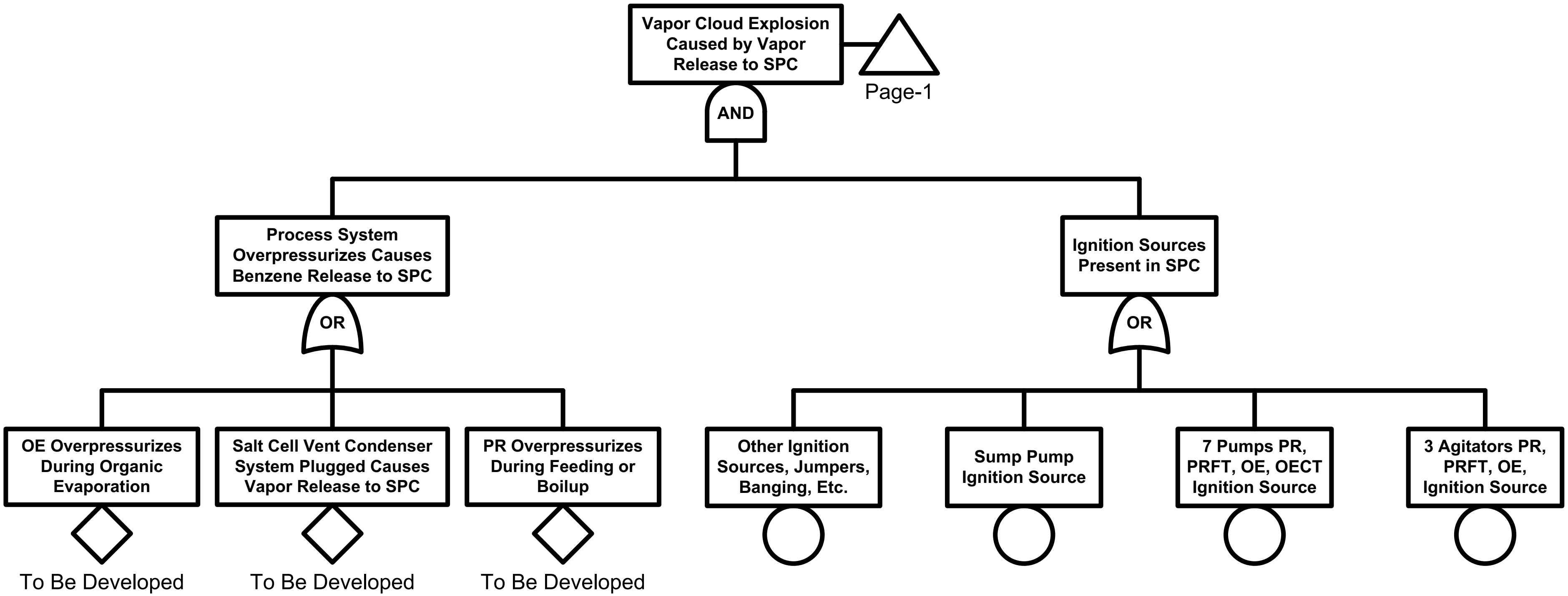


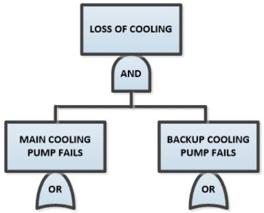




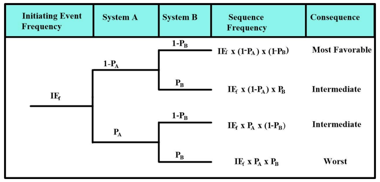
Vapor Cloud Explosion Caused by Vapor Release to SPC (Salt Process Cell)

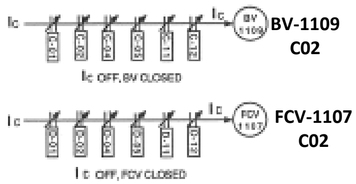






SPC Interlock Configuration





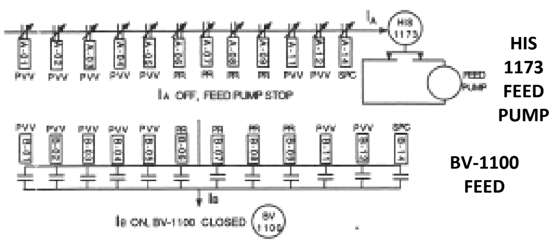
INTERLOCK CONDITION

COMPONENT	NORMAL	ACTIVATED
BV-1109	CURRENT	NO CURRENT
FCV-1107	CURRENT	NO CURRENT

NOTES:

- (C) DENOTES CONTROLLED VARIABLE
- (S) DENOTES SENSED VARIABLE
- [2] DENOTES INTERLOCK NUMBER 2
- [D-01] DENOTES RELAY D-01
- (Ic-11) DENOTES CURRENT THRU [C-11]
- (Ic) DENOTES CURRENT TO OPERATE BV-1109
- (Ic) DENOTES CURRENT TO OPERATE FCV-110'

CHW = CHILLED WATER
CAL ERR = CALIBRATION ERROR
EXPLOSN = EXPLOSION
FC = FAILS CLOSE
FH = FAILS HIGH
FL = FAILS LOW
FO = FAILS OPEN
FTC = FAILS TO CLOSE
FTO = FAILS TO OPEN
FTR = FAILS TO RUN
FTS = FAILS TO STOP
HTR = HEATER
INACT = INACTIVE
INST = INSTRUMENT
INV CLS = INADVERTENTLY CLOSED
OVRHT = OVERHEAT
P L = PRESSURE LOW
REV = REVERSED
SPH = SET POINT HIGH
SPL = SET POINT LOW
STNBY = STANDBY



INTERLOCK CONDITION

COMPONENT	NORMAL	ACTIVATED
FEED PUMP	CURRENT	NO CURRENT
PPT BV-1100	NO CURRENT	CURRENT

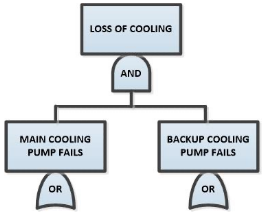
NOTES:

- (C) DENOTES CONTROLLED VARIABLE
- (S) DENOTES SENSED VARIABLE
- [2] DENOTES INTERLOCK LOOP NUMBER 2
- [B-01] DENOTES RELAY B-01
- (IB-11) DENOTES CURRENT THRU [B-11]
- (IB) DENOTES CURRENT TO OPERATE BV-1100
- (IA) DENOTES CURRENT TO KEEP FEED PUMP RUNNING

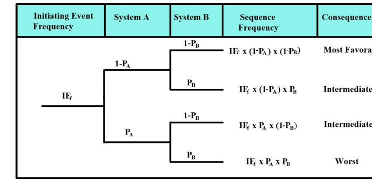
* * 0/- FT-1106 INACT/REV MEANS FT-1106 GAIN = 0, WHEN INACT GAIN = -, WHEN REV.

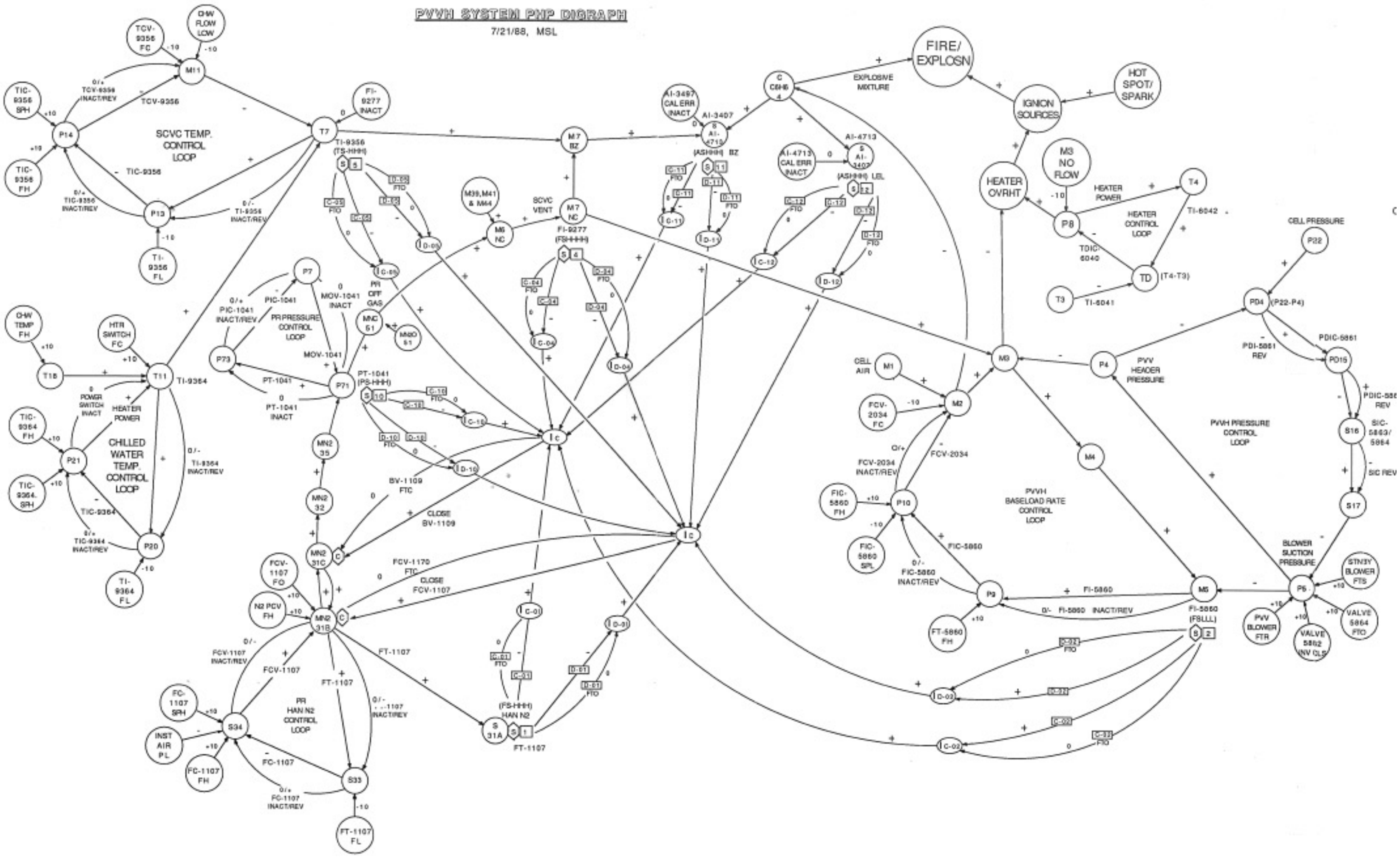
\# SEE PVVH DIAGRAPH FOR DETAILS

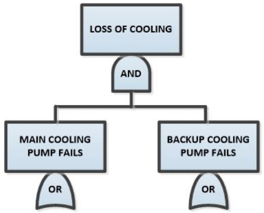
CAL ERR = CALIBRATION ERROR
DCS = DISTRIBUTED CONTROL SYSTEM
FC = FAILS CLOSE
FH = FAILS HIGH
FL = FAILS LOW
FO = FAILS OPEN
FTC = FAILS TO CLOSE
FTO = FAILS TO OPEN
INACT = INACTIVE
INST = INSTRUMENT
INADV CLS = INADVERTENTLY CLOSED
P H = PRESSURE HIGH
P L = PRESSURE LOW
R C = RANDOM CAUSES
REV = REVERSED
SPH = SET POINT HIGH
SPL = SET POINT LOW



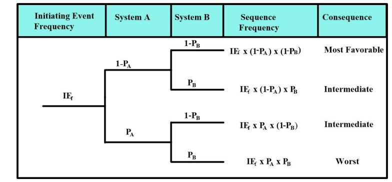
PVVH DIGRAPH

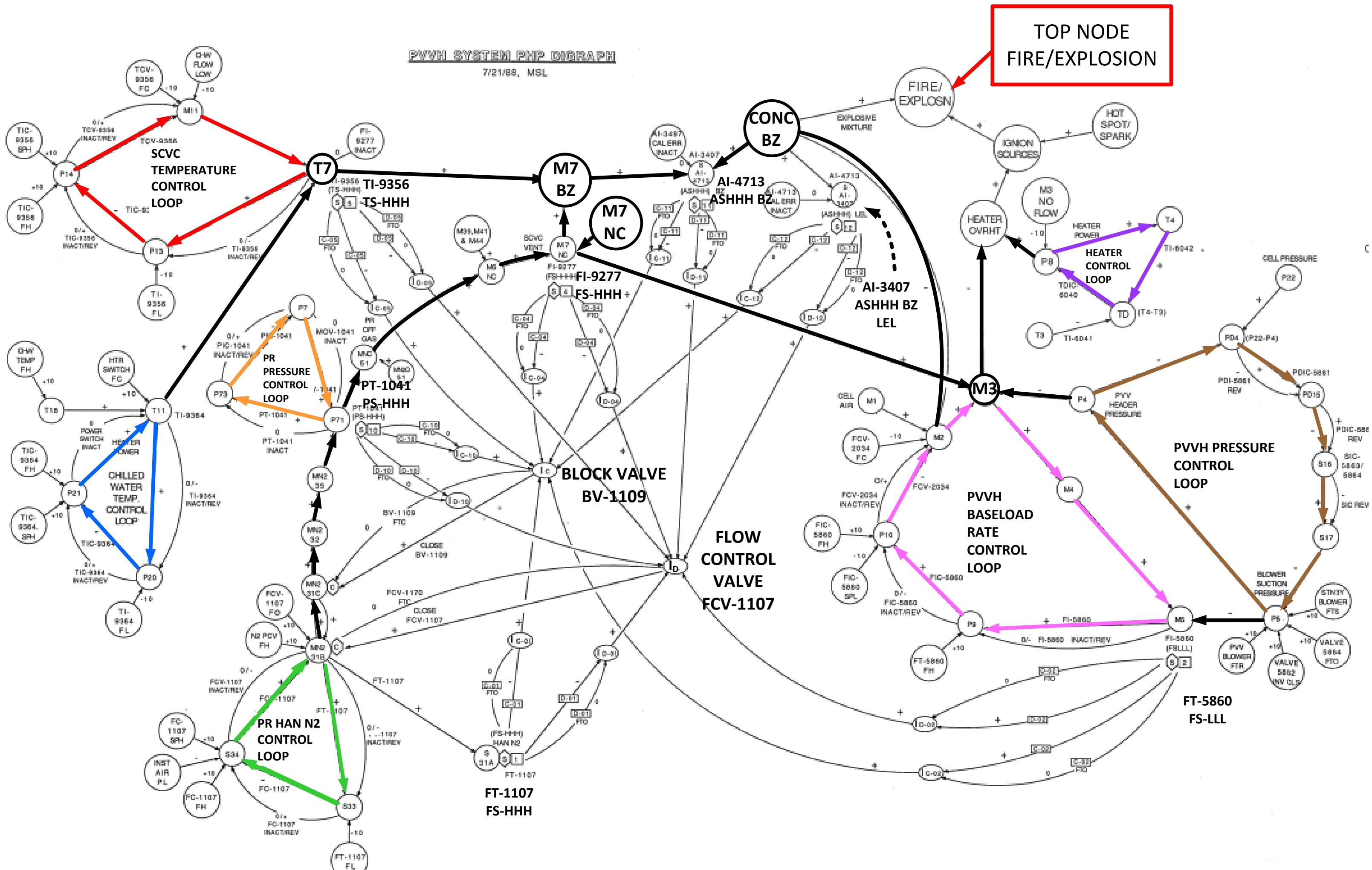


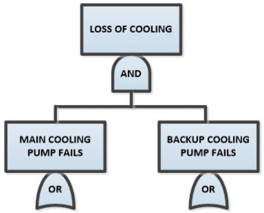




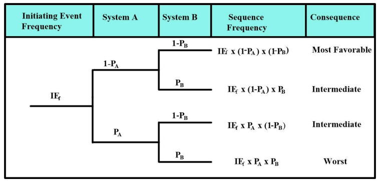
PVVH DIGRAPH COLOR CODED







Number of Min Cut Sets according to order for level 3 hazard events



ORDER	1	2	3	4	5	6	7
NUMBER OF MIN CUT SETS	0	0	0	94	532	419	55

NUMBER OF MIN CUT SETS = 1101

ORDER REFERS TO THE NUMBER OF BASIC EVENTS IN A MINIMAL CUT SET

NUMBER OF BASIC EVENTS = 2000

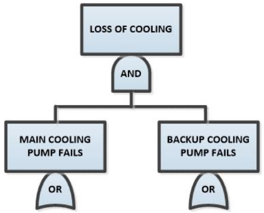
NUMBER OF INITIATING EVENTS = 500

NUMBER OF ENABLING EVENTS = 1500

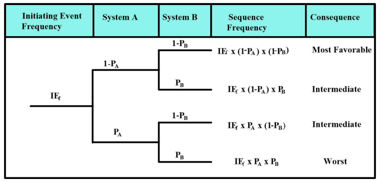
TABLE A-1
TOP EVENTS DESCRIBING FIRE/EXPLOSION

TOP EVENT DESCRIPTION	8 DIGIT NAME FOR TOP EVENT	LEVEL 3 HAZARD CLASSIFICATION?	SHEET NO. *	ANNUAL FREQUENCY YR-1
INSIDE PROCESS INCLUDING PVVH				
FIRE/EXPLOSION WITHIN PRFT	TOP-PRFT	YES	FE-2	**4.5 E-7**
FIRE/EXPLOSION WITHIN PR (FEEDING PERIOD)	TOP-PR--	YES	PR-1	**8.7 E-8**
FIRE/EXPLOSION WITHIN PR (NON-FEEDING PERIOD)	TOP-PR--	YES	FE-4	**8.0 E-6**
FIRE/EXPLOSION WITHIN OE	TOP-OE--	YES	FE-8	**9.3 E-7**
FIRE/EXPLOSION WITHIN OECT	TOP-OECT	YES	FE-10	**3.4 E-7**
FIRE/EXPLOSION WITHIN PVVH (FEEDING PERIOD)	TOP-PVVH	YES	PV-1	**1.7 E-8**
FIRE/EXPLOSION WITHIN PVVH (NON-FEEDING PERIOD)	TOP-PVVH	YES	FE-12	**3.4 E-10**
OUTSIDE PROCESS				
LARGE FIRE	TOPLFIRE	YES	FE-23	**5.5 E-7**
SMALL FIRE NOT EXTINGUISHED	TOPSFIRE	NO	FE-25	**3.0 E-4**
EXPLOSION CAUSING REVERSE FLOW OUT OF SPC	TOPLARGE	YES	FE-30	**4.7 E-5**
SUM OF LEVEL 3 HARARD EVENT FREQUENCIES				**5.7 E-5**

*NOTES
(1) FE refers to SPC fire/explosion fault tree, Appendix B
(2) PR refers to PR fault tree during feeding, Appendix B
(3) PV refers to PVVH fault tree during feeding, Appendix B



Ranking of Initiating and Enabling Events

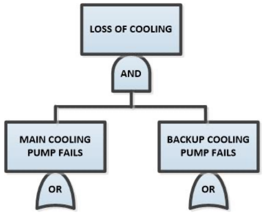


		IMPORTANCE VALUE					
8-DIGIT NAME	LOCATION INDEX	INITIATOR* (1)	ENABLER (2)	TOTAL (1) + (2)	RANK TOTAL	INSPECTION INTERVAL **	FULL BASIC EVENT DESCRIPTION
OPP11.HI	[E-3],[F-3] [G-5],[F-5]	.252	.262	0.514	1	ANNOUNCED	IGNITION SOURCES 7 PUMPS PR, PRFT, OE, OECT (SUMP PUMP SYSTEM WORKS)
PRDISTCY			.344	0.344	2	N/A	BENZENE GENERATION IN PR 4/43
PAG----i	[E-3]	.165	.164	0.329	3	ANNOUNCED	PR AGITATOR IGNITION SOURCE DURING PR FEEDING
PRCO2---			.329	0.329	3	N/A	FEED PERIOD 2/44 HRS HI FLOW CO_2 REQUIRED
QSF1107F			.270	0.270	4	6 MONTHS	PR CO_2 FT-1107 INACTIVE
7CPDCS-1		.094	.094	0.188	5	ANNOUNCED	DCS GENERATES SIGNAL TO CLOSE BV-1109
RVK----K	[E-4]		.168	0.168	6	1 MONTH	PR STEAM BLOCK VALVE FAILS TO CLOSE
RVA10270	[E-3]	.034	.134	0.168	6	ANNOUNCED	PR STEAM FLOW VALVE FCV 1027 FAILS WIDE OPEN
QPR-70C2			.165	0.165	7	N/A	PR TEMP ABOVE 70°C 17/44 HRS
7CPDCS-F			.122	0.122	8	ANNOUNCED	DCS FAILS TO ALARM
RSW1041F	[D-3]		.117	0.117	9	1 MONTH	PSHH 1041 INACTIVE (PR PRESSURE)
GSW9313F	[G-5]		.117	0.117	9	1 MONTH	PSHH 9313 INACTIVE (OE PRESSURE)

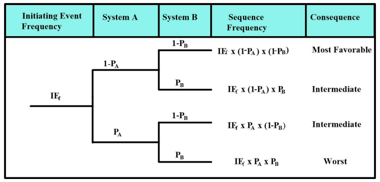
* A blank indicates that the event is an enabling event only
** Announced failure means that the failure is detected when it occurs

T14-1

84



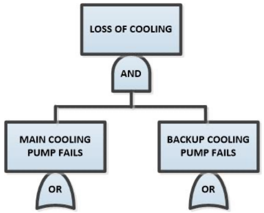
Ranking of Initiating and Enabling Events Continued



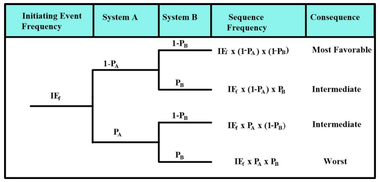
		IMPORTANCE VALUE					
8-DIGIT NAME	LOCATION INDEX	INITIATOR* (1)	ENABLER (2)	TOTAL (1) + (2)	RANK TOTAL	INSPECTION INTERVAL **	FULL BASIC EVENT DESCRIPTION
OAG11.HI		.038	.040	0.078	10	ANNOUNCED	3 AGITATORS PR, PRFT, OE IGNITION SURGES
OAG11.HI	[E-3],[F-3] [G-5]	.038	.040	0.078	10	ANNOUNCED	3 AGITATOR PR, PRFT, OE, IGNITION SOURCES
GRY9313D			.070	0.070	11	6 MONTHS	RELAY 9313 FAILS TO OPEN (OE PRESS HH)
7RY1041D			.070	0.070	11	6 MONTHS	RELAY 1041 FAILS TO OPEN (PR PRESS HH)
7ITSPC-2			.063	0.063	12	N/A	SUMP PUMP SYSTEM WORKS
VDA----1		.003	.050	0.053	13	ANNOUNCED	ALL 3 DAMPERS FAILS CLOSED
BHCOWSTL		.046	.001	0.047	14	ANNOUNCED	TWO HANFORD CONNECTORS LEAK
QSF/107Z		.021	.021	0.042	15	ANNOUNCED	FT-1107 FAILS HIGH
UCN1041Y	[D-3]	.008	.031	0.039	16	ANNOUNCED	PIC 1041 FAILS LOW/INACTIVE PR PRESS
QTI11071		.016	.016	0.032	17	ANNOUNCED	FCV-1107 DELAYED TIMER FAILURE
7RYCR3CD			.032	0.032	17	6 MONTHS	RELAY CR3C CONTACTS FAIL TO OPEN O2 ANALYZER 3405
9TW----F		.023	.008	0.031	18	ANNOUNCED	INADEQUATE HEAT REMOVAL TO COOLING TOWER SYSTEM
1SL5927F	[E-2]		.027	0.027	19	6 MONTHS	BUBBLER 5927 INACTIVE (SUMP LEVEL)

* A blank indicates that the event is an enabling event only
** Announced failure means that the failure is detected when it occurs

T14-2



TWO TOP MIN CUT SETS EXPLOSIVE CONCENTRATION



MIN CUT SET #111 (EXPLOSIVE CONCENTRATION WITHIN PR DURING FEEDING

EVENT RATE = 7.2E-07/HR -- 6.3E-03/YR

1. **DCS GENERATES SIGNAL TO CLOSE BV-1109 (i)2.0 x 10^{-4}/hr**
2. **BENZENE CONCENTRATION IN PR BETWEEN LEL AND UEL (e)1.0**
3. **FEED PERIOD 2/44 HOURS HIGH FLOW $C0_2$ REQUIRED (e) 0.045**
4. **FT 1107 INACTIVE (e)7.8 x 10^{-5}/hr (6 months)**

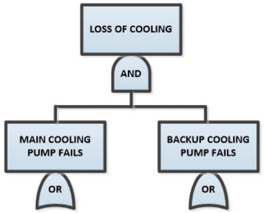
MIN CUT SET #3 (EXPLOSIVE CONENTRATION WITHIN SPC CAUSED BY BENZENE VAPOR RELEASE TO SPC FROM PR DURING ORGANIC EVAPORATION AND BOILUP)

EVENT RATE = 2.3E-9/HR – 2.0E-05/YR

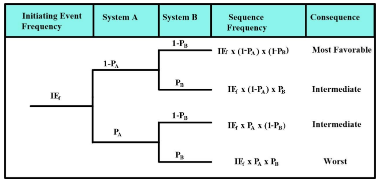
1. **BENZENE GENERATION IN PR 4/44 0.093**
2. **PR STEAM FLOW VALVE FCV 1027 FAILS WIDE OPEN (i)2.2 x 10^{-6}/hr**
3. **PR STEAM FLOW BLOCK VALVE FAILS TO CLOSE (e)6.2 x10^{-5}/hr (1 month)**

(i) Denotes an event which can function as an initiating event (e) Denotes an enabling event

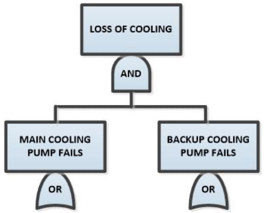
DCS is distributed control system



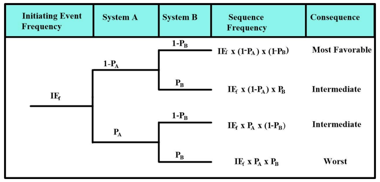
Salt Process Cell Study



- Why use Benzene?
- Comment was made “too complicate to model”
- Team Members were trained on the use of directed graphs to generate fault trees (5 to 7 members)
- Used Chorine Vaporizer Study as a case study
- Numerous meetings with SMEs during the course of the study – changed fault trees on the basis of these meetings
- Study Duration 7 years

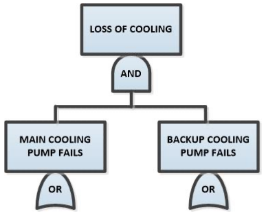


Salt Process Cell Study

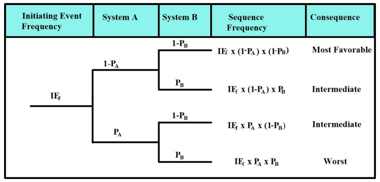


- 200 pages of fault trees were generated
- 2000 basic events
  - ~500 initiating events
  - ~1500 enabling events
- HAN addition was eliminated – wash precipitate prior to feeding
- DuPont goal of 1.0 E-4 annual frequency achieved for each scenario
  - At least one independent interlock for each hazardous process condition
  - Double block valve for ventilation system for air in leakage

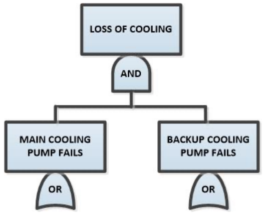
88



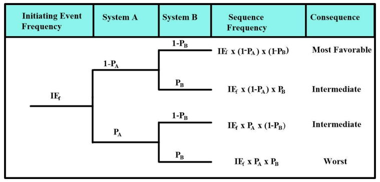
Salt Process Cell Study Insights



- In1997 the decision was made not to use the salt process cell – formation of ammonium nitrate issue
- Supernate containing Cesium remains in tank 48
- Sludge however still was processed at DWPF
- Discussions with Colin Dunglinson to obtain guidance and advice as the study was conducted
- Most Interesting study of my career
- Hundreds of pages of fault trees were peer reviewed -- at each review discussion events were identified as either initiating, enabling or both



Salt Process Cell Study Insights Continued



- Use of directed graphs helped understand how complex control systems can cause or pass a disturbance
- Trained Study Team Members to perform digraph analysis
- Ranking of Analysis Techniques by SRP engineers used in the SPC study
  - 1 Fault Tree Analysis (most useful)
  - 2 Process Hazards Reviews (second most useful)
  - 3 Failure Modes and Effects analysis (least useful)
- SRP supported the study by providing SMEs, Resources and process information to conduct a very complicated Study