Fault Tree Analysis of Sequential Systems

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Fault tree analysis is a systems safety technique for determining the logical combinations of events which could cause a specific hazard to occur. Digraph models are proposed which describe sequential relationships between events. A computer program which automatically constructs fault trees from digraph models is illustrated for an air-drying process.

Introduction

Fault tree analysis has been used in the aerospace, electronics, nuclear, and chemical industries to aid in (1) the discovery and control of failures before they occur; (2) the analysis of accidents, and (3) the planning of maintenance activities (Fussell, 1974; Powers, 1974). In the use of the fault tree method many safety analysts have expressed concern over the ability of the method to handle sequentially dependent events.

Esary recently illustrated the problem of applying fault tree analysis to sequential systems (Esary and Ziehms, 1975). In his analysis he considered a phased-mission in which the status and function of the components within a system depend on the phase (time sequence) of the mission. Esary presented a fault tree for the phased mission which was composed of sub-trees, one for each phase in the mission. He also presented an excellent discussion of the difficulties involved in calculating the probability of system success given the sequential interdependence of events. In this paper we present a strategy for partially automating the synthesis of fault trees when sequential interdependencies are considered. The key to the method is the development of cause and effect models which explicitly consider the possible sequential interactions between events. These models are used in an algorithm which automatically generates fault trees.

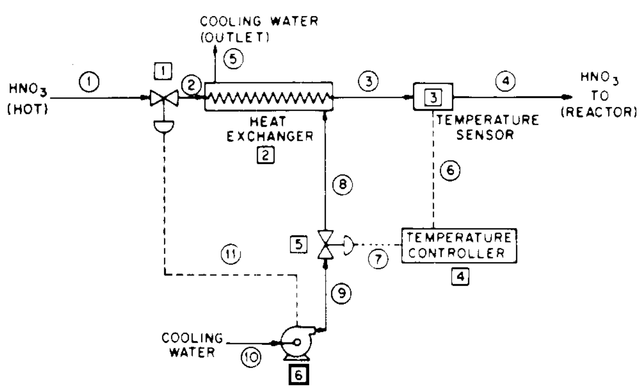


Figure 1. Flow diagram for part of a nitrification process. When low pump speed is sensed at the pump, valve 1 is closed.

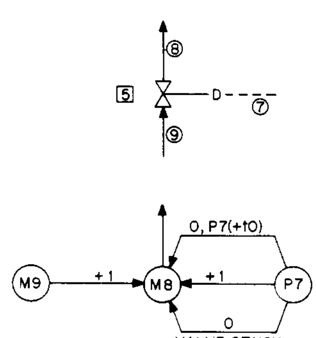


Figure 2. A cause-and-effect model for a control valve.

Digraph Models

In a previous paper (Lapp, 1977), we have developed the concept of a digraph model for the description of both the normal and failed behavior of components in interconnected systems. The models will be briefly reviewed here and extended to sequential situations.

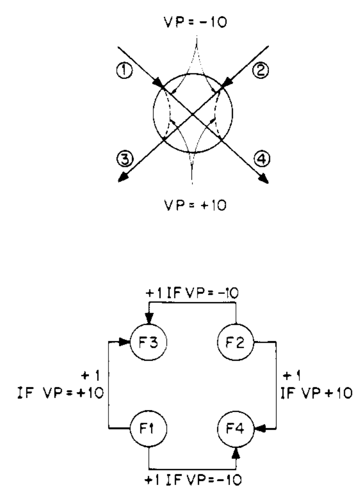


Figure 3. Cause-and-effect model for a four-way valve.

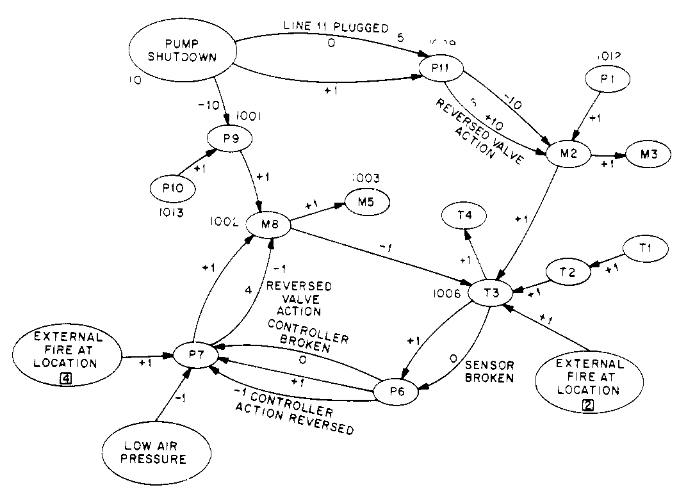


Figure 4. A partial cause-and-effect model for the output variable temperature in stream 4 (T4) in Figure 1.

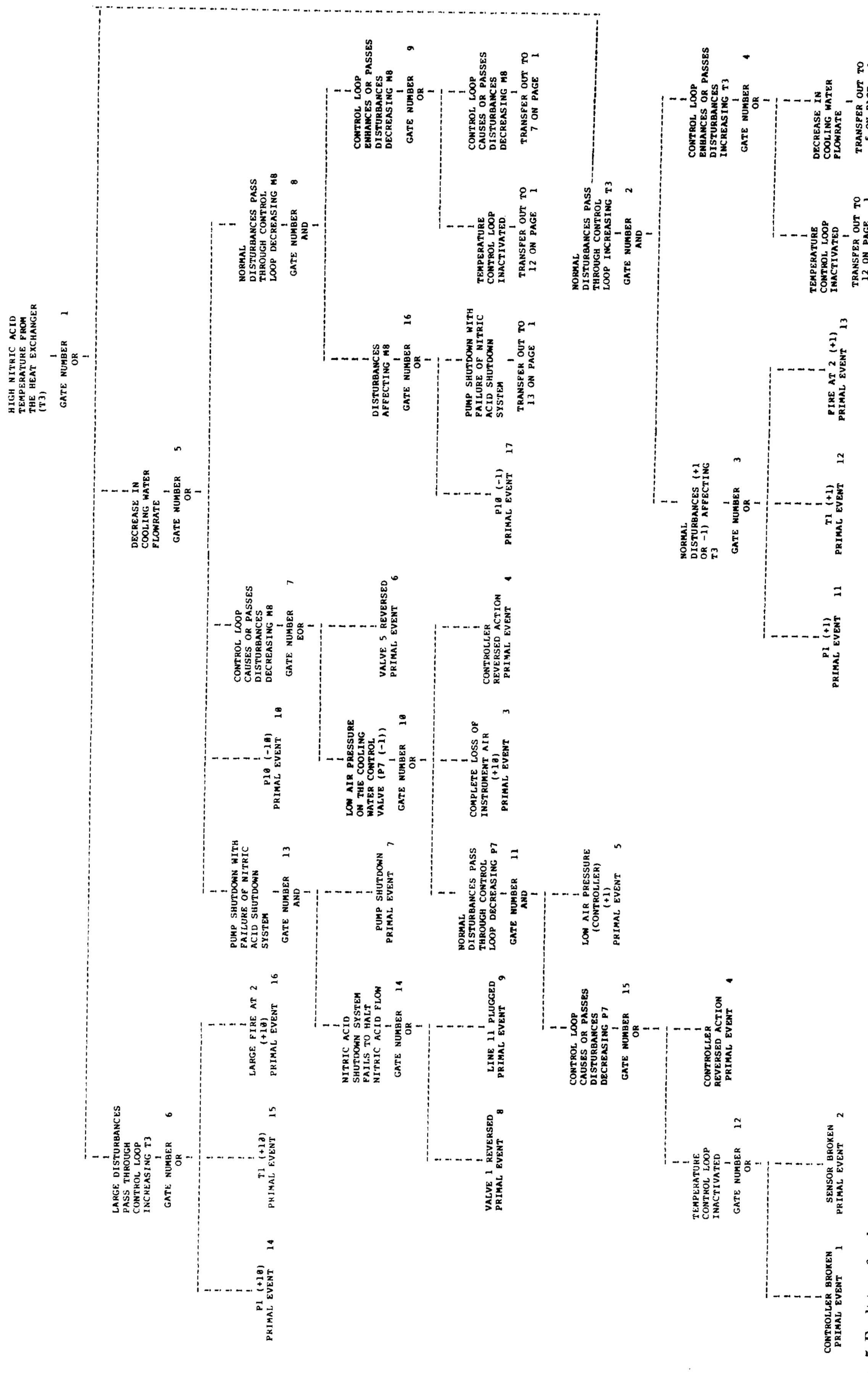


Figure 5. Fault tree for the event T4 too high.

Table I. Operating Procedure for Fixed-Bed Drier System

Time period	Time since beginning of cycle, h	Value position (steam connections)			Bed status	
		3W	4WI	4WII	Bed I	Bed II
1	1 2	11→12	18→19 AND 22→23	20→21 AND 24→25	Regeneration	In service
2	3	11→18	18→19 AND 22→23	20→21 AND 24→25	Cooling	In service
3	4 5	11→12	18→23 AND 22→19	20→25 AND 24→21	In service	Regeneration
4	6	11→18	18→23 AND 22→19	20→25 AND 24→21	In service	Cooling
		Return to Time Period 1				

In developing logic models for physical systems, it is necessary to capture the cause-and-effect nature of interactions which occur between the variables which describe the system (i.e., temperatures, pressures, flow rates, concentrations, operator action, voltages, valve positions, etc.) and events which occur within the system (i.e., valve failure, fire, explosion, operator error, weather changes, etc.). For example, consider the flow sheet given in Figure 1. The system is composed of valves, pumps, heat exchangers, etc. In order to determine how failures or deviations in input variables propagate through the system, it is possible to construct digraphs whose nodes represent events or variables and whose edges represent the relationships between the nodes. Figure 2 illustrates a cause and effect model for valve 5 in this system. Note that the edges may be event dependent. That is, a relationship between two variables may be dependent on the value of other variables or events in the system. For example, the gain between the pressure on the valve actuator P7 and the mass flow rate leaving the valve M8 is normally +1. An increase in pressure opens the valve and allows a higher flow rate. However, if the pressure on the actuator is very high (P7 = +10) the gain is 0. The valve is wide open and further increases in pressure P7 do not give an increase in the flow rate M8.

Table II. Sequential Dryer Process Events

Title event number	Probability	Text
1	2.00×10^{-3}	4-Way valve leaks across
2	5.00×10^{-8}	Fire at Bed I
3	1.20×10^{-4}	No alumina in Bed I, or channeling
4	7.15×10^{-4}	4-Way valve II motor failure
5	3.30×10^{-1}	Time = 1
6	1.67×10^{-1}	Time = 2
7	4.72×10^{-6}	4-Way valve II timer changes at wrong time
8	5.00×10^{-8}	Fire at Bed II
9	1.20×10^{-4}	No alumina in Bed II, or channeling
10	1.67×10^{-1}	Time = 4
11	4.72×10^{-6}	4-Way valve II timer fails
12	8.63×10^{-5}	4-Way valve II control line 29 cut
13	3.30×10^{-1}	Time = 3
14	5.00×10^{-4}	Inlet air flow up
15	5.00×10^{-4}	Proportionating valve pressure up (P10)
16	7.15×10^{-4}	4-Way valve I motor failure
17	7.99×10^{-5}	Heater leaks steam into air
18	5.00×10^{-4}	Inlet air water concentration up
19	7.15×10^{-4}	3-Way valve motor failure
20	4.72×10^{-6}	4-Way valve I timer changes at wrong time
21	4.72×10^{-6}	4-Way valve I timer fails
22	8.63×10^{-5}	4-Way valve I control line 28 cut
23	1.00×10^{-5}	Water separator trap clogged
24	2.10×10^{-3}	Valve 6 closed
25	5.00×10^{-8}	External fire at separator
26	4.72×10^{-6}	3-Way valve timer changes at wrong time
27	4.72×10^{-6}	3-Way valve timer fails
28	8.63×10^{-5}	3-Way valve control line 27 cut
29	5.00×10^{-4}	Cooling water flow down
30	5.00×10^{-4}	Cooling water temperature up
31	2.99×10^{-3}	Cooler fouled
32	5.00×10^{-8}	External fire at cooler
33	2.10×10^{-3}	Valve 4 closed
36	5.00×10^{-4}	Inlet Air pressure up

If the edges in a digraph are made dependent on other events in the system, it is possible to capture in one digraph the sequential behavior of the complete system. Consider the four-way valve shown in Figure 3. When the valve is in position 1 (valve position = VP = +10) the flow is from stream 1 to stream 3 and from stream 2 to stream 4. In position 2 (valve position = VP = −10) the flow is from stream 2 to stream 3 and from stream 1 to stream 4. A digraph for this valve is given in Figure 3 where VP is the valve position. If, from another

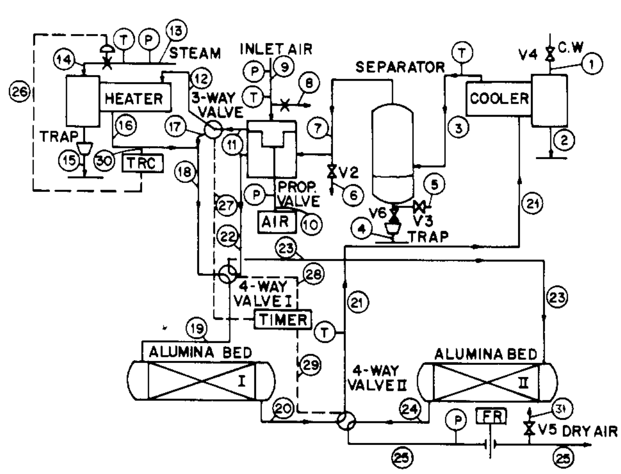
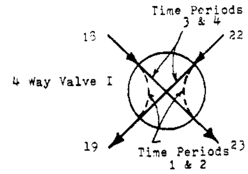


Figure 6. Flow diagram of a utility air drying process. After King (1970).



	F19	T19	C19	F23	T23	C23
F18	+1					
T18		+1				
C18			+1			
F22				+1		
T22					+1	
C22						+1
Failures: Plug	-10			-10		
Leak Across	- 1			+ 1		
Leak Across	C18 to C23 Gain +1, T18 to T23 Gain +1					

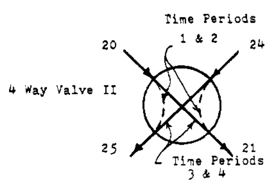
Time Periods 1 AND 2

VP = +10

	F19	+19	C19	F23	T23	C23
F18				+1		
T18					+1	
C18						+1
F22	+1					
T22		+1				
C22			+1			
'ailures: Plug	-10			-10		
Leak Across	+ 1			- 1		
Leak Across	C18 to C19 Gain +1, T18 to T19 Gain +1					

Time Periods 3 AND 4

VP = -10



	F21	T21	C21	F25	T25	C25
F20	+1					
T20		+1				
C20			+1			
F24				+1		
T24					+1	
C24						+1
Plug	-10			-10		
Leak Across	- 1			+ 1		
Leak Across	C20 to C25 Gain +1, T20 to T25 Gain +1					

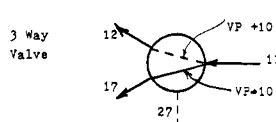
Time Periods 1 AND 2

VP = +10

	F21	T21	C21	F25	T25	C25
F20				+1		
T20					+1	
C20						+1
F24	+1					
T24		+1				
C24			+1			
Plug	-10			-10		
Leak Across	+ 1			- 1		
Leak Across	C20 to C21 Gain +1, T20 to T21 Gain +1					

Time Periods 3 AND 4

VP = -10

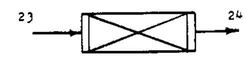


	VP = +10				VP = -10			
	F12	T12	C12	F17	F17	T17	C17	F12
F11	+1				+1			
T11		+1				+1		
C11			+1				+1	
Failures: Valve Leaks Across	-1			+1	-1			+1
	Use VP = -10 Gains for T and C				Use VP = +10 Gains for T and C			
Plugged Valve	-10				-10			

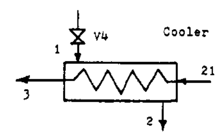
Alumina Bed I

	Time Period 1 (Regeneration)			Time Period 2 (Cooling)			Time Period 3 AND 4 (In Service)		
	F20	T20	C20	F20	T20	C20	F20	T20	C20
F19	+1	-1	-1	+1	+1	0	+1	0	+1
T19	0	+1	+1	0	+1	0	0	+1	+1
C19	0	0	+1	0	0	+1	0	0	+1
Failures									
No alumina in Bed I (also channeling)	0	+1	-1	0	+1	0	0	0	+1
Plugged Bed	-10	0	0	-10	0	0	-10	0	0
Leak Out	- 1	0	0	- 1	0	0	- 1	0	-1
Fire	0	+1	+1	0	+1	0	0	+1	+1

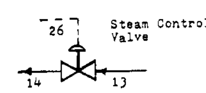
Alumina Bed II



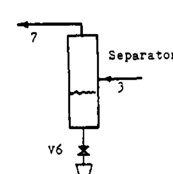
	Time Period 1 AND 2 (In Service)			Time Period 3 (Regeneration)			Time Period 4 (Cooling)		
	F24	T24	C24	F24	T24	C24	F24	T24	C24
F23	+1	0	+1	+1	-1	-1	+1	+1	0
T23	0	+1	+1	0	+1	+1	0	+1	0
C23	0	0	+1	0	0	+1	0	0	+1
Failures	0	0	+1	0	+1	-1	0	+1	0
No alumina in Bed II (channeling)	0	0	+1	0	+1	-1	0	+1	0
Plugged Bed	-10	0	0	-10	0	0	-10	0	0
Leak Out	- 1	0	-1	- 1	0	0	- 1	0	0
Fire	0	+1	+1	0	+1	+1	0	[illegible]	0



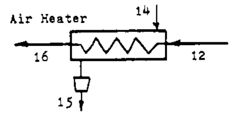
	F2	T2	F3	T3	C3
F1	+1	-1	0	-1	-1
T1	0	+1	0	+1	+1
F21	0	+1	+1	+1	+1
T21	0	+1	0	+1	+1
C21	0	0	0	0	+1
Failures					
External Fire	0	+1	0	+1	+1
Fouling	0	+1	0	+1	+1
V4 Open Wide	+10	-10	0	-10	-10
V4 Closed	-10	+10	0	+10	+10



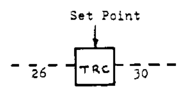
	F14	T14
P26	-1	0
F13	+1	0
T13	0	+1
Failures: Line 13 plugged	-10	0
Valve Reversed	Change P26 to F14 Gain to +1	
Valve Fails Closed	-10	0
Valve Fails Open	+10	0



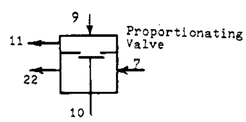
	F7	T7	C7	F4	T4
F3	+1	0	0	+1	0
T3	0	+1	+1	0	+1
C3	0	0	+1	0	0
Failures					0
Trap Plugged	+1	0	+1	-1	-0
Fire	0	+1	+1	-10	+1
V6 Closed	+1	0	+1	-10	0



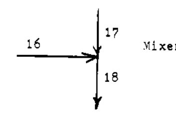
	F16	T16	C16	F15	T15
F12	[illegible]	-1	0	0	-1
T12	0	+1	0	0	+1
C12	0	0	+1	0	0
F14	0	+1	0	[illegible]	0
Failures: External Fire	0	+1	0	0	+1
Steam Leak into Air Side	+1	+1	+1	-1	-1
Trap Plugged	0	-1	0	-10	-1



	P26
P30	+1
Set Point	+1
Failures: Fire	+1
Controller Broken	Change P30 to P26 Gain to 0
Controller on Manual	Change P30 to P26 Gain to 0
Controller Reversed	Change P30 to P26 Gain to -1



	F11	T11	C11	F22	T22	C22
F7	+1			+1		
T7					+1	
C7						+1
F9	+1			+1		
T9		+1			+1	
C9			+1			[illegible]
P10	+1			-1		
P10(+10)	F9 to F22 Gain = 0; C9 to C22 Gain = 0; T9 to T22 Gain = 0.					



	Time Periods 1 AND 3			Time Periods 2 AND 4		
	F18	T18	C18	F18	T18	C18
F16	+1					
T16		+1				
C16			+1			
F17				+1		
T17					+1	
C17						+1

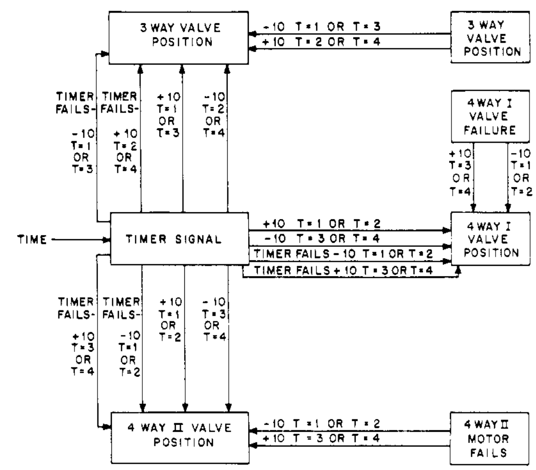


Figure 7. Input–output models for the equipment in the utility air drying process.

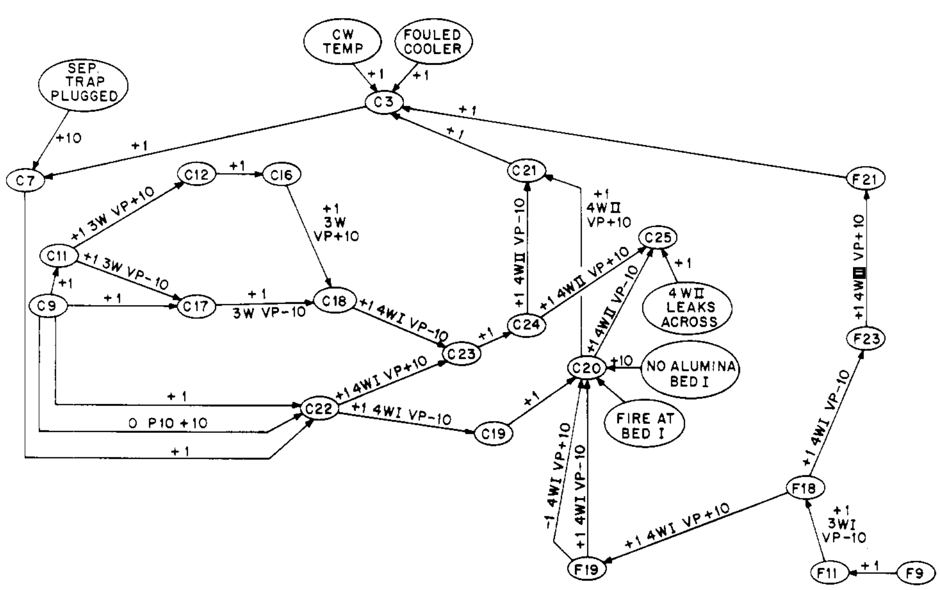
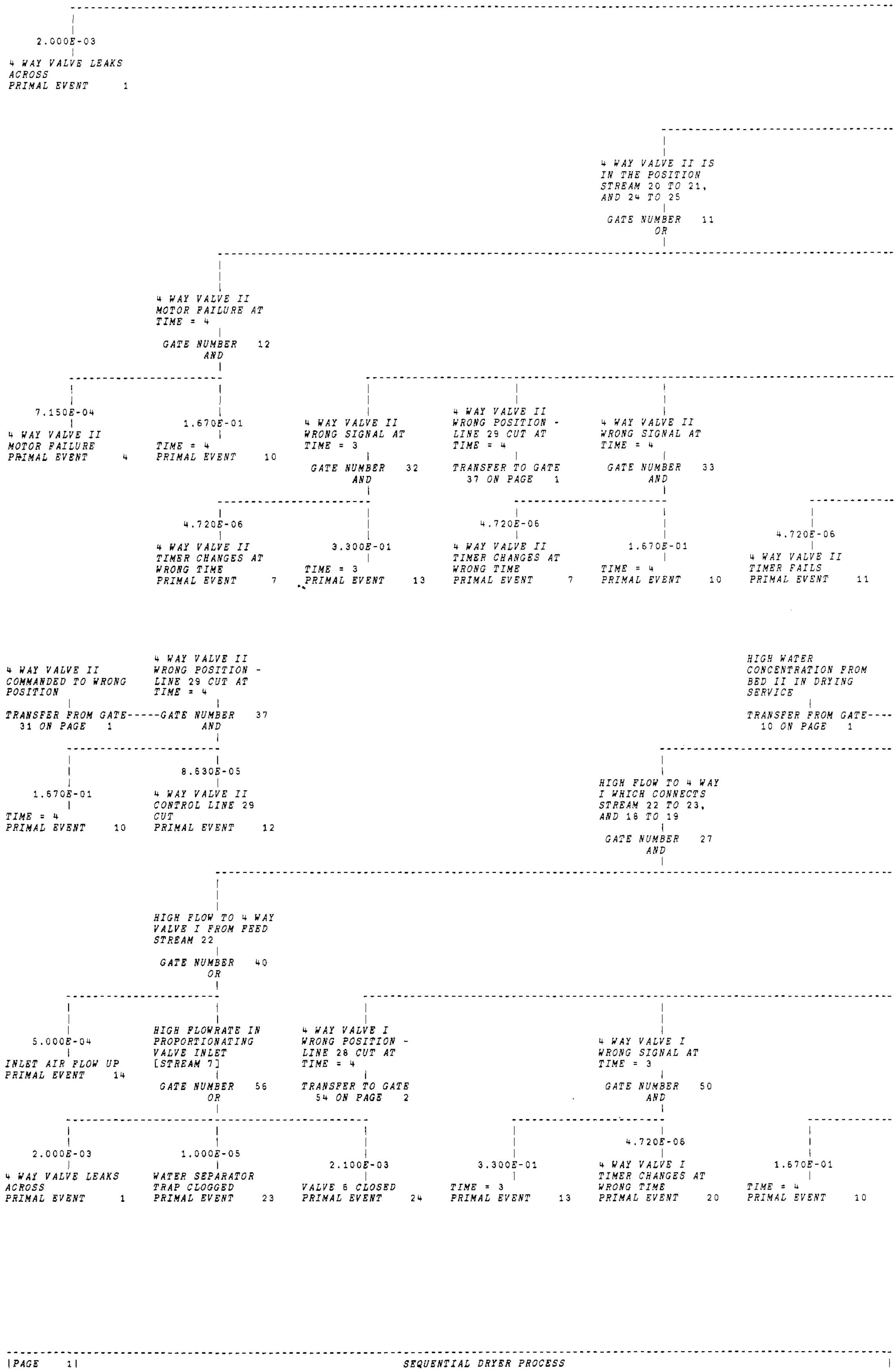


Figure 8. Part of the digraph for the utility air drying process.

part of the system, the position of the four-way valve is commanded to a particular sequence of positions, these sequences will be conditionals which modify the relationships between F1, F2, F3, and F4. For example, the event F3 (+1) equals (FI (+1) AND VP (+10)) OR (F2 (+1) AND VP (−10)). If VP (+10) is dependent on other events they may be expanded into the appropriate Boolean expression and substituted for VP (+10).

Digraph models of this type are able to describe both combinational and sequential logic relationships. They are much more compact than truth tables, decision tables, or finite state models. In addition, the Boolean logic is computed from



2.000E-03
4 WAY VALVE LEAKS ACROSS
PRIMAL EVENT 1
4 WAY VALVE II IS IN THE POSITION STREAM 20 TO 21, AND 24 TO 25
GATE NUMBER 11
OR
4 WAY VALVE II MOTOR FAILURE AT TIME = 4
GATE NUMBER 12
AND
7.150E-04
4 WAY VALVE II MOTOR FAILURE
PRIMAL EVENT 4
1.670E-01
TIME = 4
PRIMAL EVENT 10
4 WAY VALVE II WRONG SIGNAL AT TIME = 3
GATE NUMBER 32
AND
4 WAY VALVE II WRONG POSITION - LINE 29 CUT AT TIME = 4
TRANSFER TO GATE 37 ON PAGE 1
4 WAY VALVE II WRONG SIGNAL AT TIME = 4
GATE NUMBER 33
AND
4.720E-06
4 WAY VALVE II TIMER CHANGES AT WRONG TIME
PRIMAL EVENT 7
3.300E-01
TIME = 3
PRIMAL EVENT 13
4.720E-06
4 WAY VALVE II TIMER CHANGES AT WRONG TIME
PRIMAL EVENT 7
1.670E-01
TIME = 4
PRIMAL EVENT 10
4.720E-06
4 WAY VALVE II TIMER FAILS
PRIMAL EVENT 11
4 WAY VALVE II COMMANDED TO WRONG POSITION
TRANSFER FROM GATE 31 ON PAGE 1
4 WAY VALVE II WRONG POSITION - LINE 29 CUT AT TIME = 4
GATE NUMBER 37
AND
1.670E-01
TIME = 4
PRIMAL EVENT 10
8.630E-05
4 WAY VALVE II CONTROL LINE 29 CUT
PRIMAL EVENT 12
HIGH WATER CONCENTRATION FROM BED II IN DRYING SERVICE
TRANSFER FROM GATE 10 ON PAGE 1
HIGH FLOW TO 4 WAY I WHICH CONNECTS STREAM 22 TO 23, AND 18 TO 19
GATE NUMBER 27
AND
HIGH FLOW TO 4 WAY VALVE I FROM FEED STREAM 22
GATE NUMBER 40
OR
5.000E-04
INLET AIR FLOW UP
PRIMAL EVENT 14
HIGH FLOWRATE IN PROPORTIONATING VALVE INLET [STREAM 7]
GATE NUMBER 56
OR
4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 4
TRANSFER TO GATE 54 ON PAGE 2
4 WAY VALVE I WRONG SIGNAL AT TIME = 3
GATE NUMBER 50
AND
2.000E-03
4 WAY VALVE LEAKS ACROSS
PRIMAL EVENT 1
1.000E-05
WATER SEPARATOR TRAP CLOGGED
PRIMAL EVENT 23
2.100E-03
VALVE 6 CLOSED
PRIMAL EVENT 24
3.300E-01
TIME = 3
PRIMAL EVENT 13
4.720E-06
4 WAY VALVE I TIMER CHANGES AT WRONG TIME
PRIMAL EVENT 20
1.670E-01
TIME = 4
PRIMAL EVENT 10
PAGE 11
SEQUENTIAL DRYER PROCESS

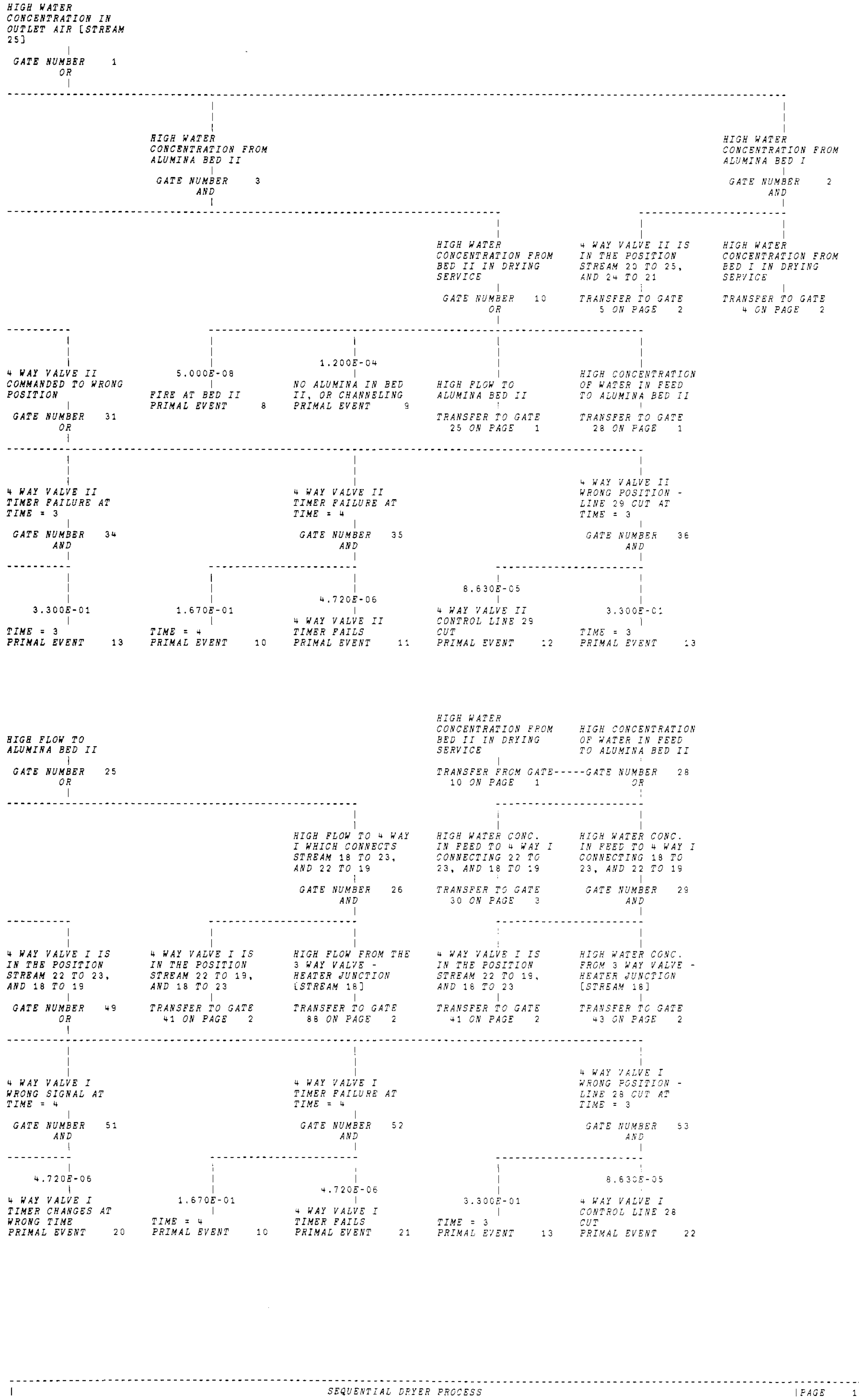
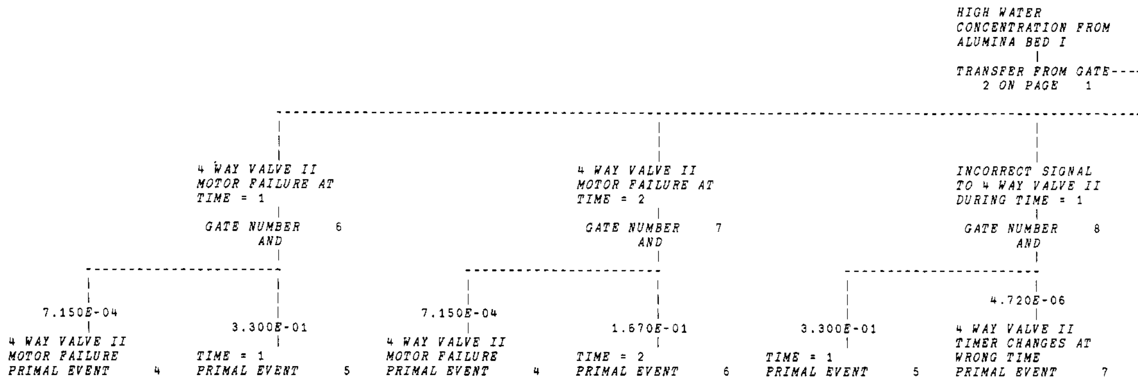
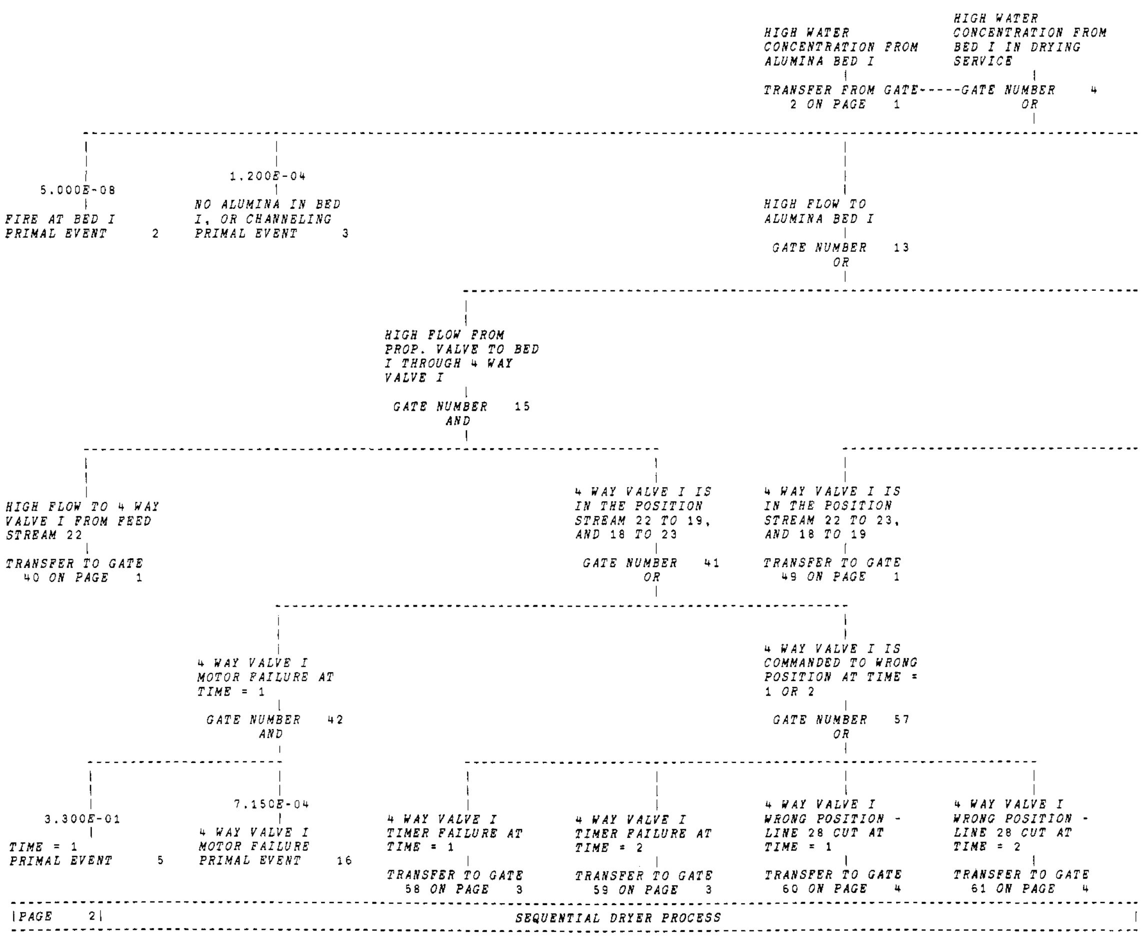


Figure 9 *continues*


HIGH WATER CONCENTRATION FROM ALUMINA BED I
TRANSFER FROM GATE---- 2 ON PAGE 1
4 WAY VALVE II MOTOR FAILURE AT TIME = 1
GATE NUMBER 6 AND
4 WAY VALVE II MOTOR FAILURE AT TIME = 2
GATE NUMBER 7 AND
INCORRECT SIGNAL TO 4 WAY VALVE II DURING TIME = 1
GATE NUMBER 8 AND
7.150E-04
4 WAY VALVE II MOTOR FAILURE PRIMAL EVENT 4
3.300E-01
TIME = 1 PRIMAL EVENT 5
7.150E-04
4 WAY VALVE II MOTOR FAILURE PRIMAL EVENT 4
1.670E-01
TIME = 2 PRIMAL EVENT 6
3.300E-01
TIME = 1 PRIMAL EVENT 5
4.720E-06
4 WAY VALVE II TIMER CHANGES AT WRONG TIME PRIMAL EVENT 7


HIGH WATER CONCENTRATION FROM ALUMINA BED I
TRANSFER FROM GATE-----GATE NUMBER 4
2 ON PAGE 1
HIGH WATER CONCENTRATION FROM BED I IN DRYING SERVICE
OR
5.000E-08
FIRE AT BED I PRIMAL EVENT 2
1.200E-04
NO ALUMINA IN BED I, OR CHANNELING PRIMAL EVENT 3
HIGH FLOW TO ALUMINA BED I
GATE NUMBER 13 OR
HIGH FLOW FROM PROP. VALVE TO BED I THROUGH 4 WAY VALVE I
GATE NUMBER 15 AND
HIGH FLOW TO 4 WAY VALVE I FROM FEED STREAM 22
TRANSFER TO GATE 40 ON PAGE 1
4 WAY VALVE I IS IN THE POSITION STREAM 22 TO 19, AND 18 TO 23
GATE NUMBER 41 OR
4 WAY VALVE I IS IN THE POSITION STREAM 22 TO 23, AND 18 TO 19
TRANSFER TO GATE 49 ON PAGE 1
4 WAY VALVE I MOTOR FAILURE AT TIME = 1
GATE NUMBER 42 AND
4 WAY VALVE I IS COMMANDED TO WRONG POSITION AT TIME = 1 OR 2
GATE NUMBER 57 OR
3.300E-01
TIME = 1 PRIMAL EVENT 5
7.150E-04
4 WAY VALVE I MOTOR FAILURE PRIMAL EVENT 16
4 WAY VALVE I TIMER FAILURE AT TIME = 1
TRANSFER TO GATE 58 ON PAGE 3
4 WAY VALVE I TIMER FAILURE AT TIME = 2
TRANSFER TO GATE 59 ON PAGE 3
4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 1
TRANSFER TO GATE 60 ON PAGE 4
4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 2
TRANSFER TO GATE 61 ON PAGE 4
PAGE 2
SEQUENTIAL DRYER PROCESS

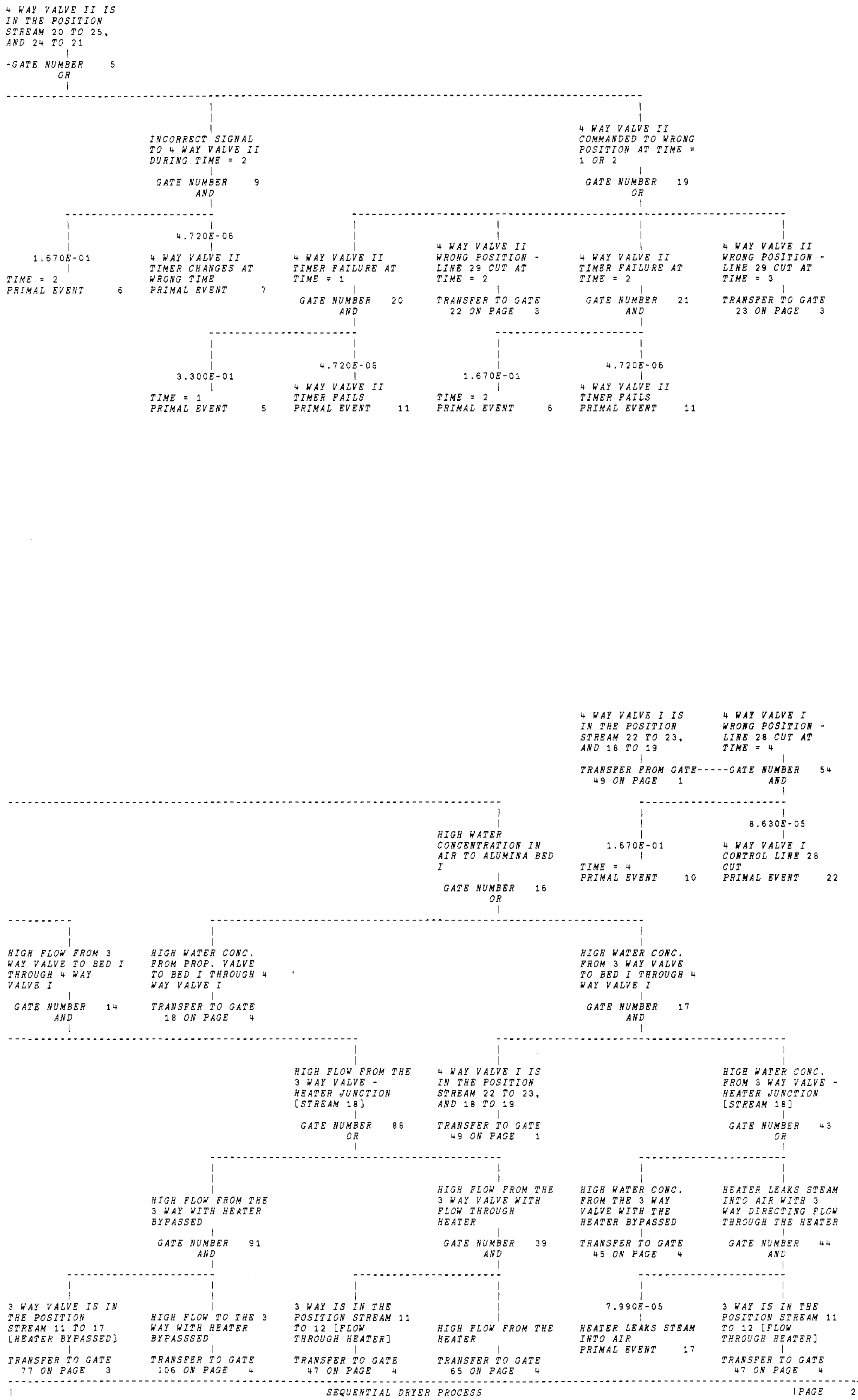


Figure 9 *continues*

```
HIGH CONCENTRATION
OF WATER IN FEED
TO ALUMINA BED II
TRANSFER FROM GATE
28 ON PAGE 1

HIGH WATER CONC.
IN FEED TO 4 WAY I
CONNECTING 22 TO
23, AND 18 TO 19
GATE NUMBER 30
AND

4 WAY VALVE II
COMMANDED TO WRONG
POSITION AT TIME =
1 OR 2
TRANSFER FROM GATE
19 ON PAGE 2

4 WAY VALVE II
WRONG POSITION -
LINE 29 CUT AT
TIME = 2
GATE NUMBER 22
AND

4 WAY VALVE II
COMMANDED TO WRONG
POSITION AT TIME =
1 OR 2
TRANSFER FROM GATE
19 ON PAGE 2

4 WAY VALVE I IS
IN THE POSITION
STREAM 22 TO 23,
AND 18 TO 19
TRANSFER TO GATE
49 ON PAGE 1

HIGH WATER CONC.
FROM PROP. VALVE
TO BED II THROUGH
4 WAY VALVE I
GATE NUMBER 46
OR

3.300E-01
TIME = 1
PRIMAL EVENT 5

8.630E-05
4 WAY VALVE II
CONTROL LINE 29
CUT
PRIMAL EVENT 12

1.670E-01
TIME = 2
PRIMAL EVENT 6

5.000E-04
INLET AIR WATER
CONCENTRATION UP
PRIMAL EVENT 18

HIGH WATER CONC.
IN PROPORTIONATING
VALVE INLET
[STREAM 7]
GATE NUMBER 64
OR

1.000E-05
WATER SEPARATOR
TRAP CLOGGED
PRIMAL EVENT 23

2.100E-03
VALVE 6 CLOSED
PRIMAL EVENT 24

5.000E-08
EXTERNAL FIRE AT
SEPARATOR
PRIMAL EVENT 25

HIGH TEMPERATURE
IN COOLER OUTLET
STREAM [STREAM 3]
GATE NUMBER 85
OR

HIGH PRESSURE IN
COOLER OUTLET
STREAM [STREAM 3]
TRANSFER TO GATE
86 ON PAGE 5

HIGH WATER
CONCENTRATION IN
COOLER OUTLET
STREAM [STREAM 3]
TRANSFER TO GATE
87 ON PAGE 6

2.000E-03
4 WAY VALVE LEAKS
ACROSS
PRIMAL EVENT 1

HIGH PRESSURE FROM
BED I WITH 4 WAY
II CONNECTING BED
I TO THE COOLER
GATE NUMBER 89
AND

5.000E-04
COOLING WATER FLOW
DOWN
PRIMAL EVENT 29

5.000E-04
COOLING WATER
TEMPERATURE UP
PRIMAL EVENT 30

2.990E-03
COOLER FOULED
PRIMAL EVENT 31

5.000E-08
EXTERNAL FIRE AT
COOLER
PRIMAL EVENT 32

4 WAY VALVE II IS
IN THE POSITION
STREAM 20 TO 21,
AND 24 TO 25
TRANSFER TO GATE
11 ON PAGE 1

HIGH PRESSURE IN
OUTLET STREAM FROM
ALUMINA BED I
GATE NUMBER 99
OR

HIGH FLOW FROM 3
WAY VALVE TO BED I
THROUGH 4 WAY
VALVE I
TRANSFER TO GATE
14 ON PAGE 2

HIGH PRESSURE FROM
3 WAY VALVE TO BED
I THROUGH 4 WAY
VALVE I
GATE NUMBER 107
AND

4 WAY VALVE I IS
IN THE POSITION
STREAM 22 TO 23,
AND 18 TO 19
TRANSFER TO GATE
49 ON PAGE 1

HIGH FLOW FROM THE
3 WAY VALVE -
HEATER JUNCTION
[STREAM 18]
GATE NUMBER 114
OR

HIGH PRESSURE IN
THE HEATER OUTLET
[STREAM 16]
TRANSFER TO GATE
115 ON PAGE 4

3 WAY VALVE IS IN
THE POSITION
STREAM 11 TO 17
[HEATER BYPASSED]
GATE NUMBER 77
OR

INCORRECT TIMER
SIGNAL TO THE 3
WAY VALVE AT TIME
= 3
GATE NUMBER 78
AND

3 WAY VALVE TIMER
FAILURE AT TIME =
1
GATE NUMBER 79
AND

3 WAY VALVE TIMER
FAILURE AT TIME =
3
GATE NUMBER 80
AND

3.300E-01
TIME = 3
PRIMAL EVENT 13

4.720E-06
3 WAY VALVE TIMER
CHANGES AT WRONG
TIME
PRIMAL EVENT 26

3.300E-01
TIME = 1
PRIMAL EVENT 5

4.720E-06
3 WAY VALVE TIMER
FAILS
PRIMAL EVENT 27

3.300E-01
TIME = 3
PRIMAL EVENT 13

4.720E-06
3 WAY VALVE TIMER
FAILS
PRIMAL EVENT 27

|PAGE 3|                SEQUENTIAL DRYER PROCESS
```

```
4 WAY VALVE II         4 WAY VALVE I IS                                4 WAY VALVE I IS
WRONG POSITION -       COMMANDED TO WRONG     4 WAY VALVE I            COMMANDED TO WRONG     4 WAY VALVE I
LINE 29 CUT AT         POSITION AT TIME =     TIMER FAILURE AT         POSITION AT TIME =     TIMER FAILURE AT
TIME = 3               1 OR 2                 TIME = 1                 1 OR 2                 TIME = 2
       |                     |                      |                        |                      |
-GATE NUMBER   23      TRANSFER FROM GATE-----GATE NUMBER   58         TRANSFER FROM GATE-----GATE NUMBER   59
     AND                 57 ON PAGE   2            AND                   57 ON PAGE   2            AND
      |                                             |                                               |
----------                   ------------------------                        ------------------------
      |                      |                      |                        |                      |
   8.630E-05                 |                      |                        |                      |
      |                      |                  4.720E-06                    |                  4.720E-06
4 WAY VALVE II           3.300E-01                  |                    1.670E-01                  |
CONTROL LINE 29              |                4 WAY VALVE I                  |                4 WAY VALVE I
CUT                    TIME = 1               TIMER FAILS              TIME = 2               TIMER FAILS
PRIMAL EVENT     12    PRIMAL EVENT      5    PRIMAL EVENT     21      PRIMAL EVENT      6    PRIMAL EVENT     21




----------
      |
      |
   2.100E-03
      |
VALVE 4 CLOSED
PRIMAL EVENT     33



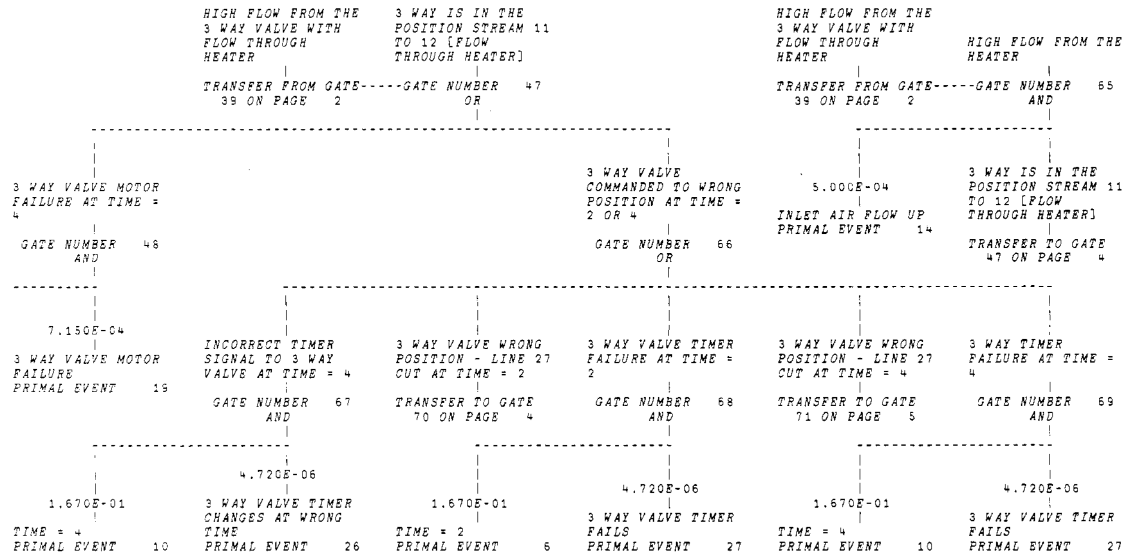

-------------------------------------------------------
                                                      |
                                                      |
                                              HIGH PRESSURE IN
                                              OUTLET FROM THE 3
                                              WAY VALVE WITH
                                              HEATER BYPASSED
                                                      |
                                               GATE NUMBER  116
                                                     AND
                                                      |
-----------------------------------------------------------------------------------------------------------------------------
                                                                                                                            |
                                                                                                                            |
                                                                                                                   HIGH PRESSURE IN
                                                                                                                   FEED TO THE 3 WAY
                                                                                                                   VALVE WITH HEATER
                                                                                                                   BYPASSED
                                                                                                                            |
                                                                                                                    GATE NUMBER  122
                                                                                                                          AND
                                                                                                                            |
-------------------------------------------------------------------------------------        ------------------------
                             |                                              |                        |                      |
                             |                                              |                        |                      |
                       3 WAY VALVE                                    3 WAY VALVE              3 WAY VALVE IS IN            |
                       CONTROL LINE [LINE                             CONTROL LINE [LINE       THE POSITION           HIGH PRESSURE IN
                       27] CUT AT TIME =                              27] CUT AT TIME =        STREAM 11 TO 17        FEED TO THE 3 WAY
                       1                                              3                        [HEATER BYPASSED]      VALVE [STREAM 11]
                             |                                              |                        |                      |
                        GATE NUMBER   81                               GATE NUMBER   82        TRANSFER TO GATE        GATE NUMBER  137
                             AND                                            AND                  77 ON PAGE   3             OR
                             |                                              |                                               |
          ------------------------                       ------------------------                    ------------------------
          |                      |                       |                      |                    |                      |
          |                  8.630E-05                   |                  8.630E-05                |                      |
          |                      |                       |                      |                5.000E-04                  |
   3.300E-01             3 WAY VALVE              3.300E-01              3 WAY VALVE                 |                HIGH PRESSURE IN
          |              CONTROL LINE 27                 |               CONTROL LINE 27       INLET AIR PRESSURE     PROPORTIONATING
TIME = 1                 CUT                     TIME = 3                CUT                   UP                     VALVE INLET
PRIMAL EVENT      5      PRIMAL EVENT     28     PRIMAL EVENT     13     PRIMAL EVENT     28   PRIMAL EVENT     36    [STREAM 7]
                                                                                                                            |
                                                                                                                      TRANSFER TO GATE
                                                                                                                       123 ON PAGE   5
--------------------------------------------------------------------------------------------------------------------------------------
|                                             SEQUENTIAL DRYER PROCESS                                                  |PAGE    3|
--------------------------------------------------------------------------------------------------------------------------------------
```

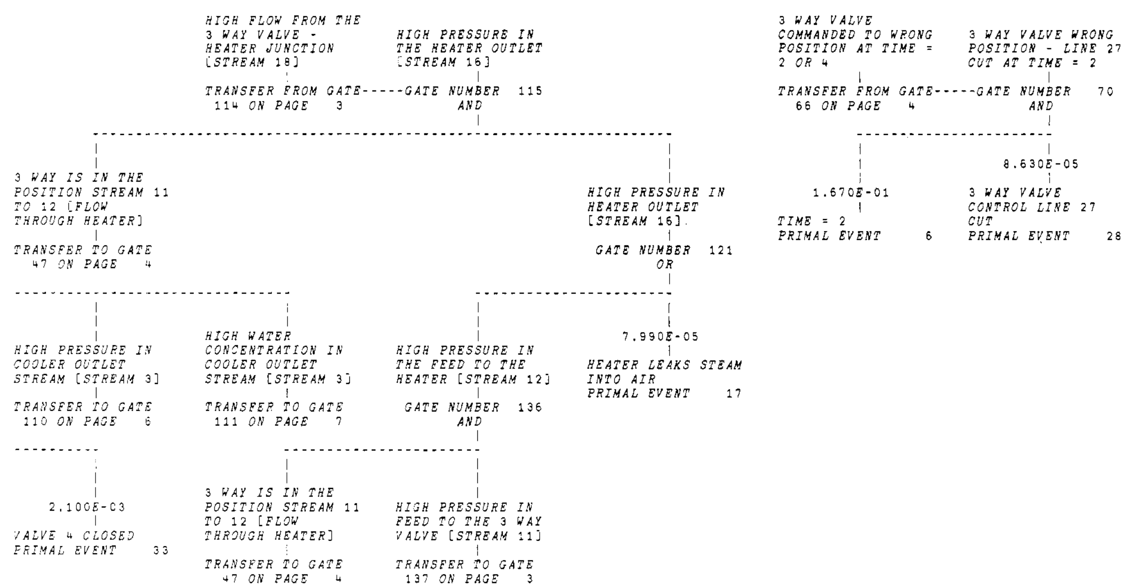
Figure 9 *continues*

```
4 WAY VALVE I IS    4 WAY VALVE I       4 WAY VALVE I IS    4 WAY VALVE I
COMMANDED TO WRONG  WRONG POSITION -    COMMANDED TO WRONG  WRONG POSITION -    HIGH FLOW FROM THE  HIGH FLOW TO THE 3
POSITION AT TIME =  LINE 28 CUT AT      POSITION AT TIME =  LINE 28 CUT AT      3 WAY WITH HEATER   WAY WITH HEATER
1 OR 2              TIME = 1            1 OR 2              TIME = 2            BYPASSED            BYPASSSED
      |                   |                   |                   |                   |                   |
TRANSFER FROM GATE-----GATE NUMBER  60  TRANSFER FROM GATE-----GATE NUMBER  61  TRANSFER FROM GATE-----GATE NUMBER  106
  57 ON PAGE   2         AND              57 ON PAGE   2         AND              91 ON PAGE   2         AND
                          |                                       |                                       |
         ----------------------                  ----------------------                  ----------------------
         |                |                      |                |                      |                |
         |           8.630E-05                   |           8.630E-05                   |                |
         |                |                      |                |                      |          3 WAY VALVE IS IN
    3.300E-01       4 WAY VALVE I           1.670E-01       4 WAY VALVE I           5.000E-04       THE POSITION
         |          CONTROL LINE 28              |          CONTROL LINE 28              |          STREAM 11 TO 17
TIME = 1            CUT                 TIME = 2            CUT                 INLET AIR FLOW UP   [HEATER BYPASSED]
PRIMAL EVENT    5   PRIMAL EVENT   22   PRIMAL EVENT    6   PRIMAL EVENT   22   PRIMAL EVENT   14         |
                                                                                                    TRANSFER TO GATE
                                                                                                      77 ON PAGE   3
                                                                                                          |
                                                                                                          -------------
                                                                                                          |
                                                                                                          |
                                                                                                      1.670E-01
                                                                                                          |
                                                                                                    TIME = 4
                                                                                                    PRIMAL EVENT   10




HIGH WATER CONC.    HIGH WATER CONC.                        HIGH WATER          HIGH WATER CONC.
FROM 3 WAY VALVE -  FROM THE 3 WAY                          CONCENTRATION IN    FROM PROP. VALVE
HEATER JUNCTION     VALVE WITH THE                          AIR TO ALUMINA BED  TO BED I THROUGH 4
[STREAM 18]         HEATER BYPASSED                         I                   WAY VALVE I
      |                   |                                       |                   |
TRANSFER FROM GATE-----GATE NUMBER  45                      TRANSFER FROM GATE-----GATE NUMBER  18
  43 ON PAGE   2         AND                                  16 ON PAGE   2         AND
                          |                                                           |
         ----------------------                  ------------------------------------------------------------
         |                |                      |                                                          |
         |                |                      |                                                          |
3 WAY VALVE IS IN   HIGH WATER          4 WAY VALVE I IS                                                HIGH WATER CONC.
THE POSITION        CONCENTRATION FROM  IN THE POSITION                                                 IN PROPORTIONATING
STREAM 11 TO 17     THE 3 WAY OUTLET    STREAM 22 TO 19,                                                VALVE INLET
[HEATER BYPASSED]   [STREAM 17]         AND 18 TO 23                                                    [STREAM 7]
      |                   |                   |                                                             |
TRANSFER TO GATE     GATE NUMBER  63    TRANSFER TO GATE                                                 GATE NUMBER  72
  77 ON PAGE   3         AND              41 ON PAGE   2                                                     OR
                          |                                                                                 |
         ----------------------                  --------------------------------------------------------------------------
         |                |                      |                  |                   |                   |
         |                |                      |                  |                   |                   |
    5.000E-04       3 WAY VALVE IS IN       1.000E-05               |                   |              5.000E-06
         |          THE POSITION                |             HIGH TEMPERATURE      2.100E-03               |
INLET AIR WATER     STREAM 11 TO 17     WATER SEPARATOR     IN COOLER OUTLET            |               EXTERNAL FIRE AT
CONCENTRATION UP    [HEATER BYPASSED]   TRAP CLOGGED        STREAM [STREAM 3]   VALVE 6 CLOSED      SEPARATOR
PRIMAL EVENT   19         |             PRIMAL EVENT   23         |             PRIMAL EVENT   24   PRIMAL EVENT   25
                    TRANSFER TO GATE                         GATE NUMBER  73
                      77 ON PAGE   3                             OR
                                                                  |
         ---------------------------------------------------------------------------------------------------------------
         |                |                   |                   |                   |                   |
         |                |                   |                   |                   |                   |
    2.000E-03       HIGH PRESSURE FROM  5.000E-04           5.000E-04                 |              5.000E-08
         |          BED II WITH 4 WAY         |                   |               2.990E-03               |
4 WAY VALVE LEAKS   II CONNECTING BED   COOLING WATER FLOW  COOLING WATER             |               EXTERNAL FIRE AT
ACROSS              II TO THE COOLER    DOWN                TEMPERATURE UP      COOLER FOULED       COOLER
PRIMAL EVENT    1         |             PRIMAL EVENT   29   PRIMAL EVENT   30   PRIMAL EVENT   31   PRIMAL EVENT   32
                     GATE NUMBER  74
                         AND
                          |
         ----------------------
         |                |
         |                |
4 WAY VALVE II IS         |
IN THE POSITION     HIGH PRESSURE IN
STREAM 20 TO 25,    OUTLET STREAM FROM
AND 24 TO 21        ALUMINA BED II
      |                   |
TRANSFER TO GATE     GATE NUMBER  75
  5 ON PAGE   2          OR
                          |
         ----------------------
         |                |
         |                |
HIGH FLOW TO 4 WAY  HIGH PRESSURE FROM
I WHICH CONNECTS    3 WAY VALVE TO BED
STREAM 18 TO 23,    II THROUGH 4 WAY
AND 22 TO 19        VALVE I
      |                   |
TRANSFER TO GATE    TRANSFER TO GATE
  26 ON PAGE   1      83 ON PAGE   5
------------------------------------------------------------------------------------------------------------------------
|PAGE    4|                                         SEQUENTIAL DRYER PROCESS
------------------------------------------------------------------------------------------------------------------------
```





SEQUENTIAL DRYER PROCESS |PAGE 4|

Figure 9 *continues*

HIGH PRESSURE IN FEED TO THE 3 WAY VALVE [STREAM 11]
TRANSFER FROM GATE 137 ON PAGE 3

HIGH PRESSURE IN PROPORTIONATING VALVE INLET [STREAM 7]
GATE NUMBER 123
OR

5.000E-06
EXTERNAL FIRE AT SEPARATOR
PRIMAL EVENT 25

HIGH TEMPERATURE IN THE COOLER OUTLET [STREAM 3]
GATE NUMBER 138
OR

2.000E-03
4 WAY VALVE LEAKS ACROSS
PRIMAL EVENT 1

5.000E-04
COOLING WATER FLOW DOWN
PRIMAL EVENT 29

5.000E-04
COOLING WATER TEMPERATURE UP
PRIMAL EVENT 30

2.990E-03
COOLER FOULED
PRIMAL EVENT 31

5.000E-08
EXTERNAL FIRE AT COOLER
PRIMAL EVENT 32

2.100E-03
VALVE 4 CLOSED
PRIMAL EVENT 33

4 WAY VALVE II IS IN THE POSITION STREAM 20 TO 21, AND 24 TO 25
TRANSFER TO GATE 11 ON PAGE 1

HIGH WATER CONC. IN PROPORTIONATING VALVE INLET [STREAM 7]
TRANSFER FROM GATE 64 ON PAGE 3

HIGH PRESSURE IN COOLER OUTLET STREAM [STREAM 3]
GATE NUMBER 86
OR

5.000E-04
COOLING WATER FLOW DOWN
PRIMAL EVENT 29

5.000E-04
COOLING WATER TEMPERATURE UP
PRIMAL EVENT 30

2.990E-03
COOLER FOULED
PRIMAL EVENT 31

5.000E-08
EXTERNAL FIRE AT COOLER
PRIMAL EVENT 32

2.100E-03
VALVE 4 CLOSED
PRIMAL EVENT 33

HIGH FLOW FROM BED I WITH 4 WAY II CONNECTING BED I TO THE COOLER
TRANSFER TO GATE 92 ON PAGE 5

HIGH PRESSURE IN FEED TO THE 3 WAY VALVE WITH HEATER BYPASSED
GATE NUMBER 96
AND

HIGH PRESSURE IN FEED TO THE 3 WAY VALVE [STREAM 11]
GATE NUMBER 97
OR

3 WAY VALVE IS IN THE POSITION STREAM 11 TO 17 [HEATER BYPASSED]
TRANSFER TO GATE 77 ON PAGE 3

5.000E-04
INLET AIR PRESSURE UP
PRIMAL EVENT 36

HIGH PRESSURE IN PROPORTIONATING VALVE INLET [STREAM 7]
TRANSFER TO GATE 98 ON PAGE 6

3 WAY IS IN THE POSITION STREAM 11 TO 12 [FLOW THROUGH HEATER]
TRANSFER TO GATE 47 ON PAGE 4

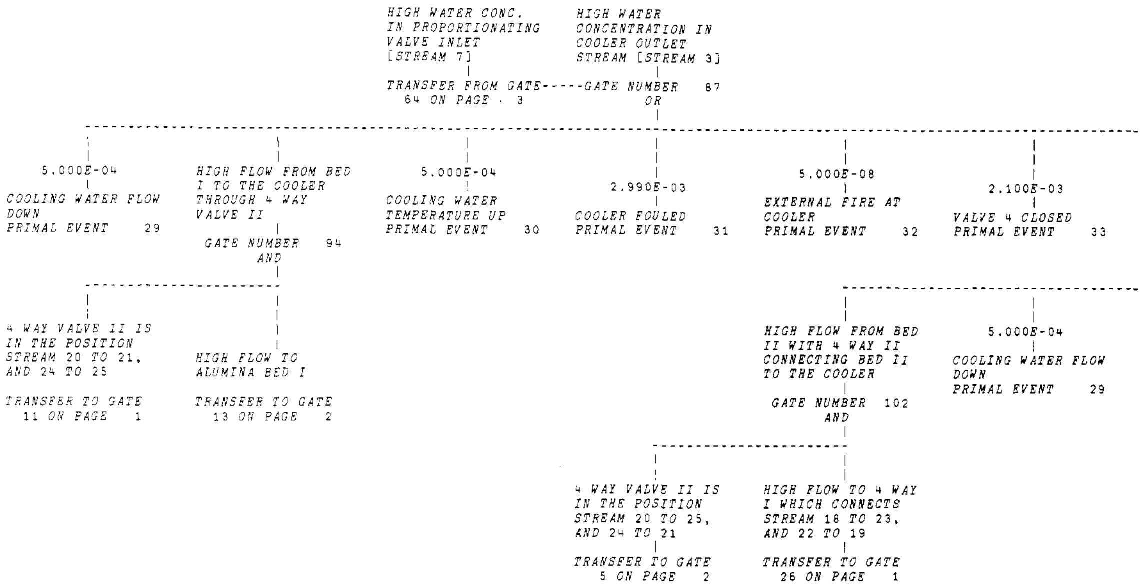
PAGE 51 SEQUENTIAL DRYER PROCESS

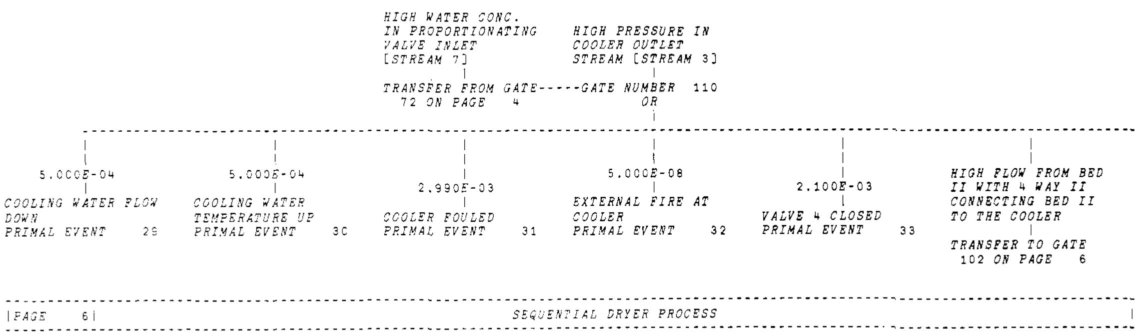
```
                                                                                3 WAY VALVE
                                                                                COMMANDED TO WRONG   3 WAY VALVE WRONG
                                                                                POSITION AT TIME =   POSITION - LINE 27
                                                                                2 OR 4               CUT AT TIME = 4
                                                                                     |                    |
                                                                                TRANSFER FROM GATE-----GATE NUMBER   71
                                                                                  66 ON PAGE   4          AND
                                                                                                           |
----------------------------------------------------------------------                -----------------------
                                                                     |                |                    |
                                                                     |                |               8.630E-05
                                                                     |                |                    |
                                                               HIGH PRESSURE IN   1.670E-01           3 WAY VALVE
                                                               THE COOLER OUTLET      |               CONTROL LINE 27
                                                               [STREAM 3]         TIME = 4            CUT
                                                                     |            PRIMAL EVENT   10   PRIMAL EVENT   26
                                                               GATE NUMBER  139
                                                                     OR
                                                                     |
      ----------------------------------------------------------------------------------------------------------
      |                   |                   |                   |                   |                   |
      |                   |                   |                   |                   |                   |
HIGH FLOW FROM BED    5.000E-04           5.000E-04               |               5.000E-08               |
I WITH 4 WAY II           |                   |               2.990E-03               |               2.100E-03
CONNECTING BED I    COOLING WATER FLOW  COOLING WATER             |               EXTERNAL FIRE AT        |
TO THE COOLER       DOWN                TEMPERATURE UP      COOLER FOULED       COOLER              VALVE 4 CLOSED
      |             PRIMAL EVENT   29   PRIMAL EVENT   30   PRIMAL EVENT   31   PRIMAL EVENT   32   PRIMAL EVENT   33
 GATE NUMBER   92
     AND
      |
----------
      |
      |
HIGH FLOW FROM 3
WAY VALVE TO BED I
THROUGH 4 WAY
VALVE I
      |
TRANSFER TO GATE
  14 ON PAGE   2

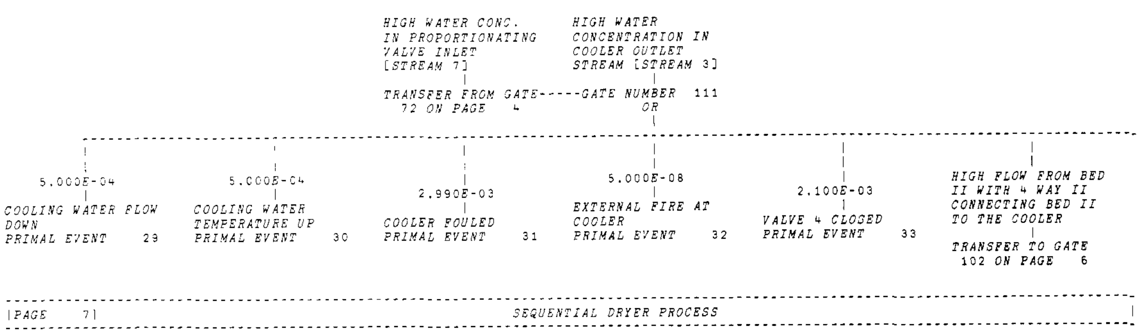



                                        HIGH PRESSURE FROM
                    HIGH PRESSURE IN    3 WAY VALVE TO BED
                    OUTLET STREAM FROM  II THROUGH 4 WAY
                    ALUMINA BED II      VALVE I
                          |                   |
                    TRANSFER FROM GATE-----GATE NUMBER   83
                      75 ON PAGE   4          AND
                                               |
----------                -----------------------
      |                   |                   |
      |                   |                   |
HIGH PRESSURE FROM  HIGH PRESSURE FROM  4 WAY VALVE I IS
BED I WITH 4 WAY    THE 3 WAY VALVE -   IN THE POSITION
II CONNECTING BED   HEATER JUNCTION     STREAM 22 TO 19,
I TO THE COOLER     [STREAM 18]         AND 18 TO 23
      |                   |                   |
TRANSFER TO GATE     GATE NUMBER   84   TRANSFER TO GATE
  89 ON PAGE   3          OR              41 ON PAGE   2
                          |
      -------------------------------------------
      |                                       |
      |                                       |
HIGH PRESSURE IN                              |
OUTLET FROM THE 3                       HIGH PRESSURE IN
WAY VALVE WITH                          THE HEATER OUTLET
HEATER BYPASSED                         [STREAM 16]
      |                                       |
 GATE NUMBER   95                        GATE NUMBER  103
     AND                                     AND
      |                                       |
----------                -----------------------
      |                   |                   |
      |                   |                   |
3 WAY VALVE IS IN         |             3 WAY IS IN THE
THE POSITION        HIGH PRESSURE IN    POSITION STREAM 11
STREAM 11 TO 17     THE HEATER OUTLET   TO 12 [FLOW
[HEATER BYPASSED]   [STREAM 16]         THROUGH HEATER]
      |                   |                   |
TRANSFER TO GATE     GATE NUMBER  104   TRANSFER TO GATE
  77 ON PAGE   3          OR              47 ON PAGE   4
                          |
      ---------------------
      |                   |
      |                   |
      |               7.990E-05
HIGH PRESSURE IN          |
THE FEED TO THE     HEATER LEAKS STEAM
HEATER [STREAM 12]  INTO AIR
      |             PRIMAL EVENT   17
 GATE NUMBER  105
     AND
      |
----------
      |
      |
      |
HIGH PRESSURE IN
FEED TO THE 3 WAY
VALVE [STREAM 11]
      |
TRANSFER TO GATE
  97 ON PAGE   5
------------------------------------------------------------------------------------------------------------------
|                                         SEQUENTIAL DRYER PROCESS                                       PAGE    5|
------------------------------------------------------------------------------------------------------------------
```

Figure 9 *continues*


HIGH WATER CONC. IN PROPORTIONATING VALVE INLET [STREAM 7]
HIGH WATER CONCENTRATION IN COOLER OUTLET STREAM [STREAM 3]
TRANSFER FROM GATE 64 ON PAGE 3
GATE NUMBER 87 OR
5.000E-04 COOLING WATER FLOW DOWN PRIMAL EVENT 29
HIGH FLOW FROM BED I TO THE COOLER THROUGH 4 WAY VALVE II
GATE NUMBER 94 AND
5.000E-04 COOLING WATER TEMPERATURE UP PRIMAL EVENT 30
2.990E-03 COOLER FOULED PRIMAL EVENT 31
5.000E-08 EXTERNAL FIRE AT COOLER PRIMAL EVENT 32
2.100E-03 VALVE 4 CLOSED PRIMAL EVENT 33
4 WAY VALVE II IS IN THE POSITION STREAM 20 TO 21, AND 24 TO 25
TRANSFER TO GATE 11 ON PAGE 1
HIGH FLOW TO ALUMINA BED I
TRANSFER TO GATE 13 ON PAGE 2
HIGH FLOW FROM BED II WITH 4 WAY II CONNECTING BED II TO THE COOLER
GATE NUMBER 102 AND
5.000E-04 COOLING WATER FLOW DOWN PRIMAL EVENT 29
4 WAY VALVE II IS IN THE POSITION STREAM 20 TO 25, AND 24 TO 21
TRANSFER TO GATE 5 ON PAGE 2
HIGH FLOW TO 4 WAY I WHICH CONNECTS STREAM 18 TO 23, AND 22 TO 19
TRANSFER TO GATE 26 ON PAGE 1


HIGH WATER CONC. IN PROPORTIONATING VALVE INLET [STREAM 7]
HIGH PRESSURE IN COOLER OUTLET STREAM [STREAM 3]
TRANSFER FROM GATE 72 ON PAGE 4
GATE NUMBER 110 OR
5.000E-04 COOLING WATER FLOW DOWN PRIMAL EVENT 29
5.000E-04 COOLING WATER TEMPERATURE UP PRIMAL EVENT 30
2.990E-03 COOLER FOULED PRIMAL EVENT 31
5.000E-08 EXTERNAL FIRE AT COOLER PRIMAL EVENT 32
2.100E-03 VALVE 4 CLOSED PRIMAL EVENT 33
HIGH FLOW FROM BED II WITH 4 WAY II CONNECTING BED II TO THE COOLER
TRANSFER TO GATE 102 ON PAGE 6
PAGE 6
SEQUENTIAL DRYER PROCESS


HIGH WATER CONC. IN PROPORTIONATING VALVE INLET [STREAM 7]
HIGH WATER CONCENTRATION IN COOLER OUTLET STREAM [STREAM 3]
TRANSFER FROM GATE 72 ON PAGE 4
GATE NUMBER 111 OR
5.000E-04 COOLING WATER FLOW DOWN PRIMAL EVENT 29
5.000E-04 COOLING WATER TEMPERATURE UP PRIMAL EVENT 30
2.990E-03 COOLER FOULED PRIMAL EVENT 31
5.000E-08 EXTERNAL FIRE AT COOLER PRIMAL EVENT 32
2.100E-03 VALVE 4 CLOSED PRIMAL EVENT 33
HIGH FLOW FROM BED II WITH 4 WAY II CONNECTING BED II TO THE COOLER
TRANSFER TO GATE 102 ON PAGE 6
PAGE 7
SEQUENTIAL DRYER PROCESS

```
                                          HIGH PRESSURE IN
                     HIGH PRESSURE IN     PROPORTIONATING
                     FEED TO THE 3 WAY    VALVE INLET
                     VALVE [STREAM 11]    [STREAM 7]
                           |                   |
                     TRANSFER FROM GATE-----GATE NUMBER   98
                       97 ON PAGE   5          OR
                                               |
----------                 ----------------------
         |                 |                   |
         |                 |                   |
HIGH PRESSURE FROM         |                   |
BED I WITH 4 WAY     HIGH PRESSURE IN     HIGH TEMPERATURE
II CONNECTING BED    THE COOLER OUTLET    IN THE COOLER
I TO THE COOLER      [STREAM 3]           OUTLET [STREAM 3]
         |                 |                   |
TRANSFER TO GATE      GATE NUMBER  101    TRANSFER TO GATE
  89 ON PAGE   3           OR               138 ON PAGE   5
-------------------------------------------------------------------
         |                 |                   |                   |
         |                 |                   |                   |
   5.000E-04               |               5.000E-06               |
         |             2.990E-03               |              2.100E-03
COOLING WATER              |              EXTERNAL FIRE AT         |
TEMPERATURE UP       COOLER FOULED        COOLER              VALVE 4 CLOSED
PRIMAL EVENT     30  PRIMAL EVENT     31  PRIMAL EVENT     32 PRIMAL EVENT     33
```

```
----------
         |
         |
HIGH PRESSURE FROM
BED II WITH 4 WAY
II CONNECTING BED
II TO THE COOLER
         |
TRANSFER TO GATE
  74 ON PAGE   4
```

```
-----------------------------------------------------------------------------------------
|                          SEQUENTIAL DRYER PROCESS                          |PAGE    6|
-----------------------------------------------------------------------------------------
```

```
----------
         |
         |
HIGH PRESSURE FROM
BED II WITH 4 WAY
II CONNECTING BED
II TO THE COOLER
         |
TRANSFER TO GATE
  74 ON PAGE   4
```

```
-----------------------------------------------------------------------------------------
|                          SEQUENTIAL DRYER PROCESS                          |PAGE    7|
-----------------------------------------------------------------------------------------
```

Figure 9 *continues*

GATE TABLE OF CONTENTS

TITLE: SEQUENTIAL DRYER PROCESS

GATE NUMBER	GATE TYPE	PROBABILITY	DEVELOPED ON PAGE	TEXT
1	OR		1	HIGH WATER CONCENTRATION IN OUTLET AIR [STREAM 25]
2	AND		1	HIGH WATER CONCENTRATION FROM ALUMINA BED I
3	AND		1	HIGH WATER CONCENTRATION FROM ALUMINA BED II
4	OR		2	HIGH WATER CONCENTRATION FROM BED I IN DRYING SERVICE
5	OR		2	4 WAY VALVE II IS IN THE POSITION STREAM 20 TO 25, AND 24 TO 21
6	AND		2	4 WAY VALVE II MOTOR FAILURE AT TIME = 1
7	AND		2	4 WAY VALVE II MOTOR FAILURE AT TIME = 2
8	AND		2	INCORRECT SIGNAL TO 4 WAY VALVE II DURING TIME = 1
9	AND		2	INCORRECT SIGNAL TO 4 WAY VALVE II DURING TIME = 2
10	OR		1	HIGH WATER CONCENTRATION FROM BED II IN DRYING SERVICE
11	OR		1	4 WAY VALVE II IS IN THE POSITION STREAM 20 TO 21, AND 24 TO 25
12	AND		1	4 WAY VALVE II MOTOR FAILURE AT TIME = 4
13	OR		2	HIGH FLOW TO ALUMINA BED I
14	AND		2	HIGH FLOW FROM 3 WAY VALVE TO BED I THROUGH 4 WAY VALVE I
15	AND		2	HIGH FLOW FROM PROP. VALVE TO BED I THROUGH 4 WAY VALVE I
16	OR		2	HIGH WATER CONCENTRATION IN AIR TO ALUMINA BED I
17	AND		2	HIGH WATER CONC. FROM 3 WAY VALVE TO BED I THROUGH 4 WAY VALVE I
18	AND		4	HIGH WATER CONC. FROM PROP. VALVE TO BED I THROUGH 4 WAY VALVE I
19	OR		2	4 WAY VALVE II COMMANDED TO WRONG POSITION AT TIME = 1 OR 2
20	AND		2	4 WAY VALVE II TIMER FAILURE AT TIME = 1
21	AND		2	4 WAY VALVE II TIMER FAILURE AT TIME = 2
22	AND		3	4 WAY VALVE II WRONG POSITION - LINE 29 CUT AT TIME = 2
23	AND		3	4 WAY VALVE II WRONG POSITION - LINE 29 CUT AT TIME = 3
25	OR		1	HIGH FLOW TO ALUMINA BED II
26	AND		1	HIGH FLOW TO 4 WAY I WHICH CONNECTS STREAM 18 TO 23, AND 22 TO 19
27	AND		1	HIGH FLOW TO 4 WAY I WHICH CONNECTS STREAM 22 TO 23, AND 18 TO 19
28	OR		1	HIGH CONCENTRATION OF WATER IN FEED TO ALUMINA BED II
29	AND		1	HIGH WATER CONC. IN FEED TO 4 WAY I CONNECTING 18 TO 23, AND 22 TO 19
30	AND		3	HIGH WATER CONC. IN FEED TO 4 WAY I CONNECTING 22 TO 23, AND 18 TO 19
31	OR		1	4 WAY VALVE II COMMANDED TO WRONG POSITION
32	AND		1	4 WAY VALVE II WRONG SIGNAL AT TIME = 3
33	AND		1	4 WAY VALVE II WRONG SIGNAL AT TIME = 4
34	AND		1	4 WAY VALVE II TIMER FAILURE AT TIME = 3
35	AND		1	4 WAY VALVE II TIMER FAILURE AT TIME = 4
36	AND		1	4 WAY VALVE II WRONG POSITION - LINE 29 CUT AT TIME = 3
37	AND		1	4 WAY VALVE II WRONG POSITION - LINE 29 CUT AT TIME = 4
39	AND		2	HIGH FLOW FROM THE 3 WAY VALVE WITH FLOW THROUGH HEATER
40	OR		1	HIGH FLOW TO 4 WAY VALVE I FROM FEED STREAM 22
41	OR		2	4 WAY VALVE I IS IN THE POSITION STREAM 22 TO 19, AND 18 TO 23
42	AND		2	4 WAY VALVE I MOTOR FAILURE AT TIME = 1
43	OR		2	HIGH WATER CONC. FROM 3 WAY VALVE - HEATER JUNCTION [STREAM 18]
44	AND		2	HEATER LEAKS STEAM INTO AIR WITH 3 WAY DIRECTING FLOW THROUGH THE HEATER
45	AND		4	HIGH WATER CONC. FROM THE 3 WAY VALVE WITH THE HEATER BYPASSED
46	OR		3	HIGH WATER CONC. FROM PROP. VALVE TO BED II THROUGH 4 WAY VALVE I
47	OR		4	3 WAY IS IN THE POSITION STREAM 11 TO 12 [FLOW THROUGH HEATER]
48	AND		4	3 WAY VALVE MOTOR FAILURE AT TIME = 4
49	OR		1	4 WAY VALVE I IS IN THE POSITION STREAM 22 TO 23, AND 18 TO 19
50	AND		1	4 WAY VALVE I WRONG SIGNAL AT TIME = 3
51	AND		1	4 WAY VALVE I WRONG SIGNAL AT TIME = 4
52	AND		1	4 WAY VALVE I TIMER FAILURE AT TIME = 4
53	AND		1	4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 3
54	AND		2	4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 4
56	OR		1	HIGH FLOWRATE IN PROPORTIONATING VALVE INLET [STREAM 7]
57	OR		2	4 WAY VALVE I IS COMMANDED TO WRONG POSITION AT TIME = 1 OR 2
58	AND		3	4 WAY VALVE I TIMER FAILURE AT TIME = 1
59	AND		3	4 WAY VALVE I TIMER FAILURE AT TIME = 2
60	AND		4	4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 1
61	AND		4	4 WAY VALVE I WRONG POSITION - LINE 28 CUT AT TIME = 2
63	AND		4	HIGH WATER CONCENTRATION FROM THE 3 WAY OUTLET [STREAM 17]
64	OR		3	HIGH WATER CONC. IN PROPORTIONATING VALVE INLET [STREAM 7]
65	AND		4	HIGH FLOW FROM THE HEATER

GATE TABLE OF CONTENTS

TITLE: SEQUENTIAL DRYER PROCESS

GATE NUMBER	GATE TYPE	PROBABILITY	DEVELOPED ON PAGE	TEXT
66	OR		4	3 WAY VALVE COMMANDED TO WRONG POSITION AT TIME = 2 OR 4
67	AND		4	INCORRECT TIMER SIGNAL TO 3 WAY VALVE AT TIME = 4
68	AND		4	3 WAY VALVE TIMER FAILURE AT TIME = 2
69	AND		4	3 WAY TIMER FAILURE AT TIME = 4
70	AND		4	3 WAY VALVE WRONG POSITION - LINE 27 CUT AT TIME = 2
71	AND		5	3 WAY VALVE WRONG POSITION - LINE 27 CUT AT TIME = 4
72	OR		4	HIGH WATER CONC. IN PROPORTIONATING VALVE INLET [STREAM 7]
73	OR		4	HIGH TEMPERATURE IN COOLER OUTLET STREAM [STREAM 3]
74	AND		4	HIGH PRESSURE FROM BED II WITH 4 WAY II CONNECTING BED II TO THE COOLER
75	OR		4	HIGH PRESSURE IN OUTLET STREAM FROM ALUMINA BED II
77	OR		3	3 WAY VALVE IS IN THE POSITION STREAM 11 TO 17 [HEATER BYPASSED]
78	AND		3	INCORRECT TIMER SIGNAL TO THE 3 WAY VALVE AT TIME = 3
79	AND		3	3 WAY VALVE TIMER FAILURE AT TIME = 1
80	AND		3	3 WAY VALVE TIMER FAILURE AT TIME = 3
81	AND		3	3 WAY VALVE CONTROL LINE [LINE 27] CUT AT TIME = 1
82	AND		3	3 WAY VALVE CONTROL LINE [LINE 27] CUT AT TIME = 3
83	AND		5	HIGH PRESSURE FROM 3 WAY VALVE TO BED II THROUGH 4 WAY VALVE I
84	OR		5	HIGH PRESSURE FROM THE 3 WAY VALVE - HEATER JUNCTION [STREAM 18]
85	OR		3	HIGH TEMPERATURE IN COOLER OUTLET STREAM [STREAM 3]
86	OR		5	HIGH PRESSURE IN COOLER OUTLET STREAM [STREAM 3]
87	OR		6	HIGH WATER CONCENTRATION IN COOLER OUTLET STREAM [STREAM 3]
88	OR		2	HIGH FLOW FROM THE 3 WAY VALVE - HEATER JUNCTION [STREAM 18]
89	AND		3	HIGH PRESSURE FROM BED I WITH 4 WAY II CONNECTING BED I TO THE COOLER
91	AND		2	HIGH FLOW FROM THE 3 WAY WITH HEATER BYPASSED
92	AND		5	HIGH FLOW FROM BED I WITH 4 WAY II CONNECTING BED I TO THE COOLER
94	AND		6	HIGH FLOW FROM BED I TO THE COOLER THROUGH 4 WAY VALVE II
95	AND		5	HIGH PRESSURE IN OUTLET FROM THE 3 WAY VALVE WITH HEATER BYPASSED
96	AND		5	HIGH PRESSURE IN FEED TO THE 3 WAY VALVE WITH HEATER BYPASSED
97	OR		5	HIGH PRESSURE IN FEED TO THE 3 WAY VALVE [STREAM 11]
98	OR		6	HIGH PRESSURE IN PROPORTIONATING VALVE INLET [STREAM 7]
99	OR		3	HIGH PRESSURE IN OUTLET STREAM FROM ALUMINA BED I
101	OR		6	HIGH PRESSURE IN THE COOLER OUTLET [STREAM 3]
102	AND		6	HIGH FLOW FROM BED II WITH 4 WAY II CONNECTING BED II TO THE COOLER
103	AND		5	HIGH PRESSURE IN THE HEATER OUTLET [STREAM 16]
104	OR		5	HIGH PRESSURE IN THE HEATER OUTLET [STREAM 16]
105	AND		5	HIGH PRESSURE IN THE FEED TO THE HEATER [STREAM 12]
106	AND		4	HIGH FLOW TO THE 3 WAY WITH HEATER BYPASSSED
107	AND		3	HIGH PRESSURE FROM 3 WAY VALVE TO BED I THROUGH 4 WAY VALVE I
110	OR		6	HIGH PRESSURE IN COOLER OUTLET STREAM [STREAM 3]
111	OR		7	HIGH WATER CONCENTRATION IN COOLER OUTLET STREAM [STREAM 3]
114	OR		3	HIGH FLOW FROM THE 3 WAY VALVE - HEATER JUNCTION [STREAM 18]
115	AND		4	HIGH PRESSURE IN THE HEATER OUTLET [STREAM 16]
116	AND		3	HIGH PRESSURE IN OUTLET FROM THE 3 WAY VALVE WITH HEATER BYPASSED
121	OR		4	HIGH PRESSURE IN HEATER OUTLET [STREAM 16]
122	AND		3	HIGH PRESSURE IN FEED TO THE 3 WAY VALVE WITH HEATER BYPASSED
123	OR		5	HIGH PRESSURE IN PROPORTIONATING VALVE INLET [STREAM 7]
136	AND		4	HIGH PRESSURE IN THE FEED TO THE HEATER [STREAM 12]
137	OR		3	HIGH PRESSURE IN FEED TO THE 3 WAY VALVE [STREAM 11]
138	OR		5	HIGH TEMPERATURE IN THE COOLER OUTLET [STREAM 3]
139	OR		5	HIGH PRESSURE IN THE COOLER OUTLET [STREAM 3]

Figure 9 *continues*

EVENT TABLE OF CONTENTS

TITLE: SEQUENTIAL DRYER PROCESS

EVENT NUMBER	PROBABILITY	DEVELOPED ON PAGE	TEXT
1	2.000E-03	1	4 WAY VALVE LEAKS ACROSS
2	5.000E-08	2	FIRE AT BED I
3	1.200E-04	2	NO ALUMINA IN BED I, OR CHANNELING
4	7.150E-04	1	4 WAY VALVE II MOTOR FAILURE
5	3.300E-01	2	TIME = 1
6	1.670E-01	2	TIME = 2
7	4.720E-06	1	4 WAY VALVE II TIMER CHANGES AT WRONG TIME
8	5.000E-08	1	FIRE AT BED II
9	1.200E-04	1	NO ALUMINA IN BED II, OR CHANNELING
10	1.670E-01	1	TIME = 4
11	4.720E-06	1	4 WAY VALVE II TIMER FAILS
12	8.630E-05	1	4 WAY VALVE II CONTROL LINE 29 CUT
13	3.300E-01	1	TIME = 3
14	5.000E-04	1	INLET AIR FLOW UP
16	7.150E-04	2	4 WAY VALVE I MOTOR FAILURE
17	7.990E-05	2	HEATER LEAKS STEAM INTO AIR
18	5.000E-04	3	INLET AIR WATER CONCENTRATION UP
19	7.150E-04	4	3 WAY VALVE MOTOR FAILURE
20	4.720E-06	1	4 WAY VALVE I TIMER CHANGES AT WRONG TIME
21	4.720E-06	1	4 WAY VALVE I TIMER FAILS
22	8.630E-05	1	4 WAY VALVE I CONTROL LINE 28 CUT
23	1.000E-05	1	WATER SEPARATOR TRAP CLOGGED
24	2.100E-03	1	VALVE 6 CLOSED
25	5.000E-08	3	EXTERNAL FIRE AT SEPARATOR
26	4.720E-06	3	3 WAY VALVE TIMER CHANGES AT WRONG TIME
27	4.720E-06	3	3 WA. VALVE TIMER FAILS
28	8.630E-05	3	3 WAY VALVE CONTROL LINE 27 CUT
29	5.000E-04	3	COOLING WATER FLOW DOWN
30	5.000E-04	3	COOLING WATER TEMPERATURE UP
31	2.990E-03	3	COOLER FOULED
32	5.000E-08	3	EXTERNAL FIRE AT COOLER
33	2.100E-03	3	VALVE 4 CLOSED
36	5.000E-04	3	INLET AIR PRESSURE UP

Figure 9. The fault tree for the event water concentration too high from the utility air dryer process.

the structure of the digraph. It is not necessary for the analyst to preordain the logic (AND, OR, etc.) of the interactions between variables.

With this type of model all foreseeable interactions may be described. What remains is to interconnect the digraph model for each piece of equipment in the system to obtain a model for the complete system. Figure 4 shows a partial digraph for the heat exchanger system shown in Figure 1. From the digraph model, fault trees may be directly deduced. The algorithm for this deduction has been described previously (Lapp, 1977). Briefly, the procedure involves starting at the node in the digraph which denotes the top event. The negative feedforward and feedback loops through a node determine how it should be logically related to its inputs. The algorithm has over 30 different logical expansions of a node. The input nodes are logically expanded in a similar manner until the complete fault tree is obtained. The consistency of intermediate events and variables is maintained during the generation of the fault tree.

After generation of the fault tree, the tree is listed, "drawn" on a line printer, and put in minimal cut-set form. The minimal cut-sets of a Boolean equation are the sets of events which are sufficient to cause the top event and do not contain any other sufficient sets of events. The fault tree for the event temperature in stream 4 (T4) too high is given in Figure 5.

The following example illustrates the application of this strategy to a sequential process for drying air.

Example: Fixed Bed Alumina Air Dryers. Figure 6 illustrates a process for drying air. Ambient air which contains water vapor enters in stream 9. The air passes through a bed of alumina (Bed I) where the water vapor is adsorbed. The dried air passes out of the process in stream 25. This process has been used by Professor C. J. King of the Department of Chemical Engineering, University of California, Berkeley, Calif., as a case study in process design.

In order to maintain a continuous supply of dry air, two beds of alumina are employed. When one bed is removing water from the inlet air, the other bed is being regenerated. Regeneration involves passing hot air through a bed which has been loaded to capacity with water. The hot air strips the water from the alumina. The hot air leaving the regenerating bed is passed through a condenser where water is removed. The air is reheated and passed through the operating dryer. The regenerated bed is then cooled with inlet air and switched back into service. The same procedure is followed for the other bed. Table I gives the sequence of operations for a complete cycle.

If the outlet air from the process contains too much water a number of pieces of valuable equipment downstream may be destroyed. What could cause the water concentration in stream 25 to be too high? One way to answer this question is to construct a fault tree for the event concentration of water too high in stream 25 (C (+1) Stream 25).

Input–output models for several of the pieces of equipment

Table III. Minimal Cut Sets

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PROBLEM ID:  SEQUENTIAL DRYER PROCESS

          162 MINIMAL CUT SETS GENERATED.

          TOP EVENT PROBABILITY= 2.0001E-03

MINIMAL CUT SET NO.      1          ITS PROBABILITY:    2.00E-03
 EVENT       1( 2.00E-03) 4 WAY VALVE LEAKS ACROSS

MINIMAL CUT SET NO.      2          ITS PROBABILITY:    2.83E-08
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       5( 3.30E-01) TIME = 1

MINIMAL CUT SET NO.      3          ITS PROBABILITY:    1.43E-08
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       6( 1.67E-01) TIME = 2

MINIMAL CUT SET NO.      4          ITS PROBABILITY:    1.43E-08
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      10( 1.67E-01) TIME = 4

MINIMAL CUT SET NO.      5          ITS PROBABILITY:    3.42E-09
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       5( 3.30E-01) TIME = 1
 EVENT      12( 8.63E-05) 4 WAY VALVE II CONTROL LINE 29 CUT

MINIMAL CUT SET NO.      6          ITS PROBABILITY:    3.42E-09
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      12( 8.63E-05) 4 WAY VALVE II CONTROL LINE 29 CUT
 EVENT      13( 3.30E-01) TIME = 3

MINIMAL CUT SET NO.      7          ITS PROBABILITY:    1.73E-09
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      10( 1.67E-01) TIME = 4
 EVENT      12( 8.63E-05) 4 WAY VALVE II CONTROL LINE 29 CUT

MINIMAL CUT SET NO.      8          ITS PROBABILITY:    1.73E-09
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       6( 1.67E-01) TIME = 2
 EVENT      12( 8.63E-05) 4 WAY VALVE II CONTROL LINE 29 CUT

MINIMAL CUT SET NO.      9          ITS PROBABILITY:    5.04E-10
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       5( 3.30E-01) TIME = 1
 EVENT      16( 7.15E-04) 4 WAY VALVE I MOTOR FAILURE
 EVENT      31( 2.99E-03) COOLER FOULED

MINIMAL CUT SET NO.     10          ITS PROBABILITY:    3.54E-10
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       5( 3.30E-01) TIME = 1
 EVENT      16( 7.15E-04) 4 WAY VALVE I MOTOR FAILURE
 EVENT      24( 2.10E-03) VALVE 6 CLOSED

MINIMAL CUT SET NO.     11          ITS PROBABILITY:    3.54E-10
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       5( 3.30E-01) TIME = 1
 EVENT      16( 7.15E-04) 4 WAY VALVE I MOTOR FAILURE
 EVENT      33( 2.10E-03) VALVE 4 CLOSED

MINIMAL CUT SET NO.     12          ITS PROBABILITY:    1.87E-10
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       5( 3.30E-01) TIME = 1
 EVENT      11( 4.72E-06) 4 WAY VALVE II TIMER FAILS

MINIMAL CUT SET NO.     13          ITS PROBABILITY:    1.87E-10
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       5( 3.30E-01) TIME = 1
 EVENT       7( 4.72E-06) 4WAY VALVE II TIMER CHANGES AT WRONG
                          TIME

MINIMAL CUT SET NO.     14          ITS PROBABILITY:    1.87E-10
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      11( 4.72E-06) 4 WAY VALVE II TIMER FAILS
 EVENT      13( 3.30E-01) TIME = 3

MINIMAL CUT SET NO.     15          ITS PROBABILITY:    1.87E-10
 EVENT       7( 4.72E-06) 4WAY VALVE II TIMER CHANGES AT WRONG
                          TIME
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      13( 3.30E-01) TIME = 3

MINIMAL CUT SET NO.     16          ITS PROBABILITY:    9.46E-11
 EVENT       7( 4.72E-06) 4WAY VALVE II TIMER CHANGES AT WRONG
                          TIME
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      10( 1.67E-01) TIME = 4

MINIMAL CUT SET NO.     17          ITS PROBABILITY:    9.46E-11
 EVENT       9( 1.20E-04) NO ALUMINA IN BED II, OR CHANNELING
 EVENT      10( 1.67E-01) TIME = 4
 EVENT      11( 4.72E-06) 4 WAY VALVE II TIMER FAILS

MINIMAL CUT SET NO.     18          ITS PROBABILITY:    9.46E-11
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       6( 1.67E-01) TIME = 2
 EVENT      11( 4.72E-06) 4 WAY VALVE II TIMER FAILS

MINIMAL CUT SET NO.     19          ITS PROBABILITY:    9.46E-11
 EVENT       3( 1.20E-04) NO ALUMINA IN BED I, OR CHANNELING
 EVENT       6( 1.67E-01) TIME = 2
 EVENT       7( 4.72E-06) 4WAY VALVE II TIMER CHANGES AT WRONG
                          TIME

MINIMAL CUT SET NO.     20          ITS PROBABILITY:    8.44E-11
 EVENT       4( 7.15E-04) 4 WAY VALVE II MOTOR FAILURE
 EVENT       5( 3.30E-01) TIME = 1
 EVENT      16( 7.15E-04) 4 WAY VALVE I MOTOR FAILURE
 EVENT      30( 5.00E-04) COOLING WATER TEMPERATURE UP
```

in the system are given in Figure 7. Note the time dependent nature of the three-way valve, four-way valves, and the timer. The input–output models were interconnected to give a digraph model for the dryer system. The complete digraph for this system contained 67 nodes and 439 edges. A reduced version of the digraph is shown in Figure 8. Only the main concentration and flow interactions are shown.

The fault tree generation algorithm required 30 s of IBM 360/67 time to generate the fault tree for this system. The tree contains 143 gates and is shown in Figure 9. This tree is different from the usual fault tree in that common events such as time periods are considered.

Probability data were gathered and estimated for the events included in the tree. Table II presents the data. Over 100 cut-sets were computed for the tree. The first twenty are presented in Table III.

An analysis of the cut-sets for this system indicates the importance of leaking of the four-way valve. The results of this fault tree analysis in conjunction with economic considerations of the dryer operation and other possible design or maintenance corrections can be used to decide an appropriate action.

Conclusions

With digraph models that contain edges that depend on other variables and events, it is possible to include common sequential behavior in a system digraph. This allows the generation of a fault tree that contains events (like the sequence of valve operations) that are normally true. The analysis of the minimal cut-sets that result from this fault tree allows the analyst to focus attention on the important parts of the system.

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