INDIAN POINT 3
RECIRCULATION SYSTEM

A. SUMMARY

A.1 INTRODUCTION

The recirculation phase is evaluated in the context of a loss of coolant accident (LOCA). This phase calls for the combined operation of several systems and components--the residual heat removal system (RHRS), the containment sump, the recirculation sump and pumps, the safety injection system (SIS), and containment spray nozzles. For ease of reference, we call this group the recirculation system. This system is initiated by the operators when the water level in the refueling water storage tank (RWST) is at "low level" alarm point. The function of this system is to provide long-term core cooling and containment spray for a LOCA of any break size. For core cooling, the system can be operated in three different modes: high pressure, low pressure, and hot leg recirculation.

The analysis is carried out under the following conditions:

- Reactor trip has been successful (small LOCA).
- Injection phase has been completed successfully.
- System is analyzed for 24 hours.
- One heat exchanger can provide sufficient cooling.
- Success of the low head recirculation is defined as one low pressure pump supplying cooling water to the core for 24 hours.
- Success of the high head recirculation is defined as one safety injection pump supplying cooling to the core for 24 hours.
- Success of the containment spray recirculation is defined as one low head pump supplying water to one spray header.
- Success of the hot leg recirculation is defined as one safety injection pump supplying water to one hot leg.

A.2 RESULTS

In a small LOCA, core cooling recirculation via the safety injection (SI) pumps (hi-head recirculation) should be available. The other functions (containment spray, lo-head, and hot leg recirculation) are not necessary. Hi-head recirculation is analyzed under several conditions depending on the availability of fan coolers, the component cooling water system (CCS), and necessary electrical power supplies. The component cooling system provides the cooling water for the residual heat removal (RHR) heat exchanger. If the CCS is unavailable, the

containment fan coolers would remove the decay heat by condensing the steam generated in the core. Table 1 summarizes the boundary conditions and the results. For some respresentative cases a list of dominant contributors follows:

Hi-Head Recirculation (Small LOCA)

- With Power On All Buses, Fan Coolers Unavailable, and Component Cooling Available

	Mean
- Operator Error	3.90×10^{-4} (10%)
- All three SI pumps fail during the 24 hours	3.11×10^{-3} (76%)

- With Power on Bus 5A lost, Fan Coolers Unavailable, and Component Cooling Available

Single Failures	Mean
- MOV 1802B fails to open	1.5×10^{-3} (13%)
- MOV 822B fails to open	1.5×10^{-3} (13%)

Double Failures

- Both SI pumps (32 and 33) fail during the 24 hours	7.1×10^{-3} (62%)

In Table 1 the WASH-1400 results are quoted for comparison. However, their high pressure recirculation system (HPRS) is quite different from the hi-head recirculation system analyzed here.

The following functions should be available in a large LOCA: core cooling recirculation via the low pressure headers, containment spray, and hot leg recirculation. Part of the recirculation flow is directed into the hot legs (24 hours after the accident) in the hot leg recirculation mode. These functions are analyzed under several conditions similar to those analyzed for the hi-head recirculation, i.e., availability of fan coolers, CCS, and electric power. Tables 2 through 4 summarize the results for each case. Similar to Table 1, the WASH-1400 results are quoted for comparison. For some representative cases, a list of dominant contributors follows:

Low-Head Recirculation (Large or Medium LOCA)

- With Power On All Buses, Fan Coolers Unavailable, and Component Cooling Available

	Mean
- Operator Error	1.5×10^{-3} (99%)

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- With Power On Bus 5A Lost, Fan Coolers Unavailable, and Component Cooling Available

	Mean
- Operator error	3.9×10^{-2} (89%)
- Recirculation pump 31 fails to start	1.4×10^{-3} (3%)
- MOV 1802A fails to open	1.5×10^{-3} (3%)
- MOV 822A fails to open	1.5×10^{-3} (3%)

Containment Spray Recirculation (Large or Medium LOCA)

- With Power On All Buses

- Operator error	1.5×10^{-3} (99%)

- With Power On Bus 5A Lost

- Operator error	1.5×10^{-3} (50%)
- MOV 889B fails to open	1.5×10^{-3} (50%)

Hot Leg Recirculation (Large or Medium LOCA)

- With Power On All Buses

- MOVs 856B and 856G fail to open	2.6×10^{-5} (100%)

- With Power On Bus 5A Lost

- MOV 856B fails to open	1.5×10^{-3}

A.3 CONCLUSIONS

Operator error in activating the recirculation phase was found to be an important contributor in almost all cases that are analyzed here. Failure to initiate switchover is the main component of this failure mode. Hi-head recirculation is an exception, because the unavailability of the SI pumps due to hardware failures dominate system unreliability. In all cases the unavailability of electrical bus 5A (or 6A) has significant impact on system unreliability. However, in most cases, the simultaneous loss of both electrical buses 2A and 3A leads to a slight increase in system unreliability. Also, in most cases, the effect of fan cooler availability is insignificant.

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B. SYSTEM DESCRIPTION

B.1 PURPOSE OF THE SYSTEM

The function of the recirculation system is to provide long-term core cooling and containment spray after a loss of coolant accident (LOCA) of any break size. It recirculates the sump water back into the core and/or spray nozzles after cooling it in the RHR heat exchangers.

B.2 SYSTEM DIAGRAMS

Figures 1 and 2 show a block diagram and a piping and instrumentation diagram (P&ID) of this system. The P&ID is simplified, i.e., branching pipes with less than half the diameter of the originating pipe, such as miniflow lines, are not shown because loss of flow into these lines would not cause insufficient flow in the system.

B.3 SYSTEM CONFIGURATION AND OPERATION

B.3.1 System Configuration

The recirculation system is the combination of several systems and components. These include the RHRS, the containment sump, the recirculation sump and pumps, and the SIS. The recirculation sump is covered with gratings, screens, and baffles to clear the water of debris (particles greater than 1/4-inch) and reduce water velocity to minimize debris carryover. Water level in the sump is monitored in the control room on the safeguards panel. A drainage trench also carries the water to the sumps. The containment sump is separate from the recirculation sump and is located inside the missile barrier.

The two recirculation pumps are of vertical, centrifugal type with 3,000 gpm capacity at approximately 150 psig. The pumps are driven by 350 hp electric motors which have air-to-water heat exchangers. The motors are more than 2 feet above the highest anticipated water level. The water to these heat exchangers is supplied by the auxiliary component cooling pumps (booster pumps) or the main component cooling loop. The booster pumps are started by the safety injection signal in order to protect the motors of the recirculation pumps from possible damage caused by moisture or high temperature from containment conditions prior to, and following, the switchover to recirculation.

The RHR heat exchangers are of the vertical shell and U-tube design. The shell side contains the cooling medium (component cooling water) and the tube side the recirculated fluid. Each heat exchanger is capable, at accident conditions, of cooling 1.4 million pounds of water per hour from 213°F to 135°F.

There are a total of four pumps that can take suction from the sumps. The two recirculation pumps (located inside the containment) take suction from the recirculation sump, and the two RHR pumps (located outside the containment) take suction from the containment sump. The

configuration of components in the recirculation system is such that the l[illegible]ad pumps (i.e., recirculation or RHR pumps) take suction from a sump and pass the coolant through the RHR heat exchangers. One out of four pumps can provide sufficent coolant flow to cool the core and simultaneously spray the containment. Depending on the operator decision and the pressure in the reactor coolant system (RCS) and in containment, the flow is routed for core cooling or containment spray, or both. Priority is given to core cooling.

The RHR heat exchangers cool the sump water. Their secondary side is connected to the component cooling system (CCS). The latter is cooled by the service water system (SWS) which is drawn from the ultimate heat sink (Hudson River). The component cooling outlet valves for each heat exchanger (822A and 822B) are opened by the safeguards actuation signal. If heat exchanger cooling is not available, the fan coolers can remove the heat by condensing the steam generated in the core. Twenty minutes after accident initiation, three out of five fan coolers are sufficient for a large LOCA.

From the heat exchangers, flow can be directed in four different directions. The core and containment conditions determine which flowpath should be chosen. The path for low pressure cold leg injection is opened by the safeguards actuation signal. If the RCS pressure is above the shutoff head of the low pressure pumps (477 feet for the recirculation pumps and 372 feet for the RHR pumps), the flow is directed toward the suction line of the SIS pumps. The third path leads to the containment spray headers. Hot leg recirculation is also possible (hi-head only). The isolation valves to the hot legs are normally closed and deenergized. If one heat exchanger train is unavailable, it is possible to align the other train for simultaneous core cooling and containment spray recirculation. Also, if hi-head injection is required and the connecting line between the RHR heat exchangers and the SIS pumps is closed or failed, then the RHR pump flow can be realigned (by opening MOV 883 and manual valve 1863, and closing manual valve 846 and MOV 882) toward the suction side of the SIS pumps. The heat exchangers are bypassed in this situation and containment spray recirculation is not possible. Therefore, this mode of recirculation will be successful if the containment fan coolers can remove the heat generated in the core.

B.3.2 System Operation

The operators activate the recirculation system when they receive a "low level" signal from the RWST (a one-out-of-two system). For a large LOCA, if all pumps are running, this is about 22 minutes after the initiation of the accident. This time period could be much longer depending on the number of pumps taking suction from the refueling water storage tank. The operators also check the sump level. The switchover from the injection phase to the recirculation phase is done by eight switches (referred to as the "eight-switch sequence"). Following switchover, one spray pump is left operating until the RWST is empty. Core cooling has the first priority. Containment spray recirculation is activated later, manually; its operation depends on containment pressure.

The operators turn the recirculation switches to the "on" position, one at a time, starting with switch 1. There is a light associated with each switch which indicates that the required automatic operations are completed. If a particular switch operates on a deenergized component, the function complete light would not turn on. These are mentioned in the procedure at the related instruction. Operators would check the status of components that are affected by these switches. If some functions are not completed, they would accomplish the operations manually according to the procedure to obtain the desired actions. Switch 1 trips SI pump 32 (if all three are running), spray pump 32 (if both pumps are running) closes MOVs 887A and 887B (if SI pump 32 is stopped), and closes the discharge MOV; 866A and 866B (these are not shown in Figure 2) of the containment spray pump that has been stopped. Switch 2 activates one additional nonessential service water pump in the conventional header and one component cooling pump. Both RHR pumps are stopped and RHR suction and discharge valves (882 and 744) are closed by switch 3. Both valves are deenergized; therefore, a plant operator must energize them before they can be closed from the control room. One of the recirculation pumps is started and both discharge valves (1802A and 1802B) are opened by switch 4. Switch 5 causes the heat exchanger discharge valves 746, 747, 899A, and 899B to close and the SI pump suction valves 888A and 888B to open. It also closes the safety injection line valves 842 and 843, and closes the RHR mini flow line MOVs 743 and 1870 and arms the SI pump suction header low pressure alarm (these are not shown in Figure 2).

At switch 5, the operator has to decide whether hi-head or lo-head recirculation is required. If hi-head is required, then he continues with switch 5 and skips switch 6. If lo-head is required, he continues with switch 6. Switch 6 trips all running safety injection pumps. If three diesels or offsite power are available, switch 7 would start a second service water pump. If this is successful it would start a second component cooling pump also. If both are successful, the second recirculation pump is started also. Switch 8 closes spray pump test line valve 1813 and SI pump suction valve 1810 (suction from RWST; it is normally deenergized).

Containment spray recirculation is activated manually. After switchover to core cooling is completed, the operators trip the running spray pump (when the RWST is empty) and close the isolation valves. In lo-head recirculation, the isolation valves 889A and 889B (at the RHR heat exchanger discharge) are opened and the throttle valves, 638 and 640, are adjusted until spray flow is established. In hi-head recirculation, the operator opens MOVs 889A and 889B and verifies 1300 gpm flow to the spray rings.

Cold leg recirculation is maintained for 24 hours. At this time, according to the procedure, the operator realigns the system for combined hot and cold leg recirculation. The two hot leg connections are associated with the safety injection discharge headers, which are isolated by normally deenergized and closed valves. Therefore, a plant operator's assistance is needed to open these valves (i.e., unlock and close the appropriate MCC breakers for these valves).

Several parameters relevant to system operation are monitored on the control board. There are redundant level indicators for both sumps. Coolant flow is also indicated for lo-head discharge headers, the containment spray headers, and the two discharge pipes downstream of the SI pumps. Low pressure at the safety injection pumps suction header is annuciated in the control room.

B.4 SUPPORT SYSTEMS

This system is a composition of two emergency core cooling systems--the residual heat removal system and the safety injection system. It also uses the same piping and spray rings as the containment spray system. The plant operator is essential for the activation of this system. Electric power is necessary to run pumps and operate valves. Table 5 gives the power sources to the pumps and valves of this system.

The component cooling system cools the sump water in the RHR heat exchangers. Pump cooling is essential for the recirculation pumps. If the component cooling system is not available, the booster pumps (component cooling) can provide sufficient cooling flow. Cooling of SI pumps is accomplished by a shaft drain booster pump using component cooling water to cool the oil system. RHR pumps can function for several hours without cooling.

B.5 TEST REQUIREMENTS

The various emergency core cooling systems employed in the recirculation system are tested periodically. The description, frequencies, and names of tests performed on each component are listed in Table 6. All pumps, except for the recirculation pumps, are tested at least every month. The latter are tested at every refueling outage. The valves are tested at different intervals; also, portions of the system are used during heatup and cooldown. Table 6 shows the detail. The level indicators of the two sumps are tested for operability at every refueling outage. The recirculation switches are also tested during refueling (PT-R3A).

B.6 MAINTENANCE REQUIREMENTS

Under normal operating conditions, generally speaking, there is no maintenance on the recirculation pumps, and all the valves inside the containment.

At any given time, only one of the following components could be unavailable due to maintenance: RHR pumps, SI pumps, auxiliary component cooling pumps, and MOVs 888A, 888B, 885A, and 885B; and they cannot be out of service for more than 24 hours. All valves are included in a preventive maintenance program. One spare SI pump and one spare RHR pump and associated parts are maintained in inventory to accommodate expeditious exchange or repair when an installed pump is found to be inoperable.

B.7 TECHNICAL SPECIFICATIONS

The reactor should be maintained at cold shutdown unless at least one refueling water storage tank low level alarm is operable; one residual heat removal pump, and one heat exchanger, together with the associated piping and valves are operable; or one recirculation pump together with with its associated piping and valves are operable. Similarly, the reactor should be shut down if at least one safety injection pump remains out of service for more than 24 hours, one residual heat removal pump remains out of service for more than 24 hours, one residual heat exchanger remains out of service for more than 48 hours, or one refueling water storage tank low level alarm remains inoperable for more than 7 days.

C. GENERAL REMARKS ON LOGIC MODELS AND QUANTIFICATION

C.1 LOGIC MODEL

There are two modes of operation for this system: core cooling recirculation only, and containment spray recirculation. System configuration for core cooling recirculation depends on the type of LOCA. Only the availability of high pressure recirculation is questioned in a small LOCA. For medium and large LOCAs, low pressure, containment spray, and hot leg recirculation functions must be available. If low pressure recirculation fails, then containment spray and hot leg recirculation are failed also. Thus, four distinct states for the system are defined and discussed separately. These are:

1. High pressure recirculation when injection phase is successful.

2. Low pressure recirculation when injection phase is successful.

3. Containment spray recirculation when low pressure recirculation is available.

4. Hot leg recirculation when core cooling recirculation is available.

Each state is analyzed in a separate section. A fault tree and its minimal cutsets are given first. Then the fault tree is quantified under different conditions which are transferred from the event trees. These conditions include the avalability of the fan coolers, the component cooling system, and the electric buses. Tables 1 through 4 summarize the results.

Fault trees are constructed including the RHR heat exchangers. For sequences in which three out of five fan coolers are operating, the RHR heat exchangers are not required for successful recirculation system operation. Sufficient heat is removed by the fan coolers to prevent core damage. The effect of the fan coolers will be shown in the quantification sections.

The possibility of using line 190 (contains MOV 883 and manual valve 1863) is not considered in the fault trees. Its impact on the availabiliy of the system will be shown in the quantification sections.

The conditions common to all fault trees are:

- A LOCA has occurred.
- The reactor has been scrammed successfully.
- The injection phase has been successful.
- At least 20 minutes has passed from accident initiation.

- The water in the RWST is at low-level alarm point (at least 96,000 gallons remain in the tank).

- One RHR pump, or one recirculation pump, can provide sufficient flow for both core cooling and containment spray.

- One RHR heat exchanger can provide enough cooling.

- The component cooling system can provide sufficient cooling to the recirculation pumps when the booster pumps are unavailable.

- Mechanical failures in the heat exchangers are not considered. Their failure mode is very similar to pipe failures. Therefore, any significant damage in the heat exchangers would be detected within one day.

The specific conditions are given later as each fault tree is described.

Test and maintenance contributions are not shown in the fault tree. However, they are considered in the sections on quantification.

C.2 FAULT TREE CODING

Table 7 is a partial list of basic events, their failure modes, and the corresponding codes.

C.3 QUANTIFICATION

In the quantification sections, the unreliability of the system in 24 hours is assessed. The important factors and some unavailability values unique to this system are discussed in this section.

Time is an important factor. It appears under two different contexts; first, the total time of successful operation, and second, the available time for restoration after system failure. Success is defined as adequate core cooling and/or containment pressure control over a 24-hour period. The restoration time is very important to system activation because it defines the available time for an operator to switch over to recirculation phase. We will refer to this as a "time window" and define it as $\tau(t) = t' - t$; where t is the time when the top event occurs and t' is the time of core damage after t. For switchover, t is considered the time when the RWST water level reaches the low-level alarm point.

Switchover to the recirculation phase is a dynamic task where the operators interact with the displays on the control board. The low level alarm from the RWST is a cue for initiating this process. Flow levels are checked to determine if the desired flowpath is established.

The "Human Reliability Handbook"* is used in this study as a guide to quantify the contribution of human error under accident conditions to system unavailability. For the quantification of each human-related event we take the following steps:

1. We identify the failure modes of human error that would lead to adverse situations. We break down system failure to detailed human error failure modes. Although the state of knowledge on the frequencies of human error under accident conditions may not warrant this detailed quanitification effort, we judge that this enables us to obtain a clear picture about the role of human performance on system function. The handbook gives the following reasons in defense of a detailed analytical approach (p. 21-11):

   "a. The exercise of outlining all plausible modes of operator action decreases the probability of overlooking some important failure path.

   b. Due to the lack of error probability data for nuclear power plant tasks, it is necessary to break down operator actions to a level at which existing data can be used.

   c. The detailed approach makes it easier for analysts making independent estimates to check on the source of any disagreement and to resolve it."

2. We establish the basic human error rate based on our judgment and frequencies of similar tasks suggested by the handbook (see the chapter on "Human Error Rates" for a definition for Basic Human Rate). The most important factor influencing our judgment is the stress level in a particular accident. Skill and control board layout are also important. All the operators at the Indian Point 3 station are trained on a simulator which is similar to the control board at the plant. Also, the licensed operators practice accident mitigation (especially large LOCA) on this simulator at least once a year. The controls and instrumentation for switchover are in one general area on the control board.

3. Dependencies among the operators are established in this step (see the chapter on "Human Error Rates" for the definitions).

4. We compute the frequency of error for the team of operators using the conditional frequencies suggested by the Handbook (see the chapter on "Human Error Rates").

5. We take the results of step 4 as the median frequency. To express our uncertainty in that frequency we assign an error factor that shows the span from 95th percentile to the median. We take the

*Swain, A.D. and H.E. Guttman, "Handbook of Human Reliability," NUREG/CR-1278, Sandia Laboratories, Albuquerque, New Mexico, October 1980.

distribution as lognormal and compute the mean and variance. See the chapter on "Human Error Rates" for the reasons for choosing this distribution.

In Table 7, several events are entered under the title of "Noncomponent Events" for which data is not given in Section ____. These events are discussed hereafter.

- ECNTSUMP or ERECSUMP

  The two sumps (containment or recirculation) could be plugged by debris during a LOCA. This is deemed to be very remote because the strainers take a large area and more than one screen has to be plugged. We choose 10^{-6} (judgmentally) as the median and 100 for the error factor; then the mean and variance of lognormal distribution become:

  Mean: 5.0×10^{-5}

  Variance: 6.4×10^{-6}.

- HDISCHDN

  The safety injection (SI) part of the system is treated as an entity in one of the fault trees. This event is the failure of the SI system to align to the proper position for hi-head injection. From the section on "High Pressure Injection System" we obtain the following mean (combination of supercomponents B, C, and D in that section):

  Mean: 1.1×10^{-5}

  Variance: 1.2×10^{-8}.

- ELOHDDIS

  The low pressure injection system is treated similarly to the SIS. The failure here is unsuccessful alignment of the discharge paths for low-pressure injection. The section on the low pressure injection system gives the mean ($_{EF}$ in that section):

  Mean: 2.36×10^{-8}.

C.4 PIPING ANALYSIS

Table 8 shows the pipe failure analysis. There is no single pipe section failure that would totally disable one of the functions. In most cases the pipe failure can be detected through RWST level indicators. If pipe 361 (the connecting line between the RHR heat exchangers and lo-head injection headers) fails, the SI pumps could be used after the broken line is isolated. If pipe 60 fails, then the return line around the RHR pumps can be used. For this, MOV 883 and

manual valve 1863 would be opened and MOV 882 and manual valve 846 would be closed. Fan cooler availability is essential in this mode because the heat exchangers are bypassed. If pipe 359 fails then lo-head recirculation via lo-head discharge headers would not be possible. However, the broken pipe can be isolated by 899A and B valves and the SI pumps can be used for core cooling recirculation.

D. HIGH PRESSURE RECIRCULATION

D.1 FAULT TREE

The fault tree is shown in Figures 3 through 12 and 20 through 24. The top event is "High Pressure Recirculation Fails to Provide 300 gpm for 24 Hours." The fault tree is based on the following conditions in addition to those mentioned in Section C:

- Small LOCA has occurred.
- High pressure coolant injection has been completed successfully by the SI pumps; therefore, only pump failures are considered. This means that inadvertent blockage of flow is discounted.
- One hi-head pump is sufficient for adequate core cooling.
- If MOV 744 is needed, it should be opened from a closed position.

The minimal cutsets with one and two basic events, and with the house events treated as basic events, are shown in Table 9. Failure of pipe 60 (HPPLN60E) will fail the hi-head recirculation. This is because, in this fault tree, we have not allowed for heat exchanger bypass through line 190. However, in quantification the effect of this line is taken into consideration. The failure of the component cooling system fails heat exchanger cooling.

This fault tree is quantified under several conditions depending on the availability of fan coolers, the component cooling water system, and three electrical divisions. Table 1 gives all possible combinations of these conditions.

D.2 QUANTIFICATION

D.2.1 All Electric Buses and Component Cooling Available: Fan Coolers Unavailable

Table 10 gives the cause table. Each item in this table is discussed hereafter.

D.2.1.1 Human Error Contributions

The frequency of operator failure to establish high pressure recirculation is evaluated here. In a small LOCA, the time for switchover to the recirculation phase is definitely greater than 2 hours after the accident. More likely, it is around 10 hours. The time window for switchover is at least 60 minutes. This is relatively large and would allow the operators to take corrective actions in case of component failures and human error. This is particularly true for the RHR pumps, which can be aligned for containment sump recirculation. Also, the stress level on the operators should be moderate. That is higher than for normal operating conditions but significantly less than the stress level in a large LOCA.

Four people would be in the control room by this time. Two of the four are control board operators and at least one of them has a senior reactor operator's (SRO) license. The remaining two are the shift supervisor (SS; has SRO license) and shift technical advisor (STA). The latter does not have an operating license, but has been trained in the mechanics of accident control and plant response characteristics.

The two operators would be doing the switchover. One would be reading the procedures and the other would be manipulating the controls. The shift supervisor would be monitoring the process while checking other parts of the control board. The shift technical advisor would not be involved in the detail. He is supposed to form an independent interpretation of the instrumentation readout. Three Mile Island scenario (i.e., many people in the control room and frequent outside telephone calls) would not be experienced again because of special corrective actions mandated by the Nuclear Regulatory Commission.

We define three stages for the switchover process. In the first stage the operators follow the RWST level. This stage ends when decision is made to initiate the switchover. Errors at this stage (i.e., failure to decide to initiate switchover) may fail the system and should be attributed to all four operators. At the second stage the switchover is performed. Here, errors would be due to the two operators at the control board. The third stage starts when switchover is completed. All four operators would be looking at the indicators to see if the switchover was successful. Errors can be discovered and corrected at this stage.

Two operator-related events are identified that could lead to system failure. These are:

- Failure to initiate switchover.
- Switch 6 is turned to "on" position and no corrective actions are taken.

Three things help the operators to recognize that switchover should be initiated. First, operator training will condition them to recognize switchover requirements. Second, the procedures would lead the operators to switchover. Third, the RWST low level alarm would alert the operators.

A small LOCA may impose a moderately high stress level. The handbook suggests that the stress level may even become very high. We quote from that source (p. 17-18):

> "A LOCA is a special case. Presumably a small or slowly developing LOCA should not be accompanied by more than a moderately high level of stress for most people. Of course, in some incidents involving small LOCAs, the initial stress level may not be very high, but subsequent events may raise the stress level. For example, some operating personnel in the TMI accident, which involved a small

LOCA, were considered subject to high levels of stress at various times by the interviewers on the Kemeny Commission (Kemeny, 1979) and Rogovin Special Inquiry Group (Rogovin and Frampton, 1980)."

The basic human error frequencies must be estimated totally judgmentally, because there is no statistical data. The handbook acknowledges this and suggests some adjusting factors. We quote (p. 17-10):

"We can find no objective data from which to derive the factors to apply to human error probabilities (HEPs) and uncertainty bounds for the condition of a moderately high level of stress. On the basis of judgment, we multiply the HEP and uncertainty bounds for step-by-step, rule-based tasks performed under optimal stress levels by 2, and for tasks requiring dynamic interplay between the operator and system indications, we use a multiplier of 5."

For errors of omission (the first event is of this kind) the handbook makes the following suggestions (Table 20-15, page 20-33):

TASK	Human Error Frequency -- Best Estimate (lower bound "to" upper bound
Omit an item when preparing a list of values or set of tags.	.003 (.001 to .01)
Failure to carry out a specific oral instruction to change or restore a valve.	.001 (.0005 to .005)
Failure to initiate Level 1 tagging.	.001 (.0005 to .005)
Failure to follow established procedure or policies in valve changes or restoration.	.01 (.005 to .05)

In light of these arguments and suggestions and those given in Section C.3 we chose 6×10^{-3} as the median for the basic human error frequency and 1×10^{-3} and 3×10^{-2} as the 5th and 95th percentiles.

The dependencies among the operators are: high dependence (HD) between the two reactor operators, moderate dependence (MD) between the SS and the first two, and moderate dependence between the STA and the rest. The two reactor operators would be interacting closely and possibly one of them is a novice, thus high dependence between the two. The shift supervisor (an SRO) is less dependent on the first two, because he may not become involved in the detail. The dependency level of the STA is not clear. He may be highly dependent on the rest because he is part of the team and would follow the same line of thought. On the other hand,

since he does not have to become involved in the detail, he may interpret the indicators rather independently. We judge that an average STA would be moderately dependent (MD) on the rest of the team.

Using the formulas recommended by the handbook, error frequency of the four-person team for this task (initiation of switchover) would be:

$$6.0 \times 10^{-3} \times \left(\frac{1 + 6 \times 6 \times 10^{-3}}{7}\right)^2 \times \frac{1 + 6 \times 10^{-3}}{2} = 6.6 \times 10^{-5}.$$

We assign an error factor of 20. The mean and variance become:

Mean: 3.46×10^{-4}

Variance: 3.19×10^{-6}.

For the second event, the operators erroneously turn switch 6 to "on" position which stops all the SI pumps. However, it is possible to restore these pumps from the control board. The former may occur due to the error of two operators, that is, one reading the procedure and the other manipulating the controls. This error may be discovered by the SS or STA while the switchover is in progress or by the whole team after switchover is completed. We judge that it is more likely that the first two operators would not discover their own error. Also, the SS and STA would be highly dependent on each other. A point value for the frequency of turning switch 6 and not recovering the error is:

$$fr \begin{pmatrix} \text{switch 6} \\ \text{"on"} \end{pmatrix} \times fr \begin{pmatrix} \text{no recovery,} \\ \text{SI pumps not} \\ \text{started manually} \end{pmatrix}$$

$$= \left(6.0 \times 10^{-3} \times \frac{1 + 6 \times 10^{-3}}{2}\right) \left(6.0 \times 10^{-3} \times \frac{1 + 6 \times 10^{-3}}{2}\right)$$

$$= 9.0 \times 10^{-6}.$$

We take this as the median and assign an error factor of 20. The mean and variance for a lognormal distribution become:

Mean: 4.72×10^{-5}

Variance: 5.93×10^{-8}.

Hi-head recirculation may also fail due to a combination of human error and other causes. At least one recirculation pump may fail due to human error (during maintenance) on manual valves 753A, 753F, 753G, 753H, 753J, or 753K, and 752A, 752F, 752G, 752H, 752J, or 752K. The RHR pumps have to be aligned manually (from the control room) to provide the recirculation flow when the recirculation pumps are not available.

The booster pumps are flow-checked after maintenance or every month. Therefore, the position of manual valves 753A, 753F, 753G, 753H, 753J, or 753K, and 752A, 752F, 752G, 752H, 752J, or 752K is checked regularly. One of these valves in the closed position would result in the failure of one recirculation pump. Under normal operating conditions, these valves are never manipulated. The unavailability of these valves should be on the order of 10^{-6} or less.

The operators can switch to RHR pumps and establish the recirculation flow from the containment sump if there is no flow from the recirculation pumps. The median frequency of failure for one operator to recognize this mode of operation is judged to be 0.1. Stress level could be high for this action because of multiple failures in the recirculation pump section. With high and moderate dependencies among the operators, SE, and STA, we obtain:

$$\text{point value:} \quad 0.1 \times \left(\frac{1 + 6 \times 0.1}{7}\right)^2 \times \frac{1 + 0.1}{2} = 2.9 \times 10^{-3}.$$

This is taken as the median. An error factor of 20 reflects our degree of uncertainty. The mean and variance for the resulting lognormal distribution are:

Mean: 1.52×10^{-2}

Variance: 6.16×10^{-3}.

In case of failures in heat exchanger 31, MOVs 746 and 747 should be opened by the operators to establish flow from heat exchanger 32 to the suction side of the SI pumps. We assign the frequency distribution of failure to switch to RHR pumps to this failure mode also.

D.2.1.2 Single Hardware Failures

The only single element cutset is:

- HPPLN60E: pipe 60 rupture.

The failure of pipe 60 would fail hi-head recirculation. The maximum time that this failure may stay unnoticed is 1 week. From Section ___, pipe failure rate (mean) is 4.5×10^{-7} per hour. Then, failure frequency of line 60 is:

Mean: $8.6 \times 10^{-10} \times 24 \times 7 \times 1/2 = 1.44 \times 10^{-7}$

Variance: $(1/2 \times 24 \times 7)^2 \times 6.0 \times 10^{-17} = 4.2 \times 10^{-13}$.

D.2.1.3 Multiple Hardware Failures

The double and triple failure contributions are computed by the computer code RAS. This code orders minimal cutsets (MCS) according to their degree of contribution to the frequency of the TOP event. We take the

first few cutsets that contribute more than 90% to the frequency of the TOP event and check for repeated component types. The contribution of human error to partial system failure is also included. Some hardware failure frequencies are adjusted to reflect these errors.

In case of failures in the recirculation pump section, the operators would use the RHR pumps. The frequency of failure to switch to RHR pumps due to operator error is computed in Section D.2.1.1. The mean and variance are:

Mean: 1.52×10^{-2}

Variance: 6.16×10^{-3}.

This frequency is assigned to check valve 741 in the input to RAS.

The mean frequency of the cutsets with repeated component types is adjusted. The following minimal cutsets contained such events:

- EPMRC22S EPMRC21S ECV-741C

  If both recirculation pumps fail and operators fail to switch to RHR pumps (represented by ECV-741C), then the system will be unavailable. The unreliability of one recirculation pump is the sum of two contributors--failure during operation and failure to start. The mean and variance become:

  Mean: $1.97 \times 10^{-5} \times 24 + 1.36 \times 10^{-3} = 1.83 \times 10^{-3}$

  Variance: $1.70 \times 10^{-7} \times (24)^2 + 1.22 \times 10^{-6} = 9.91 \times 10^{-5}$.

  The mean of the frequency of both recirculation pumps failing is:

  Mean: $(1.83 \times 10^{-3})^2 + 9.91 \times 10^{-5} = 1.02 \times 10^{-4}$.

  Operator failure frequency is assigned to ECV-741C. The mean of the frequency of this minimal cutset becomes:

  Mean: $1.02 \times 10^{-4} \times 1.52 \times 10^{-2} = 1.56 \times 10^{-6}$.

- HPMSI21S HPMSI22S HPMSI23S

  The unreliability of one SI pump is equal to the sum of the frequencies of pump failure while running (in 24 hours) and pump failure to restart.

$$Q_{SI} = Q_{SIS} + \left(1 - \exp\left(-\lambda_{SI} t\right)\right) \left(1 - Q_{SIS}\right)$$

$$Q_{SIS} + \left(1 - \exp\left(-\lambda_{SI} t\right)\right)$$

where

Q_{SIS}: SI Pump failure to restart;

$\alpha = 1.36 \times 10^{-3}$, $\beta^2 = 1.22 \times 10^{-6}$

λ_{SI}: SI pump failure rate given it has started;

$\alpha = 2.31 \times 10^{-3}/hr$, $\beta^2 = 7.47 \times 10^{-5}/hr^2$

t: 24 hours

Using DPD arithmetic the mean and variance of Q_{SI} is obtained

Mean: 3.77×10^{-2}

Variance: 4.35×10^{-3}

The frequency of system failure due to hardware failures in all three SI pumps is obtained from

$$Q = Q_{SI}^3.$$

Using DPD arithmetic the mean and variance of Q is computed:

Mean: 3.11×10^{-3}

Variance: 1.67×10^{-4}

- HMV888AQ HMV888BQ

The mean and variance of the frequency of failure of an MOV to open are (from Section ___):

Mean: 1.51×10^{-3}

Variance: 2.64×10^{-6}.

The mean and variance of both valves failing are:

Mean: $(1.51 \times 10^{-3})^2 + 2.64 \times 10^{-6} = 4.88 \times 10^{-6}$

Variance: 5.03×10^{-10}.

This is a conservative measure because the valves can be opened manually within the available time window. We inspected the system diagram and concluded that MCSs with four or more elements do not contribute significantly to the top event. The results of this section are summarized in Table 10.

D.2.1.4 Maintenance Contribution

Section C.1 gives the list of components that could be unavailable due to maintenance when the system is activated. Only SI pumps are main contributors here. This is because the unavailability of RHR-related components due to operator error is much larger than the maintenance-related unavailability. Also, the auxiliary component cooling pumps do not appear in any of the minimal cutsets because the component cooling system is available. The mean and variance of the unavailability of the SI pumps due to maintenance are (from Section):

Mean: 8.13×10^{-4}

Variance: 6.22×10^{-8}.

System failure occurs if all three pumps are unavailable. The unavailability of two SI pumps due to hardware failure is computed by applying DPD arithmetic on:

$$Q = Q_{SI}^2$$

where SI is defined in Section D.2.1.3. The mean and variance of Q are:

Mean: 7.14×10^{-3}

Variance: 6.43×10^{-4}

System failure frequency due to SI pump maintenance becomes:

Mean: $3 \times 8.13 \times 10^{-4} \times 7.14 \times 10^{-3} = 1.74 \times 10^{-5}$.

D.2.1.5 Other Causes

The system does have several minimal cutsets in one compartment. The effects of external causes, fire or flood, are discussed in separate studies.

Other causes such as errors in manufacturing, installation, and design are deemed to be of low frequencies because most of the system has been tested frequently. We use the β-factor to express these causes. We choose 10^{-3} to 5×10^{-2} as the range for a β which yields a mean and variance of:

Mean: 1.4×10^{-2}

Variance: 6.1×10^{-4}.

We use the same β-factor for valves and pumps. The frequency of all three SI pumps failing (using β-factor) is:

Mean: $1.4 \times 10^{-2} \times 3.77 \times 10^{-2} = 5.28 \times 10^{-4}$.

The frequency of both MOVs 888 or both MOVs 822 failing to open (using β-factor) is:

Mean: $1.4 \times 10^{-2} \times 1.51 \times 10^{-3} = 2.10 \times 10^{-5}$.

The frequency of both recirculation pumps or both MOVs 1802 failing to operate (using β-factor) is:

Mean: $1.4 \times 10^{-2} (1.83 \times 10^{-3} + 1.51 \times 10^{-3}) = 4.66 \times 10^{-5}$.

System failure will occur if RHR pumps are not realigned also. Then:

Mean: $4.66 \times 10^{-5} \times 1.52 \times 10^{-2} = 7.09 \times 10^{-7}$.

D.2.1.6 System Unreliability

Table 10 shows the results that have been derived for the mean values of the contributors to hi-head recirculation unreliability when the fan coolers are unavailable, and component cooling and all electric buses are available. Only the main contributors are used here for uncertainty analysis. The mathematical expression for the unreliability of the system is written in terms of unreliabilities or unavailabilities of dominant contributors. The human error distributions share the same state of knowledge. Therefore, they are expressed in terms of a constant times a distribution.

$$Q_{HI\text{-}HEAD} = Q_{H1} + 0.136Q_{H1} + Q_{SI}^3 + 2Q_{MOV}^2 + 3Q_{SIM}Q_{SI}^2 + B(Q_{SI} + 2Q_{MOV})$$

where

Q_{H1}: Human error, failure to initiate switchover;

$\alpha = 3.46 \times 10^{-4}$, $\beta^2 = 3.19 \times 10^{-6}$.

Q_{MOV}: MOV fails to operate:

$\alpha = 1.51 \times 10^{-3}$, $\beta^2 = 2.64 \times 10^{-6}$.

Q_{SI}: Unreliability of an SI pump in 24 hours:

see Section D.2.1.3

Q_{SIM}: Maintenance on SI pumps:

$\alpha = 8.13 \times 10^{-4}$, $\beta^2 = 6.22 \times 10^{-8}$.

B: β-factor: $\alpha = 1.4 \times 10^{-2}$, $\beta^2 = 6.1 \times 10^{-4}$.

Using DPD arithmetic, we find for $Q_{HI\text{-}HEAD}$:

Mean: 4.10×10^{-3}

Variance: 1.68×10^{-4}

5th Percentile: 4.70×10^{-5}

95th Percentile: 6.40×10^{-3}

Median: 4.70×10^{-4}.

D.2.2 Fan Cooler and Electric Bus 5A Unavailable: Component Cooling and Electric Buses 2A, 3A, and 6A Available

Loss of electric bus 5A before safeguards actuation causes the failure of SI pump 31, recirculation pump 31, MOVs 888A, 822A, 885A, and 1802A. Since 885A is inoperable, recirculation via the RHR pumps is not possible unless this valve is opened manually. Table 11 gives the cause table. Each item in this table is discussed hereafter.

D.2.2.1 Human Error Contributions

The frequency of operator failure to establish hi-head recirculation is evaluated in Section D.2.1.1. The same results apply here also. Loss of electric bus 5A would not have significant effect on operator error rates because of a long time window.

D.2.2.2 Single Hardware Failures

The dominant single element cutsets are:

- HPPLN60E: pipe 60 rupture; mean = 1.44×10^{-7}.
- JBS336BD: MCC bus 36B failure; mean = 2.00×10^{-6}.
- MOV 1802B fails to open; mean = 1.51×10^{-3}.
- Manual valves 753A, F, G, H, J, or K in closed position; total mean = $6 \times 9 \times 10^{-8}$.
- MOV 822B fails to open; mean = 1.51×10^{-3}.

D.2.2.3 Multiple Hardware Failures

The following multiple failures would lead to system failure:

- Recirculation pump 22 fails to run (mean 1.83×10^{-3}) and operators fail to open MOV 885A and align the RHR pumps for recirculation cooling.
- MOV 888B fails to open (mean = 1.51×10^{-3}) and operators fail to open one of the MOVs 688A or 888B manually.
- Both SI pumps fail.

The frequency of human error portions of the first two events is judged to be lognormally distributed with the median at 0.1 and the error factor at 3. The mean and variance are:

Mean: 1.25×10^{-1}

Variance: 8.78×10^{-3}

Thus, the mean frequency of the first event is:

Mean: $1.83 \times 10^{-3} \times 1.25 \times 10^{-1} = 2.29 \times 10^{-4}$

The mean frequency of system MOV failure due to 888B failure and recovery is:

Mean: $1.51 \times 10^{-3} \times 1.25 \times 10^{-1} = 1.88 \times 10^{-4}$

The frequency of the event, that is the failure of both SI, is computed in Section D.2.1.4. The mean and variance are:

Mean: 7.14×10^{-3}

The contribution of other multiple hardware failures to system unavailability is very small.

D.2.2.4 Maintenance Contribution

If one SI pump is under maintenance and the other failed due to hardware failures, hi-head recirculation would be unavailable. The mean for system unavailability becomes (see Section ____ for data):

Mean: $2.00 \times 8.13 \times 10^{-4} \times 3.77 \times 10^{-2} = 6.13 \times 10^{-5}$.

D.2.2.5 Other Causes

The discussions given in Section D.2.1.5 do not apply here; except for the SI pumps, because only one train of all the redundant trains is available. The resulting mean of the frequency of both SI pump failures due to other causes becomes:

Mean: $1.40 \times 10^{-2} \times 3.77 \times 10^{-2} = 5.28 \times 10^{-4}$.

D.2.2.6 System Unreliability

Table 11 shows the results that have been derived for the mean values of the contributors to hi-head recirculation unreliability when the fan coolers and electric bus 5A are unavailable and component cooling and electric buses 2A, 3A, and 6A are available. Only the main contributors are addressed in the uncertainty analysis. The mathematical expression for the unreliability of the system in terms of the unreliabilities or unavailabilities of dominant contributors is:

$$Q_{HI-HEAD} = Q_{H1} + 0.136_{H1} + 2Q_{MOV} + Q_{RC}Q_{H2} + Q_{MOV}Q_{H2} + Q_{SI}^{2}$$

$$+ 2Q_{SIM}Q_{SI} + BC_{SI}$$

The terms are defined in Section D.2.1.6 except for:

Q_{RC}: Unreliability of a recirculation pump in 24 hours;

$\alpha = 1.83 \times 10^{-3}$, $\beta^2 = 9.91 \times 10^{-5}$.

Q_{H2}: Human Error in Opening MOV 885A manually and shifting to RHR pumps: $\alpha = 0.125$; $\beta^2 = 8.78 \times 10^{-3}$

The results of a DPD arithmetic for the unreliability of hi-head recirculation are:

Mean:	1.15×10^{-2}
Variance:	6.50×10^{-4}
5th Percentile:	1.10×10^{-3}
95th Percentile:	1.80×10^{-2}
Median:	4.20×10^{-3}.

D.2.3 Fan Coolers and Electric Bus 6A Unavailable and Component Cooling and Electric Buses 2A, 3A, and 5A Available

Loss of electric bus 6A causes the failure of SI pump 33, recirculation pump 32, RHR pump 32, MOVs 888B, 822B, 747, 885B, and 1802B. The conditions here are similar to those of Section D.2.2. Therefore, the same results apply here also.

D.2.4 Fan Coolers and Electric Buses 2A and 3A Unavailable; Component Cooling and Electric Buses 5A and 6A Available

Loss of electric buses 2A and 3A at or before safeguards actuation cause the failure of SI pump 32 and RHR pump 31. The situation here is very similar to that in Section D.2.1. The only differences in the results are introduced through the SI pump unavailability due to multiple hardware failures and maintenance plus hardware failure. Table 12 gives the cause table.

The mean and variance of the frequency of hardware failure of both SI pumps 31 and 33 are (see Section D.2.1.4):

Mean:	7.14×10^{-3}
Variance:	6.43×10^{-4}.

The mean of the unavailability of both SI pumps due to maintenance and hardware failure becomes:

Mean: $2.00 \times 8.13 \times 10^{-4} \times 3.77 \times 10^{-2} = 6.13 \times 10^{-5}$.

System unreliability is computed by the following expression which is in terms of the dominant contributors (see Table 12):

$$Q_{HI-HEAD} = Q_{H1} + 0.136Q_{H1} + Q_{SI}^2 + 2Q_{MOV}^2 + 2Q_{SIM} Q_{SI} + B(Q_{SI} + 2Q_{MOV}).$$

The terms are defined in Section D.2.1.6. Using DPD arithmetic, we find for $Q_{HI-HEAD}$:

Mean: 8.18×10^{-3}

Variance: 6.39×10^{-4}

5th Percentile: 1.20×10^{-4}

95th Percentile: 1.60×10^{-2}

Median: 9.00×10^{-4}.

D.2.5 Fan Coolers and Electric Buses 2A, 3A, and 5A (or 6A) Unavailable; Component Cooling and Electric Bus 6A (or 5A) Available

The components that may remain available under these conditions are the same as those given in Section D.2.3 except for SI pump 31 (or 32) and RHR pump 31 (or both). The mathematical expression for system unreliability becomes:

$$Q_{HI-HEAD} = Q_{H1} + 0.136Q_{H1} + Q_{RC} + 3Q_{MOV} + Q_{SI} + Q_{SIM}.$$

Credit is not given to manual valve manipulation because of high stress conditions (caused by bus failures).

Compare this with that given in Section D.2.2.6. All the terms are defined in Sections D.2.1.6 and D.2.2.6. Using DPD arithmetic on this expression, we find:

Mean: 4.52×10^{-2}

Variance: 4.37×10^{-3}

5th Percentile: 5.00×10^{-3}

95th Percentile: 0.12

Median: 2.40×10^{-2}.

D.2.6 Other Conditions When Fan Coolers Are Unavailable

If the electric buses 5A and 6A, or 2A, 3A, 5A, and 6A are unavailable, then system failure is a certainty. Also, the same is true when component cooling is unavailable.

D.2.7 Fan Coolers, All Electric Buses, and Component Cooling Available

The only difference between this case and that of Section D.2.1 is that heat exchanger availability is not addressed here. Then component cooling affects the system through the recirculation pumps only. Table 13 gives the cause table.

D.2.7.1 Human Error Contributions

The frequency of operator failure to activate high pressure recirculation is given in Section D.2.1.1. Fan cooler availability does not have any effect on this probability distribution.

D.2.7.2 Single Hardware Failures

The only single element cutset is HPPLN60E. The mean and variance of the frequency for this cutset was obtained in Section D.2.1.2:

Mean: 1.4×10^{-7}

Variance: 4.2×10^{-13}.

If line 190 is opened and line 60 is isolated, the failure of the latter would be bypassed. This switchover requires opening of a manual valve. Our judgment is that the median frequency of failure is about 0.1 and the error factor is 3. Then, the mean and variance become:

Mean: 0.12

Variance: 8.80×10^{-3}.

The mean and variance of system failure due to a failure in line 60 is obtained:

Mean: $1.4 \times 10^{-7} \times 0.12 = 1.7 \times 10^{-8}$

Variance: 1.0×10^{-14}.

D.2.7.3 Multiple Hardware Failures

In Section D.2.1.3 a method is given for identifying the main contributors to multiple hardware failures. The same approach is used here also. Similarly, operator error in switchover to RHR pumps (when recirculation pumps are failed) is incorporated in the input data to the RAS code, and the frequency of cutsets with repeated components is

corrected. The significant minimal cutsets are given in Table 13. The frequency of one MCS is adjusted to incorporate the possibility of using line 190.

- HMV888AQ HMV888BQ

In Section D.2.1.3, the mean and variance of the frequency of two valves failing to open were obtained:

Mean: 4.88×10^{-6}

Variance: 5.03×10^{-10}.

This failure is similar to failure of pipe 60; therefore, we should give credit to the fact that it may be bypassed through line 190. In Section D.2.7.2, we concluded that the mean and variance of the frequency of failure in using line 190 are:

Mean: 0.12

Variance: 8.80×10^{-3}.

The frequency of system failure yields:

Mean: $0.12 \times 4.88 \times 10^{-6} = 5.86 \times 10^{-7}$.

D.2.7.4 Maintenance Contribution

This case is similar to Section D.2.1.4 where only two sets of components are the main contributors: the SI pumps and MOVs 888A and 888B. The mean frequency of system failure due to maintenance on SI pumps is the same as that obtained in Section D.2.1.4:

Mean: 1.74×10^{-5}.

D.2.7.5 Other Causes

The results of Section D.2.1.5 apply here also, except that only one pair of valves should be considered in this case.

D.2.7.6 System Unreliability

The mathematical expression for hi-head recirculation unreliability when fan coolers, component cooling, and all electrical buses are available is written here in terms of the dominant contributors (see Table 13):

$$Q_{HI-HEAD} = Q_{H1} + 0.136Q_{H1} + Q_{SI}^3 + Q_{MOV}^2 Q_{H4} + 3\, Q_{SIM}\, Q_{SI}^2 + B\, Q_{SI} + B\, Q_{MOV}\, Q_{H4}.$$

The variables are defined in Section D.2.1.6 except for:

Q_{H4}: Failure to establish recirculation flow through line 190.

$\alpha = 0.12$; $\beta^2 = 8.8 \times 10^{-3}$.

DPD arithmetic on $Q_{HI\text{-}HEAD}$ gives:

Mean:	4.05×10^{-3}
Variance:	1.68×10^{-4}
5th Percentile:	3.50×10^{-5}
95th Percentile:	6.30×10^{-3}
Median:	4.30×10^{-4}.

D.2.8 Electric Bus 6A Unavailable; Fan Coolers, Component Cooling, and Electric Buses 2A, 3A, and 5A Available

Loss of electric bus 6A at or before safeguards actuation causes the failure of SI pump 33, recirculation pump 32, MOVs 888B, 885B, 747, and 1802B. This is similar to the conditions in Section D.2.2 except that the availability of MOVs 822A or 822B does not affect the top event. Table 14 gives the cause table. It is very similar to Table 11.

The mathematical expression for system unreliability in terms of the main contributors is:

$$Q_{HI\text{-}HEAD} = Q_{H1} + 0.136Q_{H1} + Q_{MOV} + Q_{RC}Q_{H2} + Q_{MOV}Q_{H2} + Q_{SI}^2 + 2Q_{SIM}\,Q_{SI} + BQ_{SI}$$

The results of a DPD arithmetic on this expression are:

Mean:.	1.00×10^{-2}
Variance:	6.48×10^{-4}
5th Percentile:	7.90×10^{-4}
95th Percentile:	1.60×10^{-2}
Median:	2.90×10^{-3}.

D.2.9 Electric Bus 5A Unavailable; Fan Coolers, Component Cooling, and Electric Buses 2A, 3A, and 6A Available

Loss of electric bus 5A at or before safeguards actuation causes the failure of SI pump 31, recirculation pump 31, MOVs 888A, 885A, 746, and 1802A. This is very similar to the conditions of Section D.2.8. Table 15 gives the cause table for this case. System unreliability is also given in Section D.2.8.

D.2.10 Electric Buses 2A and 3A Unavailable; Fan Coolers, Component Cooling, and Electric Buses 5A and 6A Available

Section D.2.4 discusses a similar case with the fan coolers unavailable. Table 12 applies here also except that heat exchanger-related entries should be taken out and the possibility of using line 190 should be incorporated. Table 16 is the result. The mathematical expression for system unreliability is:

$$Q_{HI\text{-}HEAD} = Q_{H1} + 0.136Q_{H} + Q_{MOV}^{2}\, Q_{H4} + Q_{SI}^{2} + 2Q_{SIM}\, Q_{SI} + BQ_{SI} + BQ_{MOV}\, Q_{H4}.$$

The terms are defined in Section D.2.1.6 and D.2.7.5. Using DPD arithmetic we obtain:

Mean:	8.13×10^{-3}
Variance:	6.45×10^{-4}
5th Percentile:	1.00×10^{-4}
95th Percentile:	1.40×10^{-2}
Median:	8.70×10^{-4}.

D.2.11 Other Conditions When Fan Coolers and Component Cooling Are Available

If electric buses 5A and 6A or 2A, 3A, 5A, and 6A are unavailable, then system failure is a certainty. If electric buses 2A, 3A, and 6A (or electric buses 2A, 3A, and 5A) are unavailable then fan coolers cannot be available.

D.2.12 Component Cooling Unavailable; Fan Coolers Available

When the fan coolers are available, component cooling appears only in relation to the recirculation pump cooling. The auxiliary component cooling pumps act as a backup to the main (CCW) loop. The failure frequencies are given in Section . The mean and variance of the unreliability of one pump in 24 hours are:

Mean: $1.65 \times 10^{-5} \times 24 + 1.36 \times 10^{-3} = 1.76 \times 10^{-3}$

Variance: $2.22 \times 10^{-8} \times (24)^{2} + 1.22 \times 10^{-6} = 1.40 \times 10^{-5}$.

The mean and variance of the unreliability of two pumps become:

Mean: $(1.76 \times 10^{-3})^2 + 1.40 \times 10^{-5} = 1.71 \times 10^{-5}$.

This unreliability is due to hardware failures. For causes other than this, the β-factor approach is applied (see Section D.2.1.5 for details). The mean of this contribution becomes:

Mean: $0.014 \times 1.76 \times 10^{-3} = 2.42 \times 10^{-5}$.

These frequencies are an order of magnitude less than the total frequencies given in Section D.2.1.2 for the failure of one recirculation pump. Therefore, the effect of component cooling availability can be dropped from the analysis when the fan coolers are available.

E. LOW PRESSURE RECIRCULATION

E.1 FAULT TREE

The top event is "Low Pressure Recirculation Fails to Provide 600 gpm for 24 Hours." Figures 14 through 16, 6 through 12, and 20 through 24 show the fault tree for this event. The fault tree is constructed for the following conditions in addition to those mentioned in Section C.1:

- Large or medium LOCA has occurred.
- Low presssure coolant injection has been completed successfully; therefore, at least one of the four discharge headers is open.
- Heat exchanger cooling is necessary.
- Two out of three SI pumps can provide sufficient cooling if the lo-head discharge headers are unavailable.
- MOV 744 would not be closed on switch 3.

In the event tree of large or medium LOCA, this event is coded as H.

Table 17 gives the minimal cutsets (MCS) with one and two basic events when the house events are treated as basic events. The only single element cutset is the component cooling system.

This fault tree is quantified under several conditions depending on the state of fan coolers, component cooling water system, and electric power. The possibility of switchover to SI pumps due inability to establish containment spray recirculation, is not addressed here because core cooling takes priority. In case of failure of hi-head recirculation the two modes of operation (lo-head and containment spray recirculation) can be activated intermittently. Table 2 gives all possible combinations from these conditions. Also, it refers to the quantification section, the cause table, and the mean and variance of the frequency of the top event.

E.2 QUANTIFICATION

E.2.1 Fan Coolers Unavailable; Component Cooling and All Electric Buses Available

The minimal cutsets and the cause tables are given in Tables 17 and 18, respectively.

E.2.1.1 Human Error Contributions

In a large LOCA, the level in the RWST would drop to the low level alarm point in about 20 minutes. At this point, the time window is 20 minutes. Four operators (similar to small LOCA) would be in the control room by this time. They would still be recovering from the

initial very high stress conditions created by the LOCA. Similar to a small LOCA, the two control board operators would be doing the switchover. The SS would be checking other parts of the control board, and because of the seriousness of the accident, he would be monitoring the process of switchover closely. The STA would not be involved in the specific detail; however, he would be monitoring the overall plant parameters.

The three stages defined for a small LOCA apply here also. However, the timing is much shorter in this case. Operator related events are discussed in two parts: first, events that lead to system failure; second, events that lead to partial failures. Two operator-related events are identified that would lead to system failure. These are:

- Failure to initiate switchover.
- Switch 5, in addition to switch 6, is turned to "on" position and no corrective actions are taken within the available time.

Three things help the operators to recognize that switchover should be initiated. First, operators would remember about the switchover from training. Second, the procedures would lead the operators to switchover. Third, the RWST low level alarm would alert the operators. A large LOCA is considered a high stress situation for the operators. The handbook equates this to emergencies in the military. It used the test results from simulated emergencies. It gives 0.25 as the point estimate for human error frequency. We interpret this as the frequency of error in one well-defined task for one operator. The suggested 5th and 95th percentiles are 0.03 and 0.75, respectively.

The handbook suggests that human error frequency within a half-hour after a large LOCA decreases from unity to 0.1 (a point estimate) given that all automatic recovery systems function normally. It would decrease to 0.25 (the human error frequency discussed earlier) if some systems do not function properly. It should be mentioned here that, switchover to the recirculation phase has always been initiated by the trainees on the simulator. Also, operators have extensive training on the simulator in coping with a large LOCA. Because of this, for switchover initiation only, we divide the basic human error by half; 0.1/2 = 0.05. The dependencies among the operators are very much similar to that in a small LOCA. Using the dependency formulas, a point value for the frequency of failure to initiate switchover becomes:

$$0.05 \times \frac{1 + 0.05}{2} \times \left(\frac{1 + 6 \times 0.05}{7}\right)^2 = 9.1 \times 10^{-4}.$$

We take this as the median and assign an error factor of 20. For lognormal distribution the mean and variance become:

Mean: 4.75×10^{-3}

Variance: 6.00×10^{-4}.

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The 5th and 95th percentiles are 4.55×10^{-5} and 1.82×10^{-2}, respectively. Note that this range includes other dependency levels; e.g., if STA has zero dependence with the rest of the operators, the point value becomes:

$$0.05 \times \frac{1 + 0.05}{2} \times \frac{1 + 6 \times 0.05}{7} \times 0.05 = 2.4 \times 10^{-4}.$$

In the second event, the operators turn switch 5 to the "on" position which closes MOVs 746 and 747 and later they turn switch 6 and trip the SI pumps. It is possible to restore these valves from the control board. The error may occur due to various reasons, e.g., errors by the operator at the control board in interpreting the instructions read to him, or the operator that reads the instructions skips some lines. This would be discovered when the flow to the cold legs is checked. The basic frequency of human error is 0.1. Using the dependence relationships a point value for the frequency of occurrence becomes:

$$0.1 \frac{1 + 0.1}{2} = 0.055.$$

This error may be discovered by all four operators within the remaining time window. In this case, it is assumed that the STA has low dependence with the rest of the team. Thus a point estimate for the frequency of the first event becomes:

$$0.055 \times 0.10 \times \frac{1 + 0.10}{2} \times \frac{1 + 6 \times 0.10}{7} \times \frac{1 + 19 \times 0.1}{20} = 1.00 \times 10^{-4}.$$

We take this as the median and assign an error factor of 20. The lognormal distribution yields:

Mean: 5.26×10^{-4}

Variance: 7.36×10^{-6}.

The 5th and 95th percentiles are 5.01×10^{-6} and 2.01×10^{-3}, respectively. Note that this range inclues other dependency or basic error rates. For example, if STA is moderately dependent and the basic human error rate for recovery is 0.25, the point estimate becomes:

$$0.055 \times 0.25 \times \frac{1 + 0.25}{2} \times \left(\frac{1 + 6 \times 0.25}{7}\right)^2 = 1.10 \times 10^{-3}.$$

Lo-head recirculation may also fail due to a combination of human error and other causes. The failure of the recirculation pumps due to human error is discussed in Section D.2.1.1. This has small impact on system unreliability. Human error on RHR pumps is significant. They have to be aligned manually (from the control room) to provide the recirculation flow when the recirculation pumps are not available.

The operators can switch to the RHR pumps and establish the recirculating flow from the containment sump. They have to reset the recirculation switch 3, also. We believe that, since the stress level would be very high due to failures in the recirculation pumps, the error rate for one operator is about 0.5 and the dependency among all four operators is very high (HD). Then, a point value for the operators to fail to switch to the RHR pumps is:

$$0.5 \times \left(\frac{1 + 0.5}{2} \right)^3 = 0.21.$$

An error factor of 3 is chosen for this frequency. The mean and variance of lognormal distribution become:

Mean: 0.26

Variance: 3.9×10^{-2}.

E.2.1.2 Single Hardware Failures

There are no single element minimal cutsets.

E.2.1.3 Multiple Hardware Failures

The approach taken here is very similar to that explained in Section D.2.1.3. Table 18 enumerates the main contributors. They are:

- Both recirculation pumps fail and operators fail to switch to RHR pumps. The mean of the unreliability of both recirculation pumps is found in Section D.2.1.3:

  Mean: 1.02×10^{-4}.

  The frequency of operator error is computed in Section E.2.1.1. Then system failure frequency yields:

  Mean: $1.02 \times 10^{-4} \times 0.26 = 2.65 \times 10^{-5}$.

- Both MOVs 1802A and 1802B fail to open and operators fail to switch to RHR pumps. The mean and variance of the frequency of failure of two MOVs are found in Section D.2.1.3:

  Mean: 4.88×10^{-6}

  Variance: 5.03×10^{-10}.

  System failure frequency yields:

  Mean: $4.88 \times 10^{-6} \times 0.26 = 1.27 \times 10^{-6}$.

- MOVs 822A and 822B fail to open. This failure mode causes total loss of cooling in the heat exchangers.

E.2.1.4 Maintenance Contribution

Only the SI pumps are the main contributors here. The contribution of RHR-related components is dominated by operators' failure to switch over.

The cutsets that are affected by maintenance consist of two-out-of-three SI pumps, one of either MOV 747 or 638, and either MOV 746 or 640.

Section D.2.1.3 gives the unreliability of one SI pump due to hardware failure:

Mean: 3.77×10^{-2}

Variance: 4.35×10^{-3},

and due to maintenance:

Mean: 8.13×10^{-4}

Variance: 6.22×10^{-8}.

Unreliability of two out of three SI pumps becomes:

Mean: $3\ (3.77 \times 10^{-2} \times 8.13 \times 10^{-4}) = 9.20 \times 10^{-5}$.

The frequency for one MOV transfer closed (see Section _______) yields:

Mean: 9.15×10^{-8}

Variance: 1.01×10^{-14}.

Mean of the frequency of two valves out of two pairs of valves failing to open is:

Mean: $4\ (9.15 \times 10^{-8})^2 + 1.01 \times 10^{-14} = 7.35 \times 10^{-14}$.

Thus, the mean frequency for system failure due to maintenance is much less than 10^{-10}.

E.2.1.5 Other Causes

The discussions given in Section D.2.1.5 apply here also. The same β-factor can be used. The failure of all SI pumps and both MOVs 888 does not cause the top event here. However, if both recirculation pumps or both MOVs 1802 fail and RHR pumps are not realigned, then system failure would occur. The same is true if both MOVs 822A and 822B fail to open.

The frequency of both recirculation pumps or both MOVs 1802 failing to operate (using β-factor) is computed in Section D.2.1.5:

Mean: 4.66×10^{-5}.

The mean of system failure frequency is:

Mean: $4.66 \times 10^{-5} \times 0.26 = 1.21 \times 10^{-5}$.

The frequency of two MOVs (822A and 822B in this case) failing to open is computed in Section D.2.1.5 (using β-factor). The mean is:

Mean: 2.10×10^{-5}.

E.2.1.6 System Unreliability

Table 18 shows the results that have been derived for the mean values of the contributors to lo-head recirculation unavailability when the fan coolers are unavailable and component cooling and all electric buses are available. Only the main contributors are used here for uncertainty analysis. The mathematical expression for the system unreliability in terms of the dominant contributors is:

$$Q_{LO\text{-}HEAD} = Q_{H1} + 0.111Q_{H1} + Q_{RC}^2\, Q_{H3} + Q_{MOV}^2\, Q_{H3} + Q_{MOV}^2 + B(Q_{RC} + Q_{MOV})\, Q_{H3} + BQ_{MOV}$$

where

Q_{H1}: Human error, failure to initiate switchover;

$\alpha = 4.75 \times 10^{-3}$, $\beta^2 = 6.0 \times 10^{-4}$

Q_{RC}: Recirculation pump unreliability;

$\alpha = 1.83 \times 10^{-3}$, $\beta^2 = 9.91 \times 10^{-5}$

Q_{H3}: Human error, failure to switch to RHR pumps;

$\alpha = 0.26$, $\beta^2 = 3.9 \times 10^{-2}$

Q_{MOV}: MOV fails to operate;

$\alpha = 1.51 \times 10^{-3}$, $\beta^2 = 2.64 \times 10^{-6}$

B: β-factor; $\alpha = 1.4 \times 10^{-2}$, $\beta^2 = 6.1 \times 10^{-4}$.

Using DPD arithmetic, we find for $Q_{LO\text{-}HEAD}$:

Mean:	5.32×10^{-3}
Variance:	1.43×10^{-4}
5th Percentile:	5.00×10^{-5}
95th Percentile:	1.40×10^{-2}
Median:	2.10×10^{-3}.

E.2.2 Fan Coolers and Electric Bus 6A Unavailable; Component Cooling and Electric Buses 2A, 3A, and 5A Available

Loss of electric bus 6A at or before safeguards actuation causes the failure of recirculation pump 32, RHR pump 32, SI pump 33, MOVs 888B, 822B, 885B, and 1802B. Since 885B is electrically inoperable, recirculation via the RHR pumps is assumed not possible. However, it may be opened manually within the available time. Table 19 gives the cause table. Each item in this table is discussed hereafter.

E.2.2.1 Human Error Contributions

The frequency of operator failure to establish lo-head recirculation is evaluated in Section E.2.1.1. The discussions there apply to this case also. Loss of electric bus 6A would have some effect on operator error rates. The handbook increases the human error frequency to 0.25. We quote from p. 17-19: "if the automatic recovery systems function normally to instigate the effects of the accident the error rate is 0.1. Otherwise, the error probability will not decrease below 0.25 but will remain at that value as long as the highly stressful conditions persist."

The discussions on human error in Section E.2.1.1 apply to this case also. Bus failure would probably occur at safeguards actuation. The operators would immediately attempt to restore the bus from the control room. In case of failure operation personnel would be dispatched to restore the bus locally. Only one operator would be occupied with bus restoration for the first few minutes. By the time of switchover initiation all four operators would be in positions similar to those described in Sections E.2.1.1 except that the SS would be receiving telephone calls regarding the failed bus.

The levels of dependency are taken as identical to those in Section E.2.1.1. Similarly, the basic human error rate is halved for failure to initiate switchover. A point value for the frequency of failure to initiate switchover becomes:

$$0.125 \times \frac{1 + 0.125}{2} \times \left(\frac{1 + 6 \times 0.125}{7}\right)^2 = 4.4 \times 10^{-3}.$$

We take this as the median and 20 for the error factor. The lognormal distribution yields:

Mean: 2.31×10^{-2}

Variance: 1.42×10^{-2}.

Error on switch 5 is discussed in Section E.2.1.1. The same arguments apply here also, except that the basic human error frequency is 0.25 in this case. Moderate dependence is given to STA. A point value for the conditional frequency of error on switch 5 is:

$$0.25 \times \frac{1 + 0.25}{2} = 0.156.$$

A point value for the conditional frequency of failure to discover the error is:

$$0.25 \times \frac{1 + 0.25}{2} \times \left(\frac{1 + 6x\ 0.25}{7}\right)^2 = 1.99 \times 10^{-2}.$$

Then a point value for the unconditional frequency of error on switch 5 is:

$$0.156 \times 0.0199 = 3.11 \times 10^{-3}.$$

Taking this as the median and assigning an error factor of 20 for a lognormal distribution we obtain:

Mean: 1.63×10^{-2}

Variance: 7.10×10^{-3}.

E.2.2.2 Other Causes

The only single event cutsets that have some impact on system unreliability are:

	Mean
• Recirculation pump 31	$= 1.83 \times 10^{-3}$
• MOV 1802A	$= 1.50 \times 10^{-3}$
• MOV 822A	$= 1.50 \times 10^{-3}$.

Unavailabilities of the components due to maintenance (see Section D.2.1.5 for details) do not contribute significantly because they are at least two orders of magnitude smaller than the total contribution of human error.

E.2.2.3 System Unavailability

DPD arithmetic is used to sum the distributions given in Sections E.2.2.1 and E.2.2.2. The mathematical expression used for system unreliability is:

$$Q_{LO\text{-}HEAD} = Q_{H2} + 0.706Q_H + Q_{RC} + 2Q_{MOV}$$

where

Q_{H2} = Human Error, failure to initiate switchover; $\alpha = 2.31 \times 10^{-2}$,

$\beta^2 = 1.42 \times 10^{-2}$.

The other terms are defined in Section E.2.1.6. The unreliability of lo-head recirculation in 24 hours after a large or medium LOCA has the following parameters:

Mean:	4.42×10^{-2}
Variance:	5.12×10^{-3}
5th Percentile:	1.90×10^{-3}
95th Percentile:	0.11
Median:	2.30×10^{-2}.

E.2.3 Fan Coolers and Electric Bus 5A Unavailable; Component Cooling and Electric Buses 2A, 3A, and 6A Available

Loss of electric bus 5A causes the failure of recirculation pump 31, RHR pump 32, SI pumps 31 and 32, and MOVs 888A, 822A, 885A, and 1802A. The situation here is almost identical to that described in Section E.2.2 where bus 6A is unavailable. The same discussions and results apply to this case also. See Section E.2.2.3 for the distribution of system unavailability.

E.2.4 Fan Coolers and Electric Buses 2A and 3A Unavailable; Component Cooling and Electric Buses 5A and 6A Available

Loss of electric buses 2A and 3A causes the failure of SI pump 32 and RHR pump 31. The situation here is very similar to that described in Section E.2.1 because these pumps (SI 32 and RHR 31) have little impact on system unavailability. However, this event would affect the operators. The results of Section E.2.2.1 apply here also. Then the system unreliability is the sum of the two dependent distributions defined in that section because other causes do not contribute significantly. The results are:

Mean:	3.94×10^{-2}
Variance:	7.53×10^{-3}
5th Percentile:	2.60×10^{-4}
95th Percentile:	0.106
Median:	7.50×10^{-3}.

E.2.5 Fan Coolers and Electric Buses 2A, 3A, and 6A (or 5A) Unavailable; Component Cooling and Electric Bus 5A (or 6A) Available

The components that would be inoperable are the same as those given in Sections E.2.2 and E.2.3 (or E.2.4). The stress level on the operators would be very high. We judge that the frequency distributions given in Section E.2.2.1 are sufficiently conservative and apply to this case also. See Section E.2.2.3 for the results.

E.2.6 Other Conditions When Fan Coolers are Unavailable

If electric buses 5A and 6A or 2A, 3A, 5A, and 6A are unavailable, then system failure is a certainty. The same is true when component cooling is unavailable.

E.2.7 All Electric Buses, Fan Coolers, and Component Cooling Available

The only difference between this case and that of Section E.2.1 is that heat exchanger cooling availability is not questioned here. Table 19 gives the cause table. It is derived from Table 18 (heat exchanger-related events are deleted). The impact of MOVs 822A and B to system unreliability is minimal. The mean frequency of two MOVs inoperable is (see Section D.2.1.3):

Mean: 4.88×10^{-6}.

This is much smaller than the mean unreliability of the system. Then, the results of Section E.2.1.6 apply to this case also.

E.2.8 Other Conditions When Fan Coolers Are Available

For different combinations of electric bus availability, the system has already been analyzed in Sections E.2.2 through E.2.5 under the conditions of fan cooler unavailability and component cooling availability. In Section E.2.3, we can see that MOV 822A has very small impact on system unreliability. Then, the results of Sections E.2.2 through E.2.5 apply to this case (i.e., fan coolers available) also. When electric buses 5A and 6A are unavailable, system failure is a certainty.

If component cooling is unavailable, then recirculation pump cooling is completely dependent on auxiliary component cooling pump unavailability. In Section D.2.13, we found that the mean of the reliability of two of these pumps is:

Mean: 1.84×10^{-5}.

The same failure mode may occur due to common cause. Using β-factor, we obtained (see Section D.2.13):

Mean: 2.42×10^{-5}.

These are much smaller than the human error contribution. Therefore, the effect of component cooling availability can be dropped from the analysis when the fan coolers are available.

F. CONTAINMENT SPRAY RECIRCULATION

F.1 FAULT TREE

The fault tree for the failure of containment spray recirculation is shown in Figures 13, 5 through 12, and 20 through 24. The top event is "Failure to Establish Containment Spray Recirculation." The fault tree is based on the following conditions in addition to those mentioned in Section C:

- Containment spray has been completed successfully.
- Fan coolers are unavailable (because otherwise containment spray would not be necessary).
- Component cooling is available.
- Backflow into the containment spray system is not considered.

In the event tree of large or medium LOCA, this event is coded as F.

This mode of operation is activated manually after the eight-switch sequence is completed. Operators open MOVs 889A and 889B and throttle MOVs 638 and 640.

Table 20 gives the minimal cutsets (MCS) with one and two elements and all house events treated as basic events. Electrical bus 5A is a single element minimal cutset because it fails MOVs 822A and 889A. Similarly, electrical buses 6A, 36A, and 36B are single element MCSs. This leads to the failure of containment spray recirculation only when core cooling recirculation is not available. However, unavailability of core cooling recirculation can only be caused by components upstream of the heat exchangers because core cooling has been successful during the injection phase (i.e., at least one path from the heat exchangers to the cold legs is available). The components located upstream of the heat exchangers are shared between these two modes of operation (core cooling and containment spray). Therefore, failure of core cooling recirculation leads to the failure of containment spray recirculation. The availability of core cooling recirculation means that there is sufficient and substantially subcooled (relative to the pressure in containment atmosphere) flow in the outlet of one of the heat exchangers. Thus, if one of MOVs 889A or B is opened then containment spray recirculation is a success. This is because, even in case of hot flow in the spray nozzles (sump water not cooled), the containment pressure will not rise substantially. The available heat exchanger provides more cooling than core heat generation. Therefore, subcooled water would be discharged into the sump. Hot flow into the nozzles can occur when one of MOVs 889A or B fail to open and the heat exchanger of the other train loses cooling capability. This can be caused by electric buses 5A, 6A, 36A, or 36B. Thus, the only minimal cutset here is the simultaneous failure of MOVs 889A and B. Nozzle failures are discounted because of low frequencies of failure.

The system is quantified under two conditions only, namely, both electrical buses are available and one electric bus 6A or 5A is available. Under other conditions system status can be determined with certainty. Table 3 summarizes the results for all the cases.

F.2 QUANTIFICATION

F.2.1 All Electric Buses Available

Table 21 gives the cause table. Each item of this table is discussed hereafter.

F.2.1.1 Human Error Contributions

Containment spray recirculation is aligned immediately after core cooling recirculation alignment is completed successfully. This (the successful realignment) may have a reassuring effect on the operators and reduce their error rates. The handbook suggests 0.1 for the error rate of one operator 30 minutes after a large LOCA. In Section E.2.1.1, the dependencies among the operators are given.

Two events must occur for the operators to ignore containment spray recirculation. First, two of the operators (HD) do not follow the procedure beyond the core cooling switchover. Second, all four operators do not recognize the need for containment spray recirculation. The frequency of the first one is:

$$0.1 \frac{1 + 0.1}{2} = 0.055.$$

The conditional frequency of the second event, given that the first one has occurred, is judged to be 0.01. Then, a point value for the frequency of system failure would be:

$$0.055 \times 0.01 = 5.5 \times 10^{-4}.$$

We take this point estimate as the median value and assign an error factor of 10 for the spread. For lognormal distribution, the mean and variance become:

Mean: 1.5×10^{-3}

Variance: 1.3×10^{-5}.

F.2.1.2 Single Hardware Failures

There are no single element cutsets.

F.2.1.3 Multiple Hardware Failures

The simultaneous failure of MOVs 889A and 889B is the dominant contributor when hardware failures are considered. The mean and variance of one valve failing to open are (data from Section _____):

Mean: 1.50×10^{-3}

Variance: 2.63×10^{-6}.

The mean frequency for both valves failing to open becomes:

Mean: $(1.50 \times 10^{-3})^2 + 2.63 \times 10^{-6} = 4.88 \times 10^{-6}$.

The remaining contributors are at least an order of magnitude smaller than 10^{-6}.

F.2.1.4 Maintenance Contribution

Maintenance does not have any effect on this event because MOVs 889A and 889B do not undergo maintenance during normal operation. Maintenance on other components would affect core cooling recirculaton, which is available when the availability of containment spray recirculation is questioned.

F.2.1.5 Other Causes

The discussions given in Section D.2.1.5 apply to this case also. The β-factor method can be used for the pair of MOVs mentioned in Section F.2.1.3. For one pair of MOVs, from Section D.2.1.5, we find:

Mean: 2.10×10^{-5}.

F.2.1.6 System Unavailability

Table 22 shows the results that have been derived for the mean values of the contributors to containment spray recirculation unavailability when the fan coolers are unavailable and component cooling and all electric buses are available. Only the main contributors are used here for uncertainty analysis. The mathematical expression for the unavailability of the system in terms of the unavailabilities of the dominant contributors is:

$$Q_{CS} = Q_{H1} + Q_{MOV}^2 + B\ Q_{MOV}$$

where:

Q_{H1}: Human error, failure to intitiate containment spray recirculation;

$\alpha = 1.50 \times 10^{-3}$, $\beta^2 = 1.30 \times 10^{-5}$

Q_{MOV}: MOV fails to operate

$\alpha = 1.51 \times 10^{-3}$, $\beta^2 = 2.64 \times 10^{-6}$

B: β-factor; $\alpha = 1.40 \times 10^{-2}$, $\beta^2 = 6.10 \times 10^{-4}$.

Using DPD arithmetic we find for Q_{CS}:

Mean:	1.50×10^{-3}
Variance:	1.31×10^{-5}
5th Percentile:	5.50×10^{-5}
95th Percentile:	5.50×10^{-3}
Median:	5.50×10^{-4}.

F.2.2 Electric Bus 5A (or 6A) Unavailable

Loss of electric bus 5A (or 6A) causes inoperability in MOVs 889A and 822A (or MOVs 889B and 822B for 6A). System availability is dependent on one train only. Table 22 gives the cause table.

F.2.2.1 Human Error Contributions

In Section E.2.2.1 operator error rates are increased because some of their attention would be drawn toward restoring the lost bus. We think that this increase does not apply to error rates on containment spray recirculation because core cooling recirculation is established successfully and it has some reassuring effect on the operators. Then we can use the results of Section F.2.1.1 for this case also.

F.2.2.2 Single Hardware Failures

The dominant single element cutset is the failure of MOV 889B (for 6A it would be MOV 889A). The frequency of MOV failure to operate is given in Section ____.

F.2.2.3 Multiple Hardware Failures

All multiple hardware contributors to the unavailability of TOP event are of the order 10^{-5} or lower.

F.2.2.4 Maintenance Contribution

Maintenance does not have any effect (see Section F.2.1.4).

F.2.2.5 Other Causes

The discussions given in Section F.2.1.5 do not apply here because only one train of the redundant trains is available.

F.2.2.6 System Unavailability

Table 22 shows the results that have been derived for the mean values of the contributors to containment spray recirculation unavailability when the fan coolers and electric bus 5A are unavailable and component

cooling and electric buses 2A, 3A, and 6A are available. Only the main contributors are used here for uncertainty analysis. The results of a DPD arithmetic for the unavailabilty of hi-head recirculation are:

Mean:	3.00×10^{-3}
Variance:	8.90×10^{-5}
5th Percentile:	4.00×10^{-4}
95th Percentile:	7.00×10^{-3}
Median:	2.00×10^{-3}.

F.2.3 Other Conditions

See Table 3 for the effect of other conditions.

G. HOT LEG RECIRCULATION

The fault tree for this event is given in Figures 18 through 26 and 7 through 12. The top event is "Failure to Establish Hot Leg Recirculation." The fault tree is constructed based on the following conditions in addition to those of Section C.1:

- Large or medium LOCA has occurred.
- RCS pressure is below 170 psig.
- One SI pump can provide sufficient coolant flow.
- SI pumps have to restart.
- Containment spray is not necessary.
- At least one sump is not blocked.

Hot leg recirculation is questioned only when core cooling recirculation has been successful. This means that recirculation flow up to the suction side of the SI pumps is available. Then, the MCS should include the SI pumps, MOVs 856B, 856G, 888A, and 888B. The time to initiate hot leg recirculation is very flexible. Therefore, it is believed that components outside the containment can be restored (if they fail) without great delay in switchover to hot leg recirculation. Thus, the only failure that we should be concerned with is failure of MOVs 856B and 856F to open. The frequency of two valves failing to operate is obtained in Section D.2.1.3. The mean is:

Mean: 4.88×10^{-6}.

The valves may fail due to causes common to both, such as errors in procedures, manufacturing, installation, and design.

In Section D.2.1.5, the frequency of two MOVs failing is computed using β-factor. The mean is:

Mean: 2.10×10^{-5}.

Unavailability of hot leg recirculation is the sum of these two distributions. Using DPD arithmetic, we obtain:

Mean:	2.57×10^{-5}
Variance:	2.00×10^{-9}
5th Percentile:	5.30×10^{-7}
95th Percentile:	6.90×10^{-5}
Median:	8.10×10^{-6}.

If one of electric buses 5A or 6A is unavailable, then system success is based on one MOV only. Table 4 shows system unavailability for these cases.

TABLE I

SUMMARY OF THE RESULTS FOR HI-HEAD RECIRCULATION (SMALL LOCA)

Conditions Transferred from the Event Tree			Data on System Unreliability in 24 Hours							
Fan Coolers Available?	CCWs Available?	Electric Buses Available	Mean	Variance	5th	Median	95th	Main Contributors	Section No. for Quantification	Table No. for Cause Table
(WASH-1400 results)			Not given	Not given	4.3×10^{-3}	9.0×10^{-3}	2.2×10^{-2}	Human error at switchover: median = 6.0×10^{-3}	-	-
No	Yes	All	4.10×10^{-3}	1.68×10^{-4}	4.7×10^{-5}	4.7×10^{-4}	6.4×10^{-3}	Hardware failures in all hi-head SI pumps: mean = 3.11×10^{-3}	D.2.1	10
No	Yes	2A, 3A, 5A	1.15×10^{-2}	6.50×10^{-4}	1.1×10^{-3}	4.2×10^{-3}	1.8×10^{-2}	Hardware failures mean = 1.11×10^{-2}	D.2.2	11
No	Yes	2A, 3A, 6A	1.15×10^{-2}	6.50×10^{-4}	1.1×10^{-3}	4.2×10^{-3}	1.8×10^{-2}	Hardware failures mean = 1.11×10^{-2}	D.2.3	11
No	Yes	5A, 6A	8.18×10^{-3}	6.39×10^{-4}	1.2×10^{-4}	9.0×10^{-4}	1.6×10^{-2}	Hardware failures in all SI pumps: mean = 7.80×10^{-3}	D.2.4	12
No	Yes	5A	4.52×10^{-2}	4.37×10^{-3}	5.0×10^{-3}	2.4×10^{-2}	0.12	Hardware failure in SI pump: mean = 3.8×10^{-2}	D.2.5	-
No	Yes	6A	4.52×10^{-2}	4.37×10^{-3}	5.0×10^{-3}	2.4×10^{-2}	0.12	Hardware failures in SI pump: mean = 3.8×10^{-2}	D.2.5	-
No	Yes	2A, 3A		System Failure					D.2.6	-
No	Yes	None		System Failure					D.2.6	-
No	No	-		System Failure					D.2.6	-
Yes	-	All	4.05×10^{-3}	1.68×10^{-4}	3.5×10^{-5}	4.3×10^{-4}	6.3×10^{-3}	Hardware failures in all SI pumps: mean = 3.11×10^{-3}	D.2.7	13

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TABLE 1 (continued)

SUMMARY OF THE RESULTS FOR HI-HEAD RECIRCULATION (SMALL LOCA)

Conditions Transferred from the Event Tree			Data on System Unreliability in 24 Hours							
Fan Coolers Available?	CCWs Available?	Electric Buses Available	Mean	Variance	5th	Median	95th	Main Contributors	Section No. for Quantification	Table No. for Cause Table
Yes	-	2A, 3A, 5A	1.00×10^{-2}	6.48×10^{-4}	7.9×10^{-4}	2.9×10^{-3}	1.6×10^{-2}	Hardware failures in all SI pumps: mean = 7.14×10^{-3}	0.2.8	14
Yes	-	2A, 3A, 6A	1.00×10^{-2}	6.48×10^{-4}	7.9×10^{-4}	2.9×10^{-3}	1.6×10^{-2}	Hardware failures in all SI pumps: mean. = 7.14×10^{-3}	0.2.9	15
Yes	-	5A, 6A	8.13×10^{-3}	6.45×10^{-4}	1.0×10^{-4}	8.7×10^{-4}	1.4×10^{-2}	Hardware failures in all SI pumps; mean = 7.14×10^{-3}	0.2.10	16

TABLE 2

SUMMARY OF THE RESULTS FOR LO-HEAD RECIRCULATION (LARGE OR MEDIUM LOCA)

Conditions Transferred from the Event Tree			Data on System Unreliability in 24 Hours					Main Contributors*	Section No. for Quantification	Table No. for Cause Table
Fan Coolers Available?	CCWs Available?	Electric Buses Available	Mean	Variance	5th	Median	95th			
(WASH-1400 results)			Not Given	Not Given	4.4×10^{-3}	1.3×10^{-2}	3.1×10^{-2}	median = 6×10^{-3}	-	-
No	Yes	All	5.32×10^{-3}	1.43×10^{-4}	5.0×10^{-5}	2.1×10^{-3}	1.4×10^{-2}	mean = 5.28×10^{-3}	E.2.1	18
No	Yes	2A, 3A, 5A	4.42×10^{-2}	5.12×10^{-3}	1.9×10^{-3}	2.3×10^{-2}	0.11	mean = 3.94×10^{-2}	E.2.2	-
No	Yes	2A, 3A, 6A	4.42×10^{-2}	5.12×10^{-3}	1.9×10^{-3}	2.3×10^{-2}	0.11	mean = 3.94×10^{-2}	E.2.3	-
No	Yes	5A, 6A	3.94×10^{-2}	7.53×10^{-3}	2.6×10^{-4}	7.5×10^{-3}	0.106	mean = 3.94×10^{-2}	E.2.4	-
No	Yes	5A	4.42×10^{-2}	5.12×10^{-3}	1.9×10^{-2}	2.3×10^{-2}	0.11	mean = 3.94×10^{-2}	E.2.5	-
No	Yes	6A	4.42×10^{-2}	5.12×10^{-3}	1.9×10^{-2}	2.3×10^{-2}	0.11	mean = 3.94×10^{-2}	E.2.6	-
No	Yes	2A, 3A	System Failure						E.2.7	-
No	Yes	None	System Failure						E.2.7	-
No	No	-	System Failure						E.2.7	-
Yes	-	All	5.32×10^{-3}	1.43×10^{-4}	5.0×10^{-5}	2.1×10^{-3}	1.4×10^{-2}	mean = 5.28×10^{-3}	E.2.8	19
Yes	-	2A, 3A, 5A	4.42×10^{-2}	5.12×10^{-3}	1.9×10^{-3}	2.3×10^{-3}	0.11	mean = 3.94×10^{-2}	E.2.9	-
Yes	-	2A, 3A, 6A	4.42×10^{-2}	5.12×10^{-3}	1.9×10^{-3}	2.3×10^{-3}	0.11	mean = 3.94×10^{-2}	E.2.9	-
Yes	-	5A, 6A	3.94×10^{-2}	7.53×10^{-3}	2.6×10^{-4}	7.5×10^{-3}	0.106	mean = 3.94×10^{-2}	E.2.9	-

* Human Error at Switchover

TABLE 3

SUMMARY OF THE RESULTS FOR CONTAINMENT SPRAY RECIRCULATION
(LARGE OR SMALL LOCA; CORE COOLING RECIRCULATION SUCCESSFUL)

Conditions Transferred from the Event Tree			Data on System Unreliability in 24 Hours					Main Contributors	Section No. for Quantification	Table No. for Cause Table
Fan Coolers Available?	CCWs Available?	Electric Buses Available	Mean	Variance	5th	Median	95th			
(WASH-1400 results)			Not Given	Not Given	2.5×10^{-5}	1.0×10^{-4}	9.0×10^{-4}	Maintenance and common mode		
No	Yes	All	1.5×10^{-3}	1.31×10^{-5}	5.5×10^{-5}	5.5×10^{-4}	5.5×10^{-3}	Human error at switchover; mean = 1.5×10^{-3}	F.2.1	21
No	Yes	2A, 3A, 5A	3.0×10^{-3}	8.90×10^{-5}	4.0×10^{-4}	2.0×10^{-3}	7.0×10^{-3}	See the cause table	F.2.2	22
No	Yes	2A, 3A, 6A	3.0×10^{-3}	8.90×10^{-5}	4.0×10^{-4}	2.0×10^{-3}	7.0×10^{-3}	See the cause table	F.2.2	22
No	Yes	5A, 6A	1.5×10^{-3}	1.31×10^{-5}	5.5×10^{-5}	5.5×10^{-4}	5.5×10^{-3}	Human error at switchover; mean = 1.5×10^{-3}	F.2.1	21
No	Yes	5A	3.0×10^{-3}	8.90×10^{-5}	4.0×10^{-4}	2.0×10^{-3}	7.0×10^{-3}	See the cause table	F.2.2	22
No	Yes	6A	3.0×10^{-3}	8.90×10^{-5}	4.0×10^{-4}	2.0×10^{-3}	7.0×10^{-3}	See the cause table	F.2.2	22
No	Yes	2A, 3A	System Failure							-
No	Yes	None	System Failure							-
No	No	-	System Failure							-
Yes	-	-	System Unavailability Not Questioned							

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TABLE 4

SUMMARY OF THE RESULTS FOR HOT LPS RECIRCULATION (LARGE LOCA)

Conditions Transferred from the Event Tree	Data on System Unreliability in 24 Hours					Main Contributors	Section No. for Quantification
Electric Buses Available	Mean	Variance	5th	Median	95th		
(WASH-1400 results)	Not Given	Not Given	4.4×10^{-3}	1.30×10^{-2}	3.10×10^{-2}	Human error or switchover median = 6×10^{-3}	-
All	2.57×10^{-5}	2.02×10^{-9}	5.3×10^{-7}	8.10×10^{-6}	6.90×10^{-5}	Common cause failures in both MOVs 856B and F mean = 2.1×10^{-5}	G
2A, 3A, 5A	1.50×10^{-3}	2.63×10^{-6}	2.4×10^{-4}	1.02×10^{-3}	4.33×10^{-3}	MOV 856F fails to open mean = 1.5×10^{-3}	G
2A, 3A, 6A	1.50×10^{-3}	2.63×10^{-6}	2.4×10^{-4}	1.02×10^{-3}	4.33×10^{-3}	MOV 856B fails to open mean = 1.5×10^{-3}	G
5A, 6A	2.57×10^{-5}	2.02×10^{-9}	5.3×10^{-6}	8.10×10^{-6}	6.90×10^{-5}	Common cause failures in both MOVs 856B and F mean = 2.1×10^{-5}	G
5A	1.50×10^{-3}	2.63×10^{-6}	2.4×10^{-4}	1.02×10^{-3}	4.33×10^{-3}	MOV 856F fails to open mean 1.5×10^{-3}	G
6A	1.50×10^{-3}	2.63×10^{-6}	2.4×10^{-4}	1.02×10^{-3}	4.33×10^{-3}	MOV 856B fails to open mean 1.5×10^{-3}	G
2A, 3A				System Failure			
None				System Failure			

TABLE 5

POWER SUPPLIES FOR THE RECIRCULATION SYSTEM COMPONENTS

Motor-Operated Valve Power Supplies

Valve Designator	MCC Bus	Valve Designator	MCC Bus
638	36B	856F	36B
640	36A	833	36B
744	36A	885A	36A
745A	36B	885B	36B
745B	36A	888A	36A
746	36A	888B	36B
747	36A	889A	36A
822A	36A	889B	36B
822B	36B	899A	36B
856A	36A	899B	36B
856B	36B	1802A	36A
856C	36A	1802B	36B
856D	36B	1869A	36A
856E	36A	1869B	36B

Pump Power Supplies

Pump	AC Bus	DC Bus
RHR 31	3A	33
RHR 32	6A	32
SI 31	5A	31
SI 32	2A	33
SI 33	6A	32
Recirculation 31	5A	31
Recirculation 32	6A	32
Auxiliary Component Cooling 31	36A	-
Auxiliary Component Cooling 32	36B	-
Auxiliary Component Cooling 33	36A	-
Auxiliary Component Cooling 34	36B	-

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TABLE 6

TEST REQUIREMENTS FOR THE RECIRCULATION SYSTEM COMPONENTS

Valve	Action	Frequency
MOVs		
744	verify open (Control Room)	monthly
	stroke test	refueling
	verify open	cold S/D
745 A,B	stroke test (Control Room)	quarterly
	verify open	monthly
	verify open	cold S/D
746	stroke	refueling
	verify open	cold S/D
		monthly
747	stroke	refueling
	verify open	cold S/D
		monthly
822 A,B	stroke test	refueling
	verify operable	cold S/D
856 A,C,D,E F,H,J,K	verify open (CCR)	monthly
	verify open	quarterly
	stroke test	unscheduled
		refueling
856 B,G	verify closed (CCR)	monthly
	stroke test and interlock test	cold S/D
	stroke test	refueling
883	verify closed	monthly
885 A,B	verify closed	monthly
	stroke test and direct observation	quarterly
888 A,B	verify closed	monthly
	stroke test and direct observation	quarterly
	stroke	refueling
	stroke	refueling

TABLE 6 (continued)

TEST REQUIREMENTS FOR THE RECIRCULATION SYSTEM COMPONENTS

Valve	Action	Frequency
889 A,B	verify closed	monthly
	stroke test	quarterly
	stroke test	refueling
899 A,B	verify open	monthly
1802 A,B	verify open	cold S/D
	verify closed	monthly
	stroke test	quarterly
	verify closed	refueling
1805	stroke test	refueling
1869 A,B	verify open	monthly
638	stroke test	quarterly
	verify open	cold S/D
640	stroke test	quarterly
	verify open	cold S/D
Manual Valves		
735 A,B	verify open	monthly
739 A,B	verify open	monthly
751 A,B	verify open	monthly
752 A,B	verify open	monthly
753 A,B,C,...,H	verify open	monthly
818 A,B	—	—
820 A,B	—	—
846	verify open	monthly
1863	—	—
Check Valves		
738 A,B	open on demand	monthly
741		refueling
755 A,B	open on demand	monthly
		refueling

TABLE 6 (continued)

TEST REQUIREMENTS FOR THE RECIRCULATION SYSTEM COMPONENTS

Valve	Action	Frequency
857 A,B,...,W	leakage test	refueling
895 A,B,C,D	leakage test	unscheduled
897 A,B,C,D	leakage test	unscheduled
838 A,B,C,D	leakage test	unscheduled
	open on demand	refueling

Level Indicators

The level indicators for containment and recirculation sumps are tested for operability at every refueling (PT-R1, PT-R2).

Pumps

Pump	Action	Frequency	Test Name
RHR 31, 32	Run for 15 to 30 minutes	monthly	PT-M18
	Run for long period	cold S/D	
SI 31, 32, 33	Run for 15 to 30 minutes	monthly	PT-M16
Recirculation 31, 32	Run for 15 to 30 minutes	refueling	PT-R13
Auxiliary Component Cooling 31, 32, 33, 34	Run for 15 to 30 minutes	monthly	

TABLE 7

FAILURE MODE OF COMPONENTS AND THEIR CODES USED IN THE FAULT TREES

Component	Failure Mode	Code Used In Fault Tree	Mean	Variance	Data Source Table B.2-2 (item)
Check Valves					
886(A,B)	Stuck closed	ECV886(A,B)C	6.91×10^{-5}	1.03×10^{-8}	3
755(A,B)		UCV755(A,B)C			
741		ECV-741C			
738(A,B)		ECV738(A,B)C			
897(A,B,C,D)		ECV897(A,B,C,D)C			
838(A,B,C,D)		ECV838(A,B,C,D)C			
857(A,B,F,M)		HCV857(A,B,F,M)C			
895(A,B,C,D)	Leakage	ECV895(A,B,C,D)L	6.91×10^{-7}	4.87×10^{-13}	4
Manual Valve					
820(A,B)	Inadvertently closed	UXV820(A,B)C	9.15×10^{-8}	1.01×10^{-14}	1
818(A,B,C,D)		UXV818(A,B,C,D)C			
751(A,B)		UXV751(A,B)C			
752(A,B)		UXV752(A,B)C			
753(A,B,...,H)		UXV753(A,B,...,H)			
739(A,B)		EXV739(A,B)C			
735(A,B)		EXV735(A,B)C			
846	Not closed by the operator during accident	EXV-846B	(see text)		
1863		EXV1863B	(see text)		

TABLE 7 (continued)

FAILURE MODE OF COMPONENTS AND THEIR CODES USED IN THE FAULT TREES

Component	Failure Mode	Code Used In Fault Tree	Mean	Variance	Data Source Table B.2-2 (item)
MOVs					
856(A,C,D,E)	Does not close due to mechanical failure	HMV856(A,C,D,E)X	1.51×10^{-3}	2.64×10^{-6}	6
888(A,B) 889(A,B) 822(A,B) 885(A,B) 856(B,F) 802(A,B)	Does not open due to mechanical failure	HMV888(A,B)Q CMV889(A,B)Q UMV822(A,B)Q EMV885(A,B)Q HMV856(B,F)Q EMV802(A,B)Q	1.51×10^{-3}	2.64×10^{-6}	6
883	Transfers open due to mechanical failure	EMV-883B	9.87×10^{-8}	4.38×10^{-12}	7
745(A,B) 744 638 640 746 747 899(A,B) 1869(A,B)	Transfers closed due to mechanical failure	EMV745(A,B)C EMV744-C EMV-638C EMV-640C EMV-746C EMV-747C EMV-899(A,B)C EMV-869(A,B)C	9.15×10^{-8}	1.01×10^{-14}	1
Pumps					
RHR(31,32) RECIRC(31,32) SI(31,32,33) Auxiliary Component Cooling (31,32,33,34)	Fails when running or fails to restart, includes motor and all other related components that are at pump location	EPMRH(31,32)S EPMRC(31,32)S EPMSI(31,32,33)S EPMCC(31,32,33,34)S	1.50×10^{-4}/hr 1.96×10^{-5}/hr 1.79×10^{-3}/hr 1.65×10^{-5}/hr	$1.74 \times 10^{-8}/hr^2$ $1.70 \times 10^{-7}/hr^2$ $4.77 \times 10^{-5}/hr^2$ $2.22 \times 10^{-8}/hr^2$	14 18 13 16

TABLE 7 (continued)

FAILURE MODE OF COMPONENTS AND THEIR CODES USED IN THE FAULT TREES

Component	Failure Mode	Code Used In Fault Tree	Mean	Variance	Data Source Table B.2-2 (item)
Pump Motors					
RHR(31,32) RECIRC(31,32) SI(31,32,33) Auxiliary Component Cooling (31,32,33,34)	Fails when running or fails to restart, includes all components that are not at pump location	EMORH(31,32)S EMORC(31,32)S EMOSI(31,32,33)S EMOCC(31,32,33,34)S	1.36×10^{-3}	1.22×10^{-6}	11
Pipes					
No. 60 No. 361	Plugged or breached	HPPLN60E HPPL361E	8.60×10^{-10}/hr 8.60×10^{-10}/hr		WASH-1400 WASH-1400
Noncomponent Events					
Containment Sump	Blockage of gratings	ECNTSUMP	5.00×10^{-5}		C.3 of this section
Recirculation Sump	Blockage of gratings	ERECSUMP	5.00×10^{-5}		C.3 of this section
Component Cooling System	System failure	UCCWFAIL	House Event		
Interlock Circuitry					
856(B,G)	Interlock fails to give permissive signal to open 856-valves	H856(B,G)ILC	(see text)		

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TABLE 7 (continued)

FAILURE MODE OF COMPONENTS AND THEIR CODES USED IN THE FAULT TREES

Component	Failure Mode	Code Used In Fault Tree	Mean	Variance	Data Source Table B.2-2 (item)
Control Circuitry for Pumps					
RHR(31,32) RECIRC(31,32) SI(31,32,33) Auxiliary Component Cooling (31,32,33,34)	Fails to provide start signal or gives inadvertent stop signal	ECNTRH(31,32)S ECNTRC(31,32)S ECNTSI(31,32,33)S ECNTCC(31,32,33,34)S	has been included as part of the pump		
Control Circuitry for Valves					
856(A,C,D,E)	Fails to provide close signal	HCNT856(A,C,D,E)	has been included as part of the MOV		
883	Inadvertently opens the valve	ECNT-883			
888(A,B) 889(A,B) 822(A,B) 885(A,B) 856(B,F) 802(A,B)	Fails to provide open signal	HCNT888(A,B) CCNT889(A,B) UCNT822(A,B) ECNT885(A,B) HCNT856(B,F) ECNT802(A,B)			

TABLE 7 (continued)

FAILURE MODE OF COMPONENTS AND THEIR CODES USED IN THE FAULT TREES

Component	Failure Mode	Code Used In Fault Tree	Mean	Variance	Data Source Table B.2-2 (item)
745(A,B)	Inadvertently closes the valve	ECNT-745(A,B)			
744		ECNT-744			
746		ECNT-746			
747		ECNT-747			
638		ECNT-638			
640		ECNT-640			
899(A,B)		ECNT-899(A,B)			
1869(A,B)		ECNT-869(A,B)			
<u>Electric Power</u>					
Bus 2A	Insufficient power	JBS-32AD	House Event		
Bus 3A		JBS-33AD			
Bus 5A		JBS-35AD			
Bus 6A		JBS-36AD			
DC Power Panel 31		4BS-321D			
DC Power Panel 32		4BS-322D			
DC Power Panel 33		4BS-323D			
DC Power Panel 34		4BS-324D			
MCC 36A		JBS336AD			
MCC 36B		JBS336BD			

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TABLE 8

SYSTEM EFFECTS OF PIPE FAILURE

Pipe Section	Diameter (inches)	System Failure	Potential For Other System Failure	Initiating Event LOCA	Comments
No. 293 (downstream of recirculation pumps).	10	Partial, RHR pumps can be used.	No	No	Would be detected during refueling outage only.
No. 9 (crosstie between the RHR heat exchangers, the connecting pipes to low pressure pumps).	10	Partial; if it is isolated by 745 valves, then one heat exchanger will be ineffective.	Yes, LPIS	No	Would be detected within one week, it can also be isolated.
No. 60 (connecting line between SI pumps and RHR heat exchangers).	8	Partial failure of hi-head recirculation, if the break is downsteam of 888 valves.	Yes, HPIS	No	Would be detected within one week.
No. 359 (crosstie between the lo-head discharge lines).	10	Partial failure of low pressure recirculation, SI pumps can be used.	Yes, LPIS	No	Would be detected within one week.

TABLE 8 (continued)

SYSTEM EFFECTS OF PIPE FAILURE

Pipe Section	Diameter (inches)	System Failure	Potential For Other System Failure	Event LOCA	Initiating Comments
No. 10, 57 (suction to RHR).	18	Partial, recirculation pumps can be used.	Yes, LPIS	No	Would be detected within one week.
No. 351, 352, 353, 350 (cold leg discharge, lo-head).	10	Partial.	No	Yes, large LOCA	
No. 16, 16A, 753, 754 (cold leg discharge, hi-head).	2	Partial, can be isolated.	No	Yes, small LOCA	
No. 56, 843 (hot leg discharge).	2	Partial, can be isolated.	No	Yes, small LOCA	

TABLE 9

THE MINIMAL CUTSETS FOR THE FAULT TREE FOR HI-HEAD RECIRCULATION WHEN THE HOUSE EVENTS ARE TREATED AS BASIC EVENTS

PRINTOUT OF MINIMAL CUT SETS FOR PHASE 1

TITLE: INSUFFICIENT FLOW IN HI-HEAD RECIRCULATION (IF-1)

CUT SETS WITH 1 BASIC EVENTS.

2) 1) HPPLHOUT 2) UCCHFAIL

CUT SETS WITH 2 BASIC EVENTS.

6)	1)	HCNI008A	HCNI008B	2)	HMV008AD	HCNI008B	3)	HCNI008A	HMV008BD	4)	HMV008AD	HMV008BD
10)	5)	LCNI069B	LCNI069A	6)	LMV069AC	LCNI069A	7)	LCNI069B	LMV069AC	8)	LMV069BC	LMV069AC
14)	9)	LCNI069B	UCNI022B	10)	LMV069BC	UCNI022B	11)	LCNI069B	UMV822BD	12)	LMV069BC	UMV822BD
18)	13)	ERECSUMP	LCNI005A	14)	ERECSUMP	LMV005AD	15)	ERECSUMP	LSB2INLC	16)	ERECSUMP	LCNI005B
22)	17)	ERECSUMP	LPVE050D	18)	ERECSUMP	LCNI-002	19)	ERECSUMP	LMV-002A	20)	ERECSUMP	LCV-751C
26)	21)	ERECSUMP	LCNISUMP	22)	ERECSUMP	LCNI755-	23)	ERECSUMP	LMV755-D	24)	LCNI069B	UCV751BC
30)	25)	LMV069BC	LCV751BC	26)	LCNI069B	UXV820BC	27)	LMV069BC	UXV820BC	28)	LCNI069B	UXV810BC
34)	29)	LMV069BC	UXV810BC	30)	LCNI069B	UXV810CC	31)	LMV069BC	UXV810CC	32)	UCV751BC	UCNI022A
38)	33)	UXV820BC	UCNI022A	34)	UXV810BC	UCNI022A	35)	UXV810CC	UCNI022A	36)	UCV751BC	UMV822AD
42)	37)	UXV820BC	UMV822AD	38)	UXV810BC	UMV822AD	39)	UXV810CC	UMV822AD	40)	UCV751BC	UCV751AC
46)	41)	UXV820BC	UCV751AC	42)	UXV810BC	UCV751AC	43)	UXV810CC	UCV751AC	44)	UCV751BC	UXV820AC
50)	45)	UXV820BC	UXV820AC	46)	UXV810BC	UXV820AC	47)	UXV810CC	UXV820AC	48)	UCV751BC	UXV810AC
54)	49)	UXV820BC	UXV810AC	50)	UXV810BC	UXV810AC	51)	UXV810CC	UXV810AC	52)	UCV751BC	UXV810DC
58)	53)	UXV820BC	UXV810DC	54)	UXV810BC	UXV810DC	55)	UXV810CC	UXV810DC	56)	UCV751BC	LXV-752C
62)	57)	UXV820BC	LXV-752C	58)	UXV810BC	LXV-752C	59)	UXV810CC	LXV-752C	60)	UCNI022B	UCNI022A
66)	61)	UMV822BD	UCNI022A	62)	UCNI022B	UMV822AD	63)	UMV822BD	UMV822AD	64)	UCNI022B	UCV751AC
70)	65)	UMV822BD	UCV751AC	66)	UCNI022B	UXV820AC	67)	UMV822BD	UXV820AC	68)	UCNI022B	UXV810AC
74)	69)	UMV822BD	UXV810AC	70)	UCNI022B	UXV810DC	71)	UMV822BD	UXV810DC	72)	UCNI022B	LXV-752C
78)	73)	UMV822BD	LXV-752C	74)	LCNI069A	UCNI022A	75)	LMV069AC	UCNI022A	76)	LCNI069A	UMV822AD
82)	77)	LMV069AC	UMV822AD	78)	LCNI069A	UCV751AC	79)	LMV069AC	UCV751AC	80)	LCNI069A	UXV820AC
86)	81)	LMV069AC	UXV820AC	82)	LCNI069A	UXV810AC	83)	LMV069AC	UXV810AC	84)	LCNI069A	UXV810DC
90)	85)	LMV069AC	UXV810DC	86)	LCNI069A	LXV-752C	87)	LMV069AC	LXV-752C	88)	HCNI008A	JBS11GBD
94)	89)	HMV008AD	JBS11GBD	90)	LCNI069B	JBS11GBD	91)	LMV069BC	JBS11GBD	92)	LCNI022A	JBS11GBD
98)	93)	LMV022AD	JBS11GBD	94)	ERECSUMP	JBS11GBD	95)	JBS11GBD	UCNI022A	96)	JBS11GBD	UMV822AD
102)	97)	LCNI755B	JBS11GBD	98)	LMV755BC	JBS11GBD	99)	JBS11GBD	LCNI755A	100)	JBS11GBD	LMV755AC
106)	101)	JBS11GBD	LCV751AC	102)	JBS11GBD	UXV820AC	103)	JBS11GBD	UXV810AC	104)	JBS11GBD	UXV810DC
110)	105)	JBS11GBD	LXV-752C	106)	HCNI008A	JBS1GA-D	107)	HMV008AD	JBS1GA-D	108)	LCNI069B	JBS1GA-D
114)	109)	LMV069BC	JBS1GA-D	110)	JBS1GA-D	LCV008AC	111)	JBS1GA-D	UXV752AC	112)	JBS1GA-D	UXV752EC
118)	113)	JBS1GA-D	LXV752GC	114)	JBS1GA-D	UXV752HC	115)	JBS1GA-D	UXV752JC	116)	JBS1GA-D	UXV752KC
122)	117)	LCNI002A	JBS1GA-D	118)	LMV002AD	JBS1GA-D	119)	JBS1GA-D	LPMRCJ1S	120)	JBS1GA-D	LPURCJ1S
126)	121)	JBS1GA-D	LCNIRCJ1	122)	ERECSUMP	JBS1GA-D	123)	JBS1GA-D	UCNI022A	124)	JBS1GA-D	UMV822AC
130)	125)	LCNI755B	JBS1GA-D	126)	LMV755BC	JBS1GA-D	127)	JBS1GA-D	LCNI755A	128)	JBS1GA-D	LMV755AC
134)	129)	JBS1GA-D	LCV751AC	130)	JBS1GA-D	UXV820AC	131)	JBS1GA-D	UXV810AC	132)	JBS1GA-D	UXV810DC

(Continued)

TABLE 9 (continued)

THE MINIMAL CUTSETS FOR THE FAULT TREE FOR HI-HEAD RECIRCULATION WHEN THE HOUSE EVENTS ARE TREATED AS BASIC EVENTS

PRINTOUT OF MINIMAL CUT SETS FOR PHASE 1

TITLE: INSUFFICIENT FLOW INFI-HEAD RECIRCULATION (IP-3)

CUT SETS WITH 2 BASIC EVENTS.

113)	133)	JBS36A-D	LXV-752C	134)	JBS336AD	HCNT0000	135)	JBS336AD	HMV00000	136)	JBS336AD	ECNT0020
152)	137)	JBS336AC	EFV0020U	138)	ERECSUMP	JBS336AD	139)	UCV751UC	JBS336AD	140)	UXV020UC	JBS336AC
150)	141)	UXV016UC	JBS336AD	142)	UXV010CC	JBS336AD	143)	UCNT0020	JBS336AD	144)	UMV0220U	JBS336AC
170)	145)	ECNT009A	JBS336AD	146)	EMV0097AC	JBS336AD	147)	JBS3360D	JBS336AD	148)	JBS36A-D	JBS336AC
158)	149)	JBS35A-D	HCNT0000	150)	JBS35A-D	HMV00000	151)	JBS35A-D	ECV0060C	152)	JBS35A-D	UXV753AC
170)	153)	JBS35A-D	LXV753CC	154)	JBS35A-D	UXV753CC	155)	JBS35A-D	UXV753BC	156)	JBS35A-D	UXV753JC
162)	157)	JBS35A-D	UXV753AC	158)	JBS35A-D	ECNT0020	159)	JBS35A-D	EMV0020U	160)	EPMRC325	JBS35A-D
160)	161)	EMORC325	JBS35A-D	162)	ECNTRC32	JBS35A-D	163)	ERECSUMP	JBS35A-D	164)	UCV751UC	JBS35A-D
170)	165)	UXV020UC	JBS35A-D	166)	UXV010UC	JBS35A-D	167)	UXV010CC	JBS35A-D	168)	UCNT0220	JBS35A-D
174)	169)	UMV0220U	JBS35A-D	170)	ECNT009A	JBS35A-D	171)	EMV0097AC	JBS35A-D	172)	JBS3360D	JBS35A-D
170)	173)	JBS36A-D	JBS35A-D	174)	4BS332-D	ECV0060C	175)	4BS332-D	UXV752AC	176)	4BS332-D	UXV752CC
152)	177)	4BS332-D	LXV752CC	178)	4BS332-D	UXV752BC	179)	4BS332-D	UXV752JC	180)	4BS332-D	UXV752AC
160)	181)	4BS332-D	EPMRC325	182)	4BS332-D	EMORC325	183)	4BS332-D	ECNTRC32	184)	ERECSUMP	4BS332-D
170)	185)	4BS332-D	JBS35A-D	186)	HPMS1335	4BS331-D	187)	HMOS1335	4BS331-D	188)	HCNTS131	4BS331-D
192)	189)	JBS36A-D	4BS331-D	190)	4BS332-D	4BS331-D						

TABLE 10

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	All	Fails	No effect	No effect
Switch No. 6 is turned to "on" position and no recovery actions are taken.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Pipe No. 60 rupture (5").	1.44×10^{-7}	Pipe No. 60	Fails	No effect	No effect
Multiple failures.					
Mechanical failure in both recirculation pumps and operator error in switching to RHR pumps.	1.56×10^{-6}	Recirculation pumps 31 and 32 and all RHR subsystems	Fails	No effect	No effect

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TABLE 10 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
All three SI pumps fail.	3.11×10^{-3}	SI pumps 31, 32, and 33	Fails	No effect	No effect
MOVs 888A and 888B do not open.	4.88×10^{-6}	MOVs 888A and 888B	Fails	No effect	No effect
MOVs 822A and 822B do not open.	4.88×10^{-6}	MOVs 822A and 822B	Fails	No effect	No effect
Testing	NR*	NR*	No effect	NR*	No effect
Maintenance and Hardware					
Maintenance on one SI pump and mechanical failure of the other two.	1.74×10^{-5}	All three SI pumps unavailable	Fails	No effect	No effect
Other Causes					
See Section D.2.1.5 for details.	5.50×10^{-4}	SI pumps or MOVs 888.	Fails	?	?
Total frequency of system failure.	4.10×10^{-3}				

*Not Relevant

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TABLE 11

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS AND ELECTRIC BUS 5A UNAVAILABLE; COMPONENT COOLING AND ELECTRICAL BUSES 2A, 3A and 6A AVAILABLE

Cause	Mean	Effects: Component	Effects: System	Effects: Other Systems	Effects: Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	NR*	Fails	Containment spray recirculation	No effect
Switch No. 6 is turned to "on" position and no recovery.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Loss of power in electric bus 36B.	2.00×10^{-6}	Movs 822A and 747	Fails	No effect	No effect
Pipe no. 60 rupture (5").	1.44×10^{-7}		Fails	No effect	No effect
MOV 1802B fails to open.	1.50×10^{-3}	MOV 1802B	Fails	No effect	No effect
Manual valves 753A, F G, H, J, or K closed	5.40×10^{-7}	Valves 753A, F G, H, J, or K	Fails	No effect	No effect

*Not Relevant

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TABLE 11 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS AND ELECTRIC BUS 5A UNAVAILABLE; COMPONENT COOLING AND ELECTRICAL BUSES 2A, 3A and 6A AVAILABLE

Cause	Mean	Effects: Component	System	Other Systems	Initiating Event
MOV 822B fails to open	1.51×10^{-3}	MOV 822B	Fails	No effect	No effect
No power at DC bus 32	3.00×10^{-8}	DC Bus 32	Fails	No effect	No effect
Multiple Failures					
SI pumps 32 and 33 fail to run.	7.14×10^{-3}	SI pumps 32 and 33	Fails	No effect	No effect
Recirc. pump 31 fails to run and operators fail to align RHR.	2.29×10^{-4}	Recirculation pump 31	Fails	No effect	No effect
MOV 888B fails to open and operators fail to open it manually.	1.88×10^{-4}	MOV 888B	Fails	No effect	No effect
Testing	NR*	NR*	No effect	NR*	No effect
Maintenance					
See Section D.2.2.4 for details	6.13×10^{-5}	SI pump 32 or 33	Fails	No effect	No effect

* Not Relevant

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TABLE 11 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS AND ELECTRIC BUS 5A UNAVAILABLE; COMPONENT COOLING AND ELECTRICAL BUSES 2A, 3A and 6A AVAILABLE

Cause	Mean	Effects: Component	Effects: System	Effects: Other Systems	Effects: Initiating Event
Other Causes					
See Section D.2.2.5 for details	5.28×10^{-4}	SI pump 32 or 33, MOV 888B or recirc pump 32 or MOV 822A	Fails	?	?
Total frequency of system failure	1.15×10^{-2}				

TABLE 12

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS AND ELECTRIC BUSES 2A and 3A UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRIC BUSES 5A and 6A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	All	Fails	Containment spray recirculation	No effect
Switch No. 6 is turned to "on" position and no recovery action.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Pipe No. 60 rupture (5").	1.44×10^{-7}		Fails	Part of containment spray recirculation	No effect
Multiple Failures					
Mechanical failure in both recirculation pumps and operator error in switching to RHR pumps.	1.56×10^{-6}	Recirculation pumps 31 and 32 and all RHR subsystems.	Fails	No effect	No effect

TABLE 12 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS AND ELECTRIC BUSES 2A and 3A UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRIC BUSES 5A and 6A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
SI pumps 31 and 33 fail.	7.14×10^{-3}	SI pumps 31 and 33	Fails	No effect	No effect
MOVs 888A and 888B do not open.	4.88×10^{-6}	MOVs 888A and 888B	Fails	No effect	No effect
MOVs 822A and 822B do not open.	4.88×10^{-6}	MOVs 822A and 822B	Fails	No effect	No effect
Testing	NR*	NR*	No effect	NR*	No effect
Maintenance and Hardware					
Maintenance on one SI pump and mechanical failure of the other.	6.13×10^{-5}	Both SI pumps 31 and 33 unavailable	Fails	No effect	No effect
Other Causes					
See Section D.2.1.5 for details	5.50×10^{-4}	SI pump or MOVs 888	Fails	?	?
Total frequency of system failure	8.18×10^{-3}				

* Not Relevant

TABLE 13

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS COMPONENT COOLING AND ALL ELECTRIC BUSES AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	All	Fails	No effect	No effect
Switch No. 6 is turned to "on" position and no recovery actions are taken.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Pipe No. 60 rupture (5").	1.70×10^{-8}		Fails	No effect	No effect
Multiple Failures					
Mechanical failure in both recirculation pumps and operator error in switching to RHR pumps.	1.56×10^{-6}	Recirculation pumps 31 and 32 and all RHR subsystems.	Fails	No effect	No effect
All three SI pumps fail.	3.11×10^{-3}	SI pumps 31, 32, and 33	Fails	No effect	No effect

TABLE 13 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH FAN COOLERS COMPONENT COOLING AND ALL ELECTRIC BUSES AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
MOVs 888A and 888B do not open.	5.86×10^{-7}	MOVs 888A and 888B	Fails	No effect	No effect
Testing	NR*	NR	No effect	NR	No effect
Maintenance and Hardware					
Maintenance on one SI pump and mechanical failure of the other two.	1.74×10^{-5}	All three SI pumps	Fails	No effect	No effect
Other Causes					
See Section D.2.7.5 for details	5.30×10^{-4}	SI pump or MOVs 888	Fails	?	?
Total frequency of system failure.	4.05×10^{-3}				

* Not Relevant

TABLE 14

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUS 6A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 2A, 3A and 5A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	NR	Fails	No effect	No effect
Switch No. 6 is turned to "on" position and no recovery.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Loss of power in electric bus 36A.	2.00×10^{-6}	MOBs 888A and 1802A	Fails	No effect	No effect
Pipe No. 60 rupture (5").	1.44×10^{-7}		Fails	No effect	No effect
MOV 1802A fails to open.	1.50×10^{-3}	MOV 1802A	Fails	No effect	No effect

TABLE 14 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUS 6A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 2A, 3A and 5A AVAILABLE

Cause	Mean	Effects: Component	System	Other Systems	Initiating Event
Manual valves 752A, F, G, H, J, or K fail closed.	5.40×10^{-7}	Valves 752A, B, G or H	Fails	No effect	No effect
No power at DC Bus 32.	3.00×10^{-8}	DC Bus 22	Fails	No effect	No effect
Multiple Failures					
SI pumps 31 and 32 fail to run.	1.00×10^{-2}	SI pumps 31 and 32	Fails	No effect	No effect
Recirc pump 31 fails to run and operators fail to align RHR.	2.29×10^{-4}	Recirc pump 31	Fails	No effect	No effect

TABLE 14 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUS 6A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 2A, 3A and 5A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
MOV 888A fails to open and operators fail to open it manually.	1.88×10^{-4}	MOV 888B	Fails	No effect	No effect
Testing	NR	NR	No effect	NR	No effect
Maintenance					
One SI pump under maintenance, the other fails due to hardware.	6.13×10^{-5}	SI pump 31	Fails	No effect	No effect
Other Causes					
See Section D.2.2.5 for details.	5.28×10^{-4}	SI pump 31 and 32 or MOV 888B or recirc pump 31 or MOV 822A	Fails	?	?
Total frequency of system failure.	1.00×10^{-2}				

TABLE 15

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUS 5A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 2A, 3A and 6A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	NR	Fails	Containment spray recirculation	No effect
Switch No. 6 is turned to "on" position and no recovery.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Loss of power in electric bus 26B.	2.00×10^{-6}	MOVs 822A and 747	Fails	No effect	No effect
Pipe No. 60 rupture (5").	1.44×10^{-7}		Fails	No effect	No effect
MOV 1802B fails to open.	1.50×10^{-3}	MOV 1802B	Fails	No effect	No effect
Manual valves 753A, F G, H, J, or K fails closed.	5.40×10^{-7}	Valve 753A, B	Fails	No effect	No effect
No power at DC Bus 31.	3.0×10^{-8}	DC Bus 22	Fails	No effect	No effect

TABLE 15 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUS 5A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 2A, 3A and 6A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Multiple Failures					
SI pumps 33 and 32 fail to run.	7.14×10^{-3}	SI pumps 33 and 32	Fails	No effect	No effect
Recirc pump 32 fails to run and operators fail to align RHR.	2.29×10^{-4}	Recirc pump 32	Fails	No effect	No effect
MOV 8888 fails to open and operators fail to open it manually.	1.88×10^{-4}	MOV 8888	Fails	No effect	No effect
Testing	NR	NR	No effect	NR	No effect
Maintenance					
See Section D.2.2.4 for details.	6.13×10^{-5}	SI pumps 33 and 32	Fails	No effect	No effect
Other Causes					
See Section D.2.2.5 for details	5.28×10^{-4}	SI pumps 33 and 32 or MOV 8888 or recirc pump 32 or MOV 822A	Fails	?	?
Total frequency of system failure.	1.00×10^{-2}				

TABLE 16

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUSES 2A and 3A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 5A and 6A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Failure to initiate switchover.	3.46×10^{-4}	All	Fails	Containment spray recirculation	No effect
Switch No. 6 is turned to "on" position and no recovery action.	4.72×10^{-5}	SI pumps stop	Fails	No effect	No effect
Hardware					
Single element cutsets.					
Pipe No. 60 rupture (5").	1.70×10^{-8}	MOVs 822A and 747	Fails	Part of containment spray recirculation	No effect
Multiple Failures					
Mechanical failure in both recirculation pumps and operator error in switching to RHR pumps.	1.56×10^{-6}	Recirculation pumps 31 and 32 and all RHR pumps	Fails	Containment spray recirculation	No effect

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TABLE 16 (continued)

CAUSES AND FREQUENCY OF FAILURE OF HI-HEAD RECIRCULATION WITH ELECTRIC BUSES 2A and 3A UNAVAILABLE; FAN COOLERS, COMPONENT COOLING AND ELECTRIC BUSES 5A and 6A AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
SI Pumps 31 and 33 fail.	7.14×10^{-3}	SI pumps 31 and 33	Fails	No effect	No effect
MOVs 888A and 888B do not open.	5.86×10^{-7}	MOVs 888A and 888B	Fails	No effect	No effect
Testing	NR*	NR	No effect	NR	No effect
Maintenance and Hardware					
Maintenance on one SI pump and mechanical failure of the other.	6.13×10^{-5}	All three SI pumps unavailable	Fails	No effect	No effect
Other Causes					
See Section D.2.1.5 for details	5.50×10^{-4}	SI Pump or MOVs 888	Fails	?	?
Total frequency of system failure.	8.13×10^{-3}				

* Not Relevant

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TABLE 17

THE MINIMAL CUTSETS FOR THE FAULT TREE FOR LO-HEAD RECIRCULATION WHEN ALL THE HOUSE EVENTS ARE TREATED AS BASIC EVENTS

PRINTOUT OF MINIMAL CUT SETS FOR PHASE 1

TITLE INSUFFICIENT FLOW IN LO-HEAD RECIRCULATION   (TP-1)

CUT SETS WITH 1 BASIC EVENTS.

1)   1) UCCHFAIL

CUT SETS WITH 2 BASIC EVENTS.

5)	1)	HPFLHGDL	LLCHUDIS	2)	HDISCHGN	LLGHDGIS	3)	LCMI755-	LXLCSUMP	4)	LMV755-C	LXLCSUMP
9)	5)	UCV751.C	LCV751UC	6)	UAV82UAC	UCV751UC	7)	UAV81UAC	UCV751UC	8)	UAV81UUC	UCV751UC
13)	9)	LAV-752C	LCV751UC	10)	UCV751AC	UAV82UUC	11)	UAV820AC	UAV820UL	12)	UXV81UAL	UAV820UL
17)	13)	UAV81UAL	LXV82UUL	14)	LAV-752C	UAV820UC	15)	UCV751AC	UXV81UUC	16)	UXV820AL	UAV81UUL
21)	17)	UAV81UAL	LXV81UUL	18)	UAV81UUL	UXV81GUC	19)	LAV-752C	UAV81UUL	20)	UCV751AC	UAV81ULL
25)	21)	UAV82UAL	LXV81LLL	22)	UAV81UAL	UAV81LLC	23)	UAV81UUC	UXV81ULL	24)	LXV-752C	UAV81ULL
29)	25)	LXLCSUMP	LLMI-UUZ	26)	LXLCSUMP	LMV-UU2X	27)	UCMIU22A	UCV751UC	28)	UMV822AU	UCV751LC
33)	29)	UCMIU22A	LAV82UUL	30)	UMV822AU	UAV820LL	31)	UCMIU22A	UXV81UUC	32)	UMV822AU	UAV81ULL
37)	33)	UCMIU22A	LAV81ULL	34)	UMV822AU	UAV81ULL	35)	LXLCSUMP	LCV-751C	36)	LXLCSUMP	LLMISUMP
41)	37)	LXLCSUMP	LLZ2INCC	38)	UCMIU22A	UCMIU22B	39)	UMV822AU	UCMIU22B	40)	UCMIU22A	UMV822CG
45)	41)	UMV822AU	LPV822UU	42)	LXLCSUMP	LCMIUU5A	43)	LXLCSUMP	LMV8U5AU	44)	UCV751AC	UCMIU22B
49)	45)	UAV82UAL	LCMIU22U	46)	UXV81UAC	UCMIU22U	47)	UAV81UUC	UCMIU22U	48)	LXV-752C	UCMIU22U
53)	49)	UCV751AC	LPV822UU	50)	UAV820AC	UMV822UC	51)	UAV81UAC	UMV822BU	52)	UXV81UUL	UMV822UC
57)	53)	LAV-752C	LPVL22UU	54)	LXLCSUMP	LLMIUU5C	55)	LXLCSUMP	LMV8U5UG	56)	UCMIU22A	JBS33GLU
61)	57)	UMV822AU	JES33GUU	58)	LCMIUU2A	JBS33GUU	59)	LMV8U2AU	JBS33GUU	60)	LCMI755B	JBS33GCG
65)	61)	IMV755UC	JES33GAU	62)	LCMI755A	JBS33GUU	63)	LMV755AC	JBS[illegible]U	64)	UCV751AC	JBS33GCC
69)	65)	UAV820AC	JES33GUU	66)	UXV81UAC	JBS33GUU	67)	UAV81UUC	JES33GUU	68)	LXV-752C	JBS33GCC
73)	69)	LXLCSUMP	JES33GUU	70)	LCV8UUAL	JBS3GA-U	71)	UAV752AC	JBS3GA-U	72)	UXV752LC	JBS3GA-U
77)	73)	UAV752UC	JES3GA-U	74)	UCMIU22A	JBS3GA-U	75)	UMV822AU	JES3GA-U	76)	LPMHLJ3S	JES3GA-U
81)	77)	LMUKCJ3S	JES3GA-U	78)	LCMIKCJC	JBS3GA-U	79)	LCMIUU2A	JBS3GA-U	80)	LPV8U2AU	JES3GA-U
85)	81)	LCMI755U	JBS3GA-U	82)	LMV755UC	JBS3GA-U	83)	LCMI755A	JBS3GA-U	84)	LPV755AC	JBS3GA-U
89)	85)	UAV752UC	JES3GA-U	86)	UAV752JC	JBS3GA-U	87)	UAV752KC	JBS3GA-U	88)	UCV751AC	JBS3GA-U
93)	89)	UAV82UAL	JES3GA-U	90)	UAV81UAC	JBS3GA-U	91)	UAV81UUC	JBS3GA-U	92)	LXV-752C	JBS3GA-U
97)	93)	LXLCSUMP	JES3GA-U	94)	JBS33GAL	UCV751UC	95)	JBS33GAU	UXV820UL	96)	JES33GAL	UAV81ULL
101)	97)	JBS33GAU	LXV81LLL	98)	JBS33GAU	UCMIU22B	99)	JBS33GAU	UMV822BU	100)	LXLCSUMP	JBS33GAL
105)	101)	LCMIU82B	JES33GAU	102)	LMV8U2UU	JBS33GAU	103)	JBS33GAU	JBS33GBU	104)	JBS33GAU	JBS3GA-U
109)	105)	LCV8UULL	JES35A-U	106)	UXV753AC	JBS35A-U	107)	UAV753JC	JBS35A-U	108)	LXV753GC	JES35A-U
113)	109)	JBS35A-U	LCV751UL	110)	JBS35A-U	UAV820UL	111)	JBS35A-U	UXV81UUC	112)	JBS35A-U	UXV81ULL
117)	113)	JBS35A-U	LCMIU22U	114)	JES35A-U	UMV822LU	115)	LMHLJ2S	JBS35A-U	116)	LMUHLJ2S	JBS35A-U
121)	117)	LCMIKCJZ	JES35A-U	118)	LXLCSUMP	JBS35A-U	119)	UAV753HC	JBS35A-U	120)	LXV753JC	JBS35A-U
125)	121)	UAV753KC	JBS35A-U	122)	LCMIUU2U	JBS35A-U	123)	LMV8U2UU	JES35A-U	124)	JBS35A-U	JES33GLL
129)	125)	JBS35A-U	JES3GA-U	126)	LXLCSUMP	4BS332-U	127)	UAV752HC	4BS332-U	128)	UAV752JC	4BS332-U
133)	129)	UAV752KC	4ES332-U	130)	LCV8UUAL	4BS332-U	131)	UAV752AC	4BS332-U	132)	UXV752LC	4BS332-U

(continued)

TABLE 17 (continued)

THE MINIMAL CUTSETS FOR THE FAULT TREE FOR LO-HEAD RECIRCULATION WHEN ALL THE HOUSE EVENTS ARE TREATED AS BASIC EVENTS

PRINTOUT OF MINIMAL CUT SETS FOR PHASE 1

TITLE: INSUFFICIENT FLOW IN LO-HEAD RECIRCULATION (TP-3)

CUT SETS WITH 2 BASIC EVENTS.

[illegible]	[illegible]	DXV7520C	4BS332-D	[illegible]	EPMRC11S	4BS332-D	[illegible]	EMORC31S	4BS332-D	[illegible]	ECHTRC31	4BS332-D
[illegible]	[illegible]	4BS332-B	3BS35A-D	[illegible]	ECOMOOTS	4BS331-D	[illegible]	4BS331-D	3BS36A-D	[illegible]	4BS331-D	4BS332-D

TABLE 18

CAUSES AND FREQUENCY OF FAILURE OF LO-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects: Component	Effects: System	Effects: Other Systems	Effects: Initiating Event
Operator Error					
Failure to initiate switchover.	4.75×10^{-3}	All	Fails	Containment spray recirculation fails	No effect
Switch No. 5 is turned to "on" position and no recovery actions are taken.	5.26×10^{-4}	MOVs 746 and 747 close	Fails	No effect	No effect
Hardware					
Single element cutsets.		There are no single element cutsets	Partial Failure	No effect	No effect
Multiple Failures					
Hardware failure in both recirculation pumps and operator error in switching to RHR Pumps.	2.65×10^{-5}	Recirculation Pumps 31 and 32 and all RHR subsystems	Fails	No effect	No effect

TABLE 18 (continued)

CAUSES AND FREQUENCY OF FAILURE OF LO-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Hardware failure in both MOVs 1802A and B and operator error in switching to RHR pumps.	1.27×10^{-6}	MOVs 1802A and 1802B and RHR subsystem	Fails	Containment Spray Recirculation Fails	No effect
MOVs 822B and 822A fail to open.	4.88×10^{-6}	MOVs 822B and 822A	Fails	Containment Spray Recirculation Fails	No effect
Testing	NR	NR	No effect	No effect	No effect

TABLE 18 (continued)

CAUSES AND FREQUENCY OF FAILURE OF LO-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Maintenance and Hardware					
Maintenance on one SI pump (See Section E.2.1.4 for details).	$\ll 10^{-8}$	See Section E.2.1.4 for details	Fails	No effect	No effect
Other Causes					
See Section E.2.1.5 for details	3.30×10^{-5}	See Section E.2.1.5 for details	Fails	Containment Spray Recirculation Fails	No effect
Total frequency of system failure.	5.32×10^{-3}				

TABLE 19

CAUSES AND FREQUENCY OF FAILURE OF LO-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects: Component	Effects: System	Effects: Other Systems	Effects: Initiating Event
Operator Error					
Failure to initiate switchover.	4.75×10^{-3}	All	Fails	Containment spray recirculation fails	No effect
Switch No. 5 is turned to "On" position and no recovery actions are taken.	5.26×10^{-4}	MOVs 746 and 747 close	Fails	No effect	No effect
Hardware					
Single element cutsets.		There are no single element cutsets	Partial	No effect	No effect
Multiple Failures					
Hardware failure in both recirculation pumps and operator error in switching to RHR Pumps.	3.74×10^{-5}	Recirculation Pumps 31 and 32 and all RHR subsystems	Fails	No effect	No effect

TABLE 19 (continued)

CAUSES AND FREQUENCY OF FAILURE OF LO-HEAD RECIRCULATION WITH FAN COOLERS UNAVAILABLE; COMPONENT COOLING AND ALL ELECTRICAL BUSES AVAILABLE

Cause	Mean	Effects: Component	Effects: System	Effects: Other Systems	Effects: Initiating Event
Hardware failure in both MOVs 1802A and B and operator error in switching to RHR pumps.	1.27×10^{-6}	MOVs 1802A and 1802B and RHR	Fails	Containment Spray Recirculation Fails	No effect
Testing	NR	NR	No effect	No effect	No effect
Maintenance and Hardware					
Maintenance on one SI pump (See Section E.2.1.4 for details).	2.24×10^{-9}	See Section E.2.1.4 for details	Fails	No effect	No effect
Other Causes					
(See Section E.2.1.5 for details).	3.30×10^{-5}	See Section E.2.1.5 for details	Fails	Containment Spray Recirculation Fails	No effect
Total frequency of system failure.	5.32×10^{-3}				

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TABLE 20

MINIMAL CUTSETS FOR CONTAINMENT SPRAY RECIRCULATION WHEN ALL HOUSE EVENTS ARE TREATED AS BASIC EVENTS

PRINTOUT OF MINIMAL CUT SETS FOR PHASE 1

TITLE INSUFFICIENT FLOW IN CONTAINMENT SPRAY RECIRCULATION (IP-1)

CUT SETS WITH 1 BASIC EVENTS.

5) 1) 4BS330CB 2) 4BS330A-D 3) 4BS330AD 4) 4BS335A-D 5) UCCHFAIL

CUT SETS WITH 2 BASIC EVENTS.

9)	1)	CCNT0094A	CCNT0094B	2)	CMV0094AU	CCNT0094B	3)	CCNT0094A	CMV0094BU	4)	CMV0094AU	CMV0094BC
[illegible]	5)	CCNT0094A	CCNT022A	6)	CMV0094AC	UCNT022A	7)	CCNT0094A	UMV0222AU	8)	CMV0094AU	UMV0222AC
[illegible]	9)	EXCCSUMP	CCNT0053A	10)	EXCCSUMP	CMV0053AU	11)	EXCCSUMP	E002INCC	12)	EXCCSUMP	CCNT0052
[illegible]	13)	EXCCSUMP	CMV0053BU	14)	EXCCSUMP	CCNT-002	15)	EXCCSUMP	CMV-002A	16)	EXCCSUMP	CCV-751C
[illegible]	17)	EXCCSUMP	CCNTSUMP	18)	CCNT755-	EXCCSUMP	19)	CMV755-U	EXCCSUMP	20)	CCNT0094A	UCV751AC
[illegible]	21)	CMV0094AC	UCV751AC	22)	CCNT0094A	UXV002AC	23)	CMV0094AU	UXV002AC	24)	CCNT0094A	UXV001AC
[illegible]	25)	CMV0094AU	UXV001AC	26)	CCNT0094A	UXV001BC	27)	CMV0094AU	UXV001BC	28)	CCNT0094A	EXV-752C
[illegible]	29)	CMV0094AU	EXV-752C	30)	UCV751AC	UCNT022B	31)	UXV002AC	UCNT022B	32)	UXV001AC	UCNT022B
[illegible]	33)	UXV001BC	CCNT022B	34)	EXV-752C	UCNT022B	35)	UCV751AC	UMV0222BU	36)	UXV002AC	UMV0222BU
[illegible]	37)	UXV001BC	UMV0222BU	38)	UXV001BC	UMV0222BU	39)	EXV-752C	UMV0222BU	40)	UCV751AC	UCV751BC
[illegible]	41)	UXV002AC	UCV751BC	42)	UXV001AC	UCV751BC	43)	UXV001BC	UCV751BC	44)	EXV-752C	UCV751BC
[illegible]	45)	UCV751AC	UXV002BC	46)	UXV002AC	UXV002BC	47)	UXV001AC	UXV002BC	48)	UXV001BC	UXV002BC
[illegible]	49)	EXV-752C	UXV002BC	50)	UCV751AC	UXV001BC	51)	UXV002AC	UXV001BC	52)	UXV001AC	UXV001BC
[illegible]	53)	UXV001BC	UXV001BC	54)	EXV-752C	UXV001BC	55)	UCV751AC	UXV001CC	56)	UXV002AC	UXV001CC
[illegible]	57)	UXV001AC	UXV001CC	58)	UXV001BC	UXV001CC	59)	EXV-752C	UXV001CC	60)	UCNT022A	UCNT022B
[illegible]	61)	UMV0222AU	UCNT022B	62)	UCNT022A	UMV0222BU	63)	UMV0222AU	UMV0222BU	64)	UCNT022A	UCV751BC
[illegible]	65)	UMV0222AU	UCV751BC	66)	UCNT022A	UXV002BC	67)	UMV0222AU	UXV002BC	68)	UCNT022A	UXV001BC
[illegible]	69)	UMV0222AU	UXV001BC	70)	UCNT022A	UXV001CC	71)	UMV0222AU	UXV001CC	72)	CCNT0094B	UCNT022B
[illegible]	73)	CMV0094BU	UCNT022B	74)	CCNT0094B	UMV0222BU	75)	CMV0094BU	UMV0222BU	76)	CCNT0094B	UCV751BC
[illegible]	77)	CMV0094BU	UCV751BC	78)	CCNT0094B	UXV002BC	79)	CMV0094BU	UXV002BC	80)	CCNT0094B	UXV001BC
[illegible]	81)	CMV0094BU	UXV001BC	82)	CCNT0094B	UXV001CC	83)	CMV0094BU	UXV001CC	84)	CCV0006AC	4BS332-B
[illegible]	85)	UXV752AC	4BS332-D	86)	UXV752BC	4BS332-D	87)	UXV752BC	4BS332-D	88)	UXV752BC	4BS332-D
[illegible]	89)	UXV752AC	4BS332-D	90)	UXV752AC	4BS332-D	91)	4BS331-D	4BS332-D	92)	EPMRC315	4BS332-B
100)	93)	EMMRC315	4BS332-D	94)	CCNTRC31	4BS332-D	95)	EXCCSUMP	4BS332-D			

TABLE 21

CAUSES AND FREQUENCIES OF FAILURE OF CONTAINMENT SPRAY RECIRCULATION WHEN LARGE LOCA HAS OCCURRED AND ALL ELECTRIC BUSES ARE AVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Operators fail to open isolation valves.	1.5×10^{-3}	MOVs 889A	Fails	No effect	No effect
Hardware					
Single events	-	There are no sinle element cutsets	Partial failure	No effect	No effect
Multiple events					
Both MOVs 889 fail to open	4.88×10^{-6}	MOVs 889A and 889B	Fails	No effect	No effect
Testing	-	-	No effect	-	-
Maintenance	-	-	No effect	-	
Other Causes					
(see Section F.2.1.5 for details)	2.1×10^{-5}	(see Section F.2.1.5)	Fails	No effect	No effect
Total frequency of system failure.	1.5×10^{-3}				

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TABLE 22

CAUSES AND FREQUENCIES OF FAILURE OF CONTAINMENT SPRAY RECIRCULATION WHEN LARGE LOCA HAS OCCURRED AND ELECTRIC BUS 5A IS UNAVAILABLE

Cause	Mean	Effects			
		Component	System	Other Systems	Initiating Event
Operator Error					
Operator fails to open isolation valves.	1.5×10^{-3}	MOVs 889A and 889B	Fails	No effect	No effect
Hardware					
Single events.					
MOV 889B fails to open	1.5×10^{-3}	MOV 889B	Fails	No effect	No effect
Testing	-	-	No effect	-	-
Maintenance	-	-	No effect	-	-
Other Causes					
(See Section F.2.2.5 for details)	-	(See Section F.2.1.5)	Fails	No effect	No effect
Total frequency of system failure.	3.0×10^{-3}				

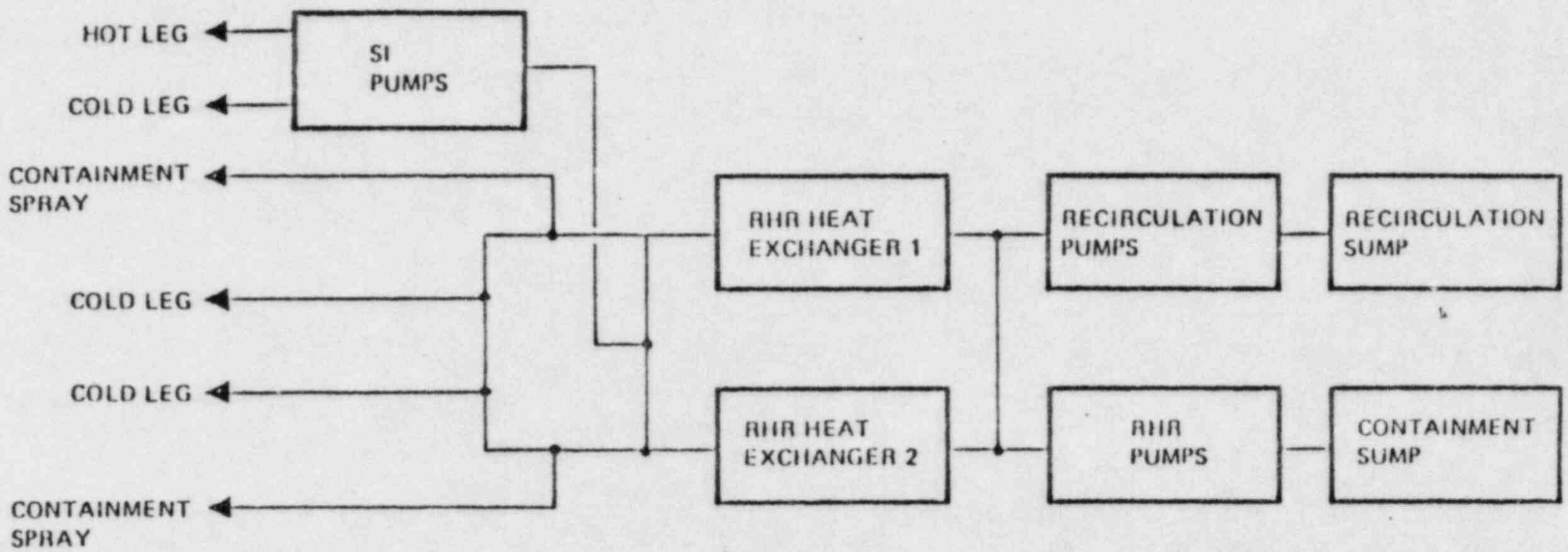


Figure 1. Recirculation System Reliability Block Diagram

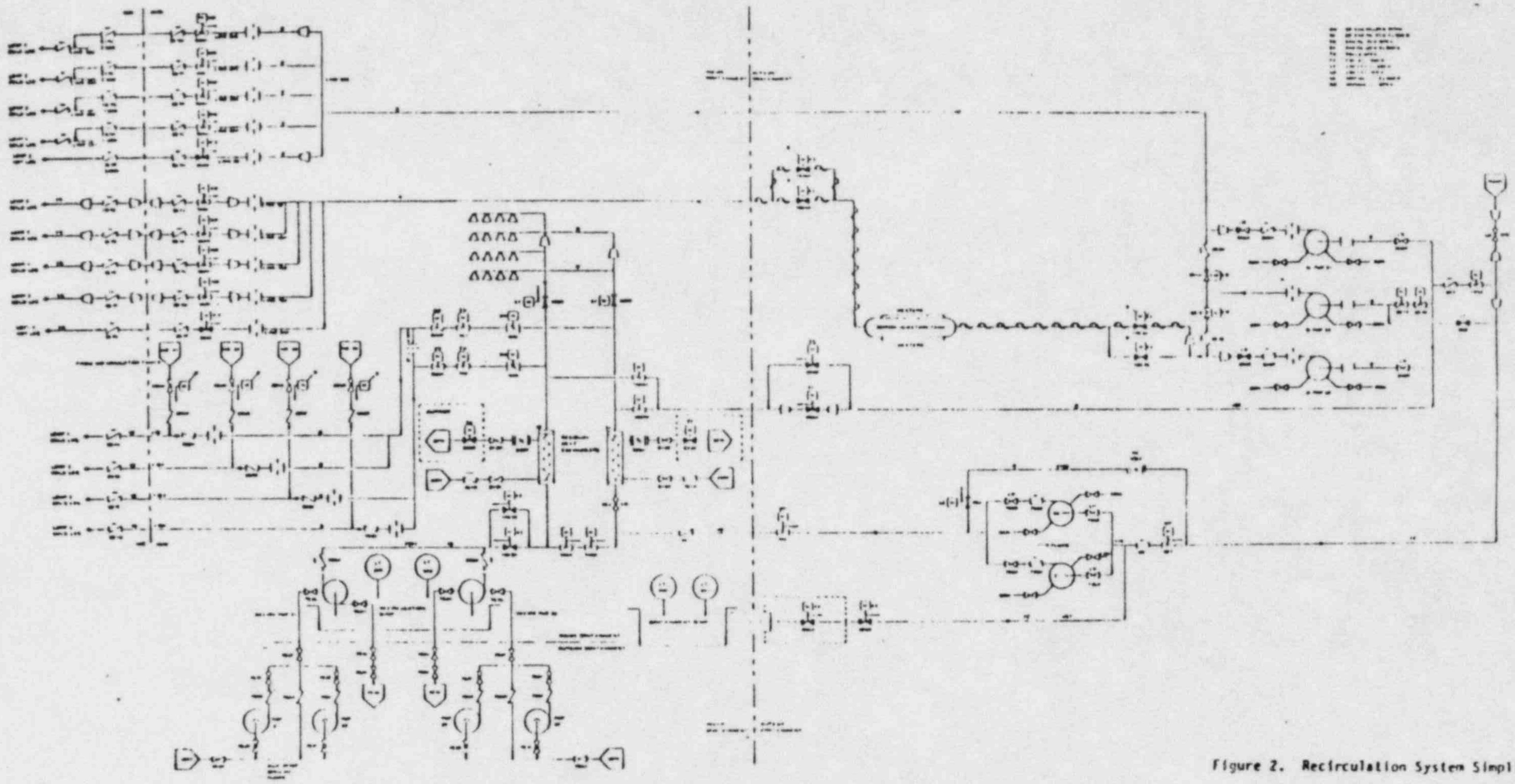


Figure 2. Recirculation System Simplified P&ID

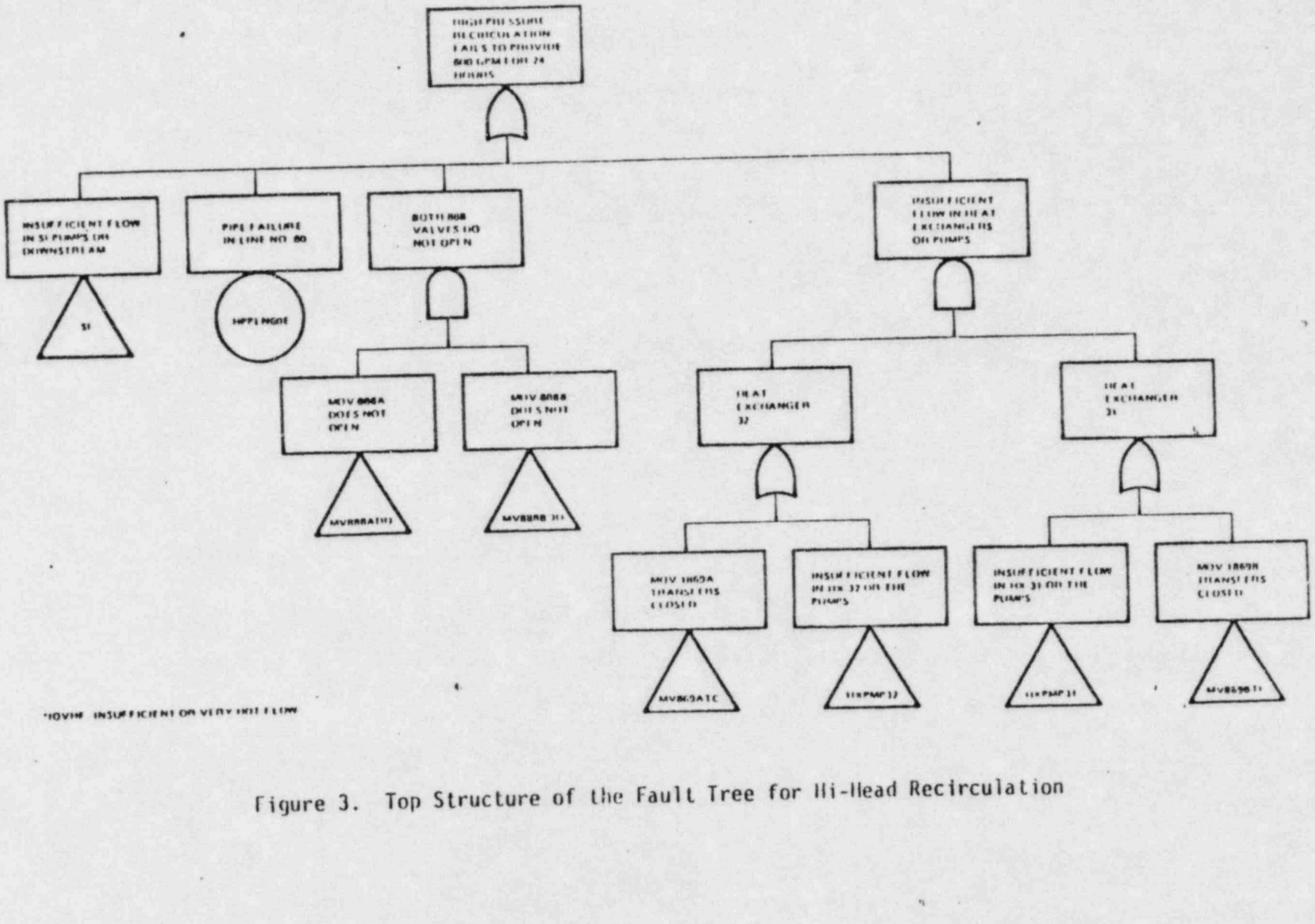


Figure 3. Top Structure of the Fault Tree for Hi-Head Recirculation

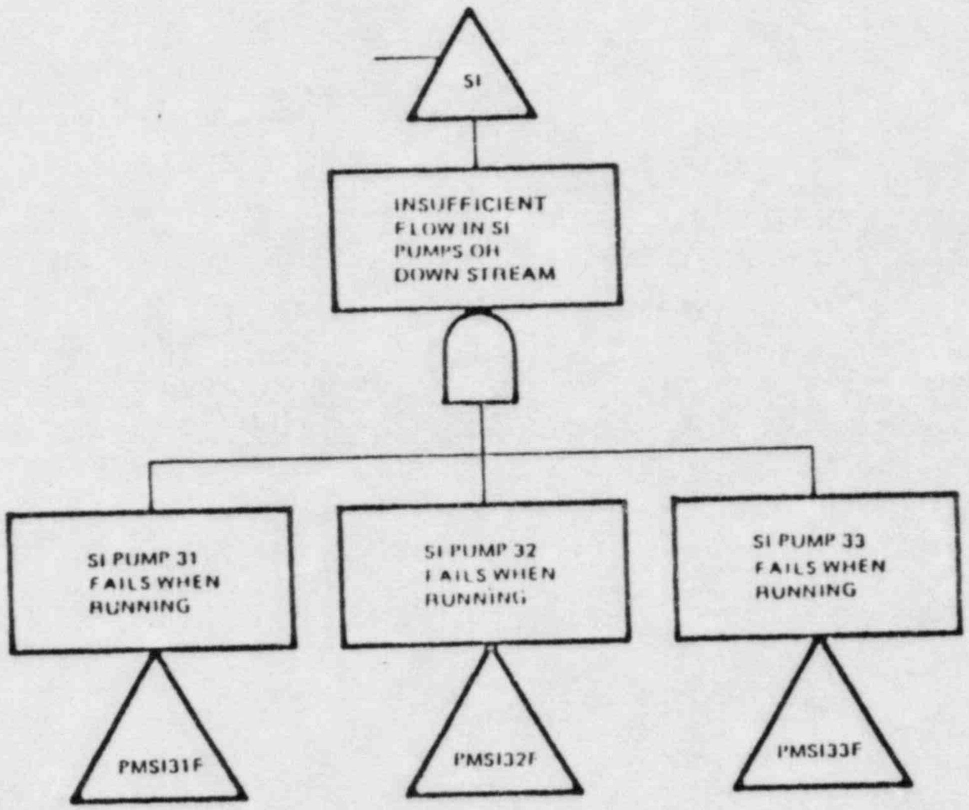
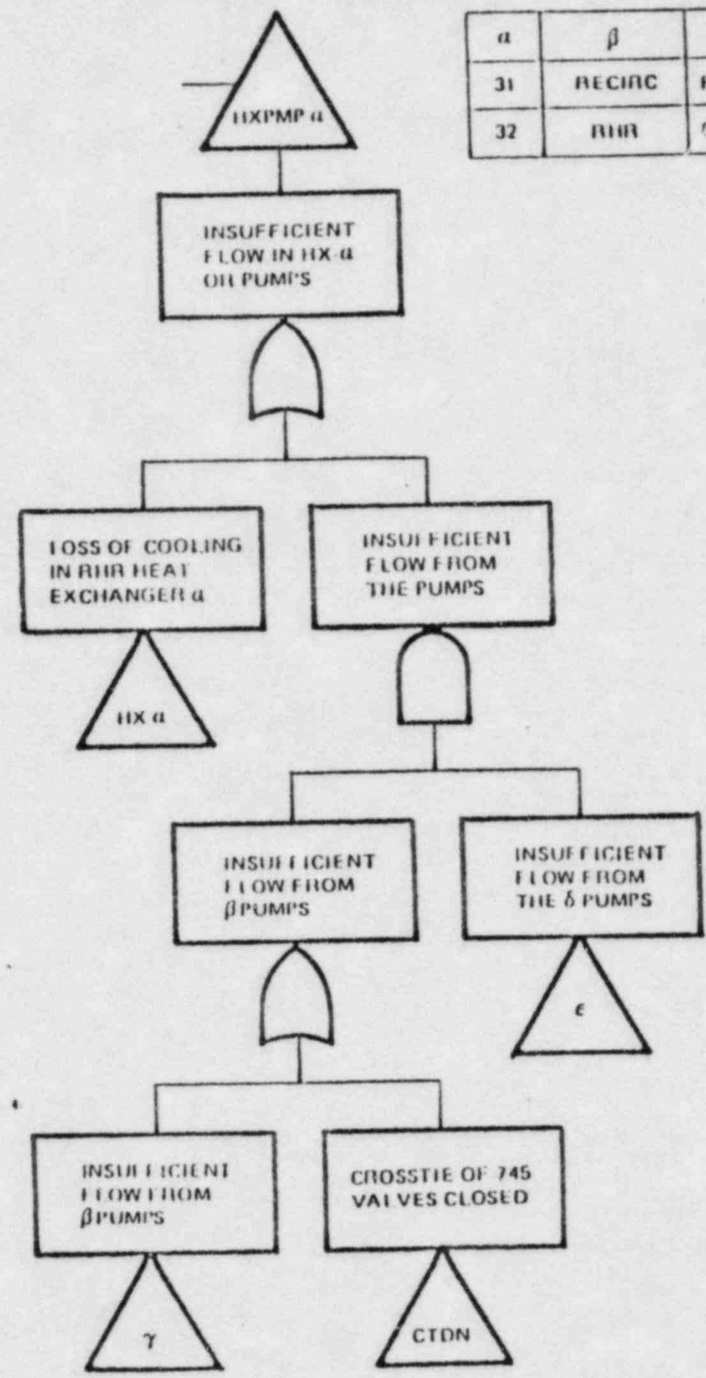
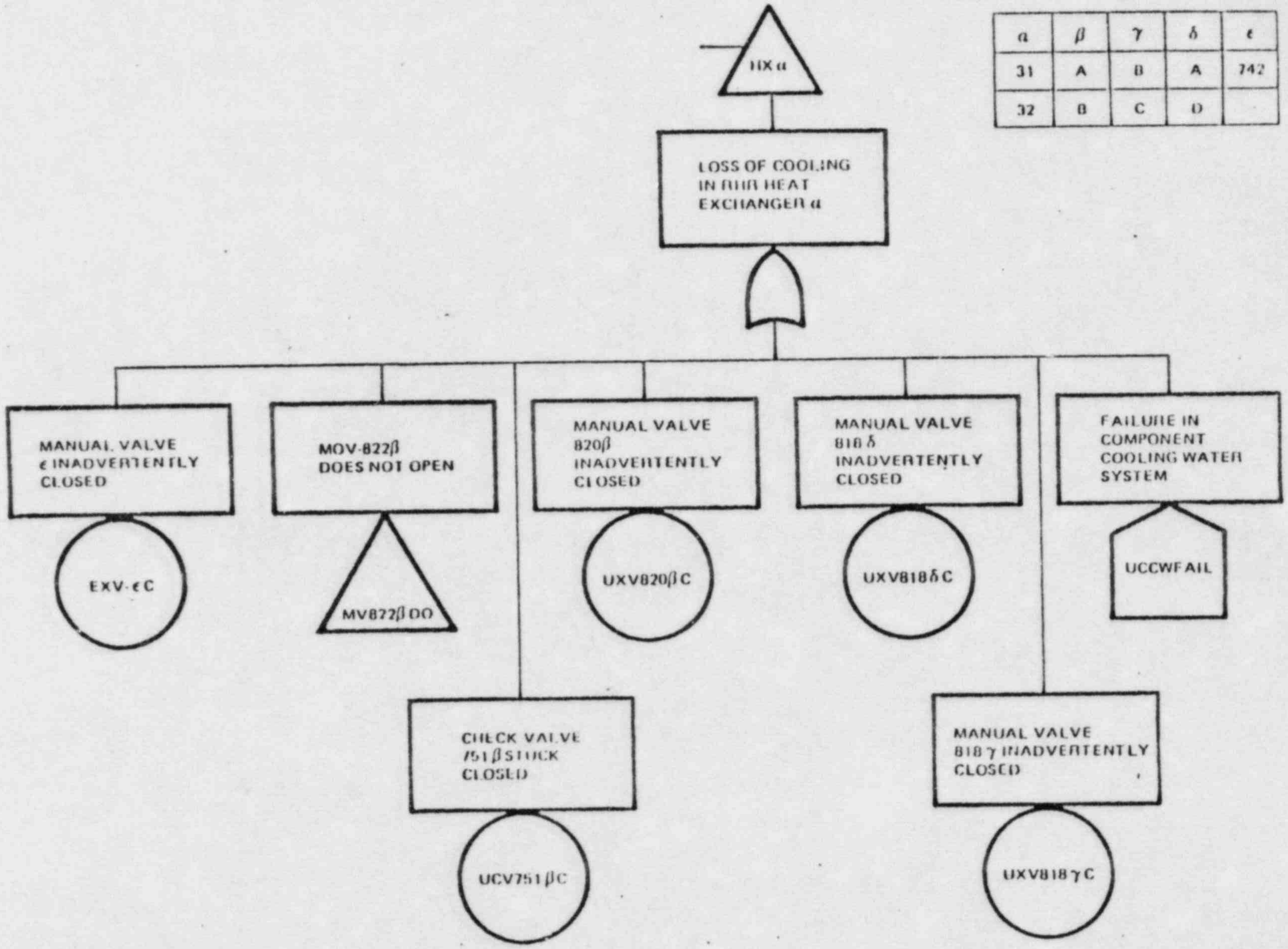


Figure 4. Fault Tree for all SI Pumps Unavailable



α	β	γ	δ	ε
31	RECIRC	REC	RHR	RHR
32	RHR	RHR	RECIRC	REC

Figure 5



α	β	γ	δ	ε
31	A	B	A	742
32	B	C	D	

Figure 6. Fault Tree for Loss of Cooling in a Heat Exchanger

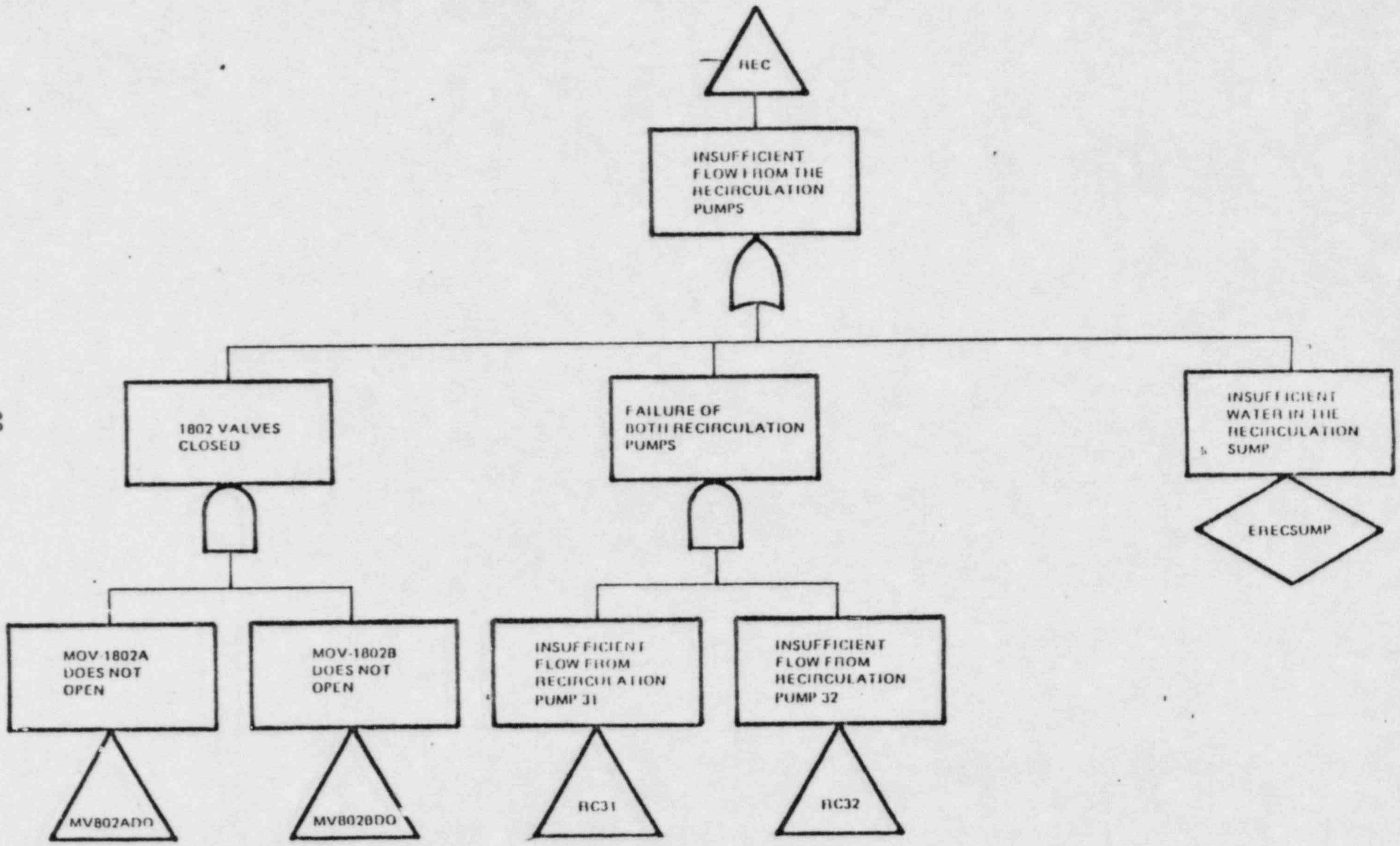


Figure 7. Fault Tree for Insufficient Flow From the Recirculation Pumps

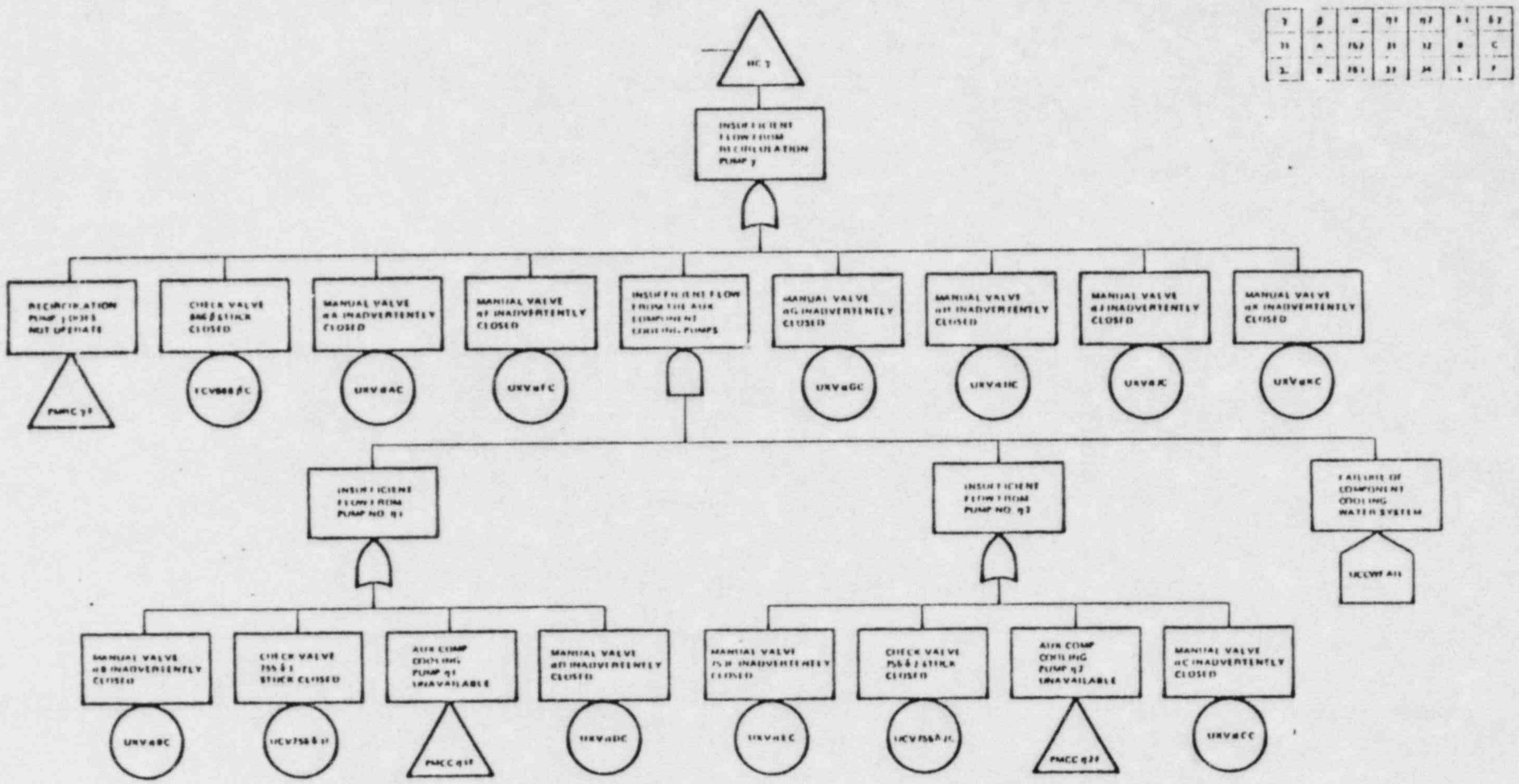


Figure 8. Fault Tree for Failures in one Recirculation Pump Train

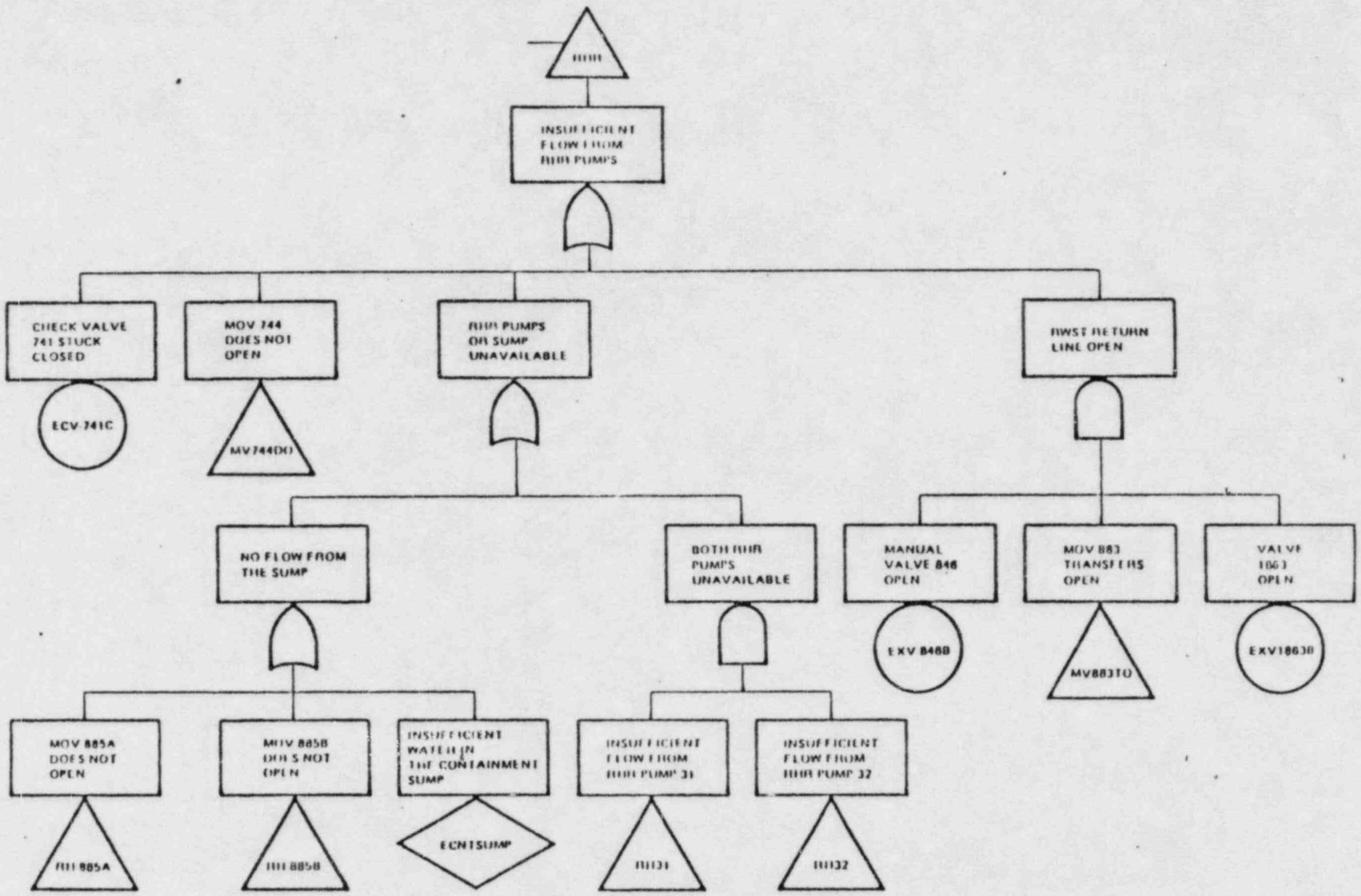


Figure 9. Fault Tree for Insufficient Flow From the RHR Pumps

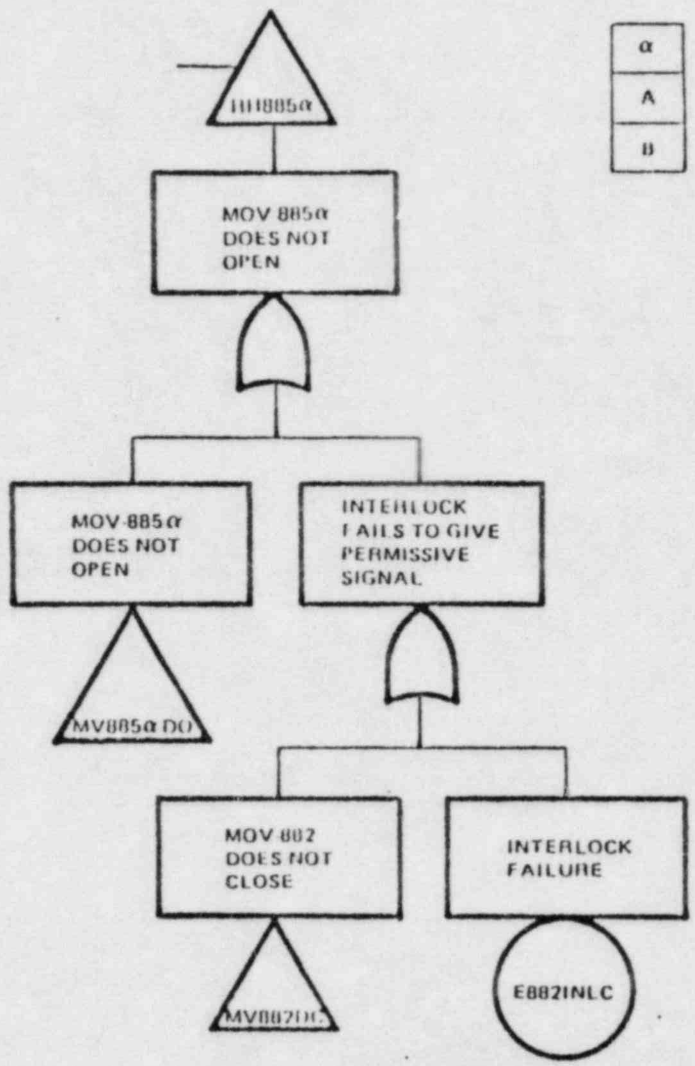


Figure 1C. Fault Tree for MOV885A (or B) Fail to Open

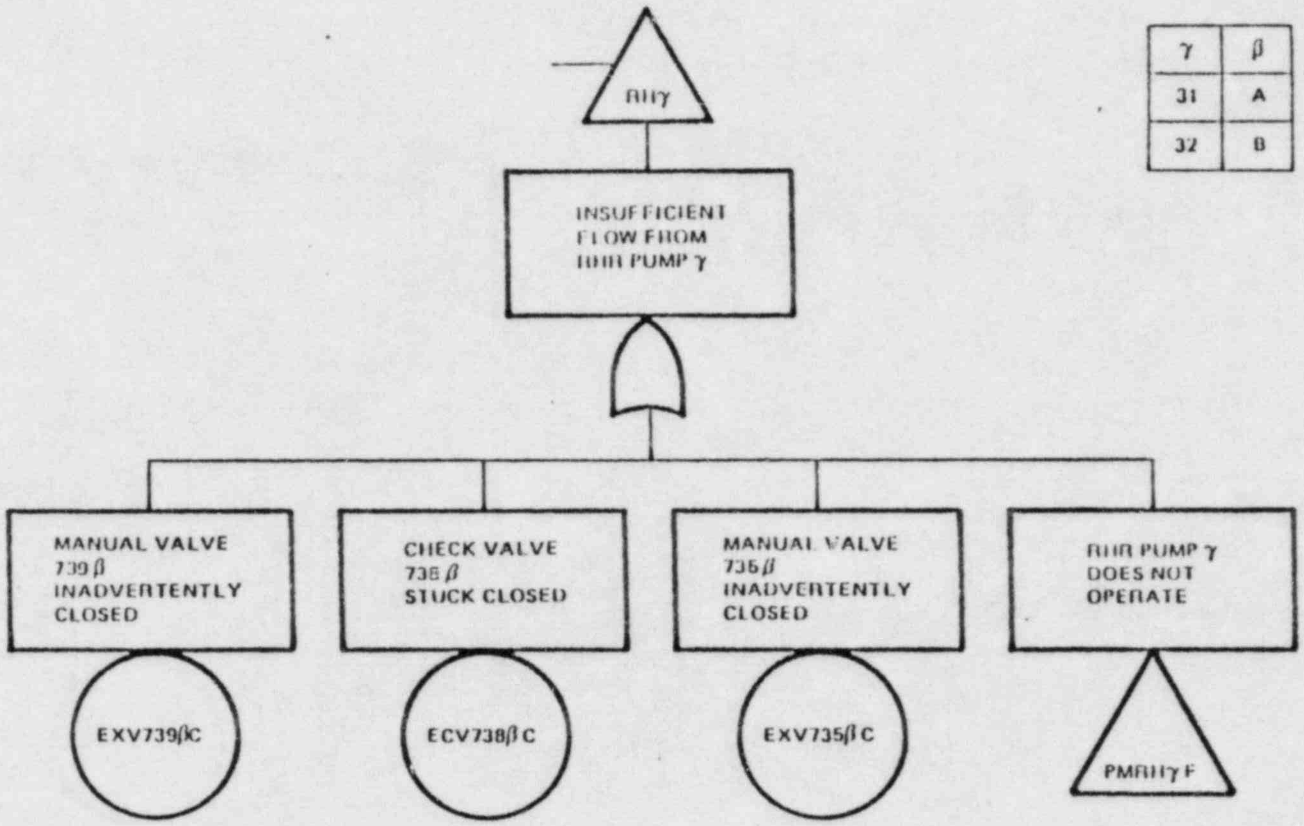


Figure 11. Fault Tree for Failures in one RHR Train

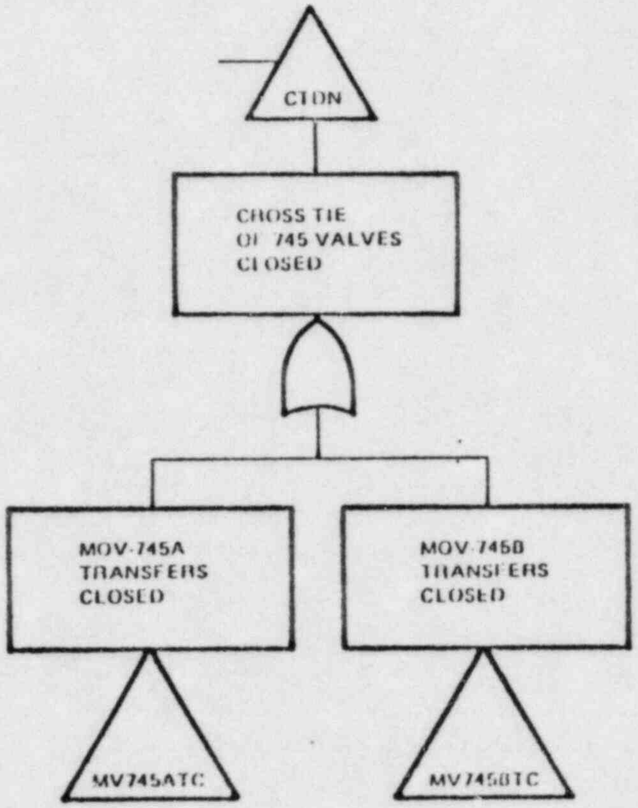


Figure 12. Fault Tree for Blockage of Crosstie Between the Two Heat Exchanger Suction Lines

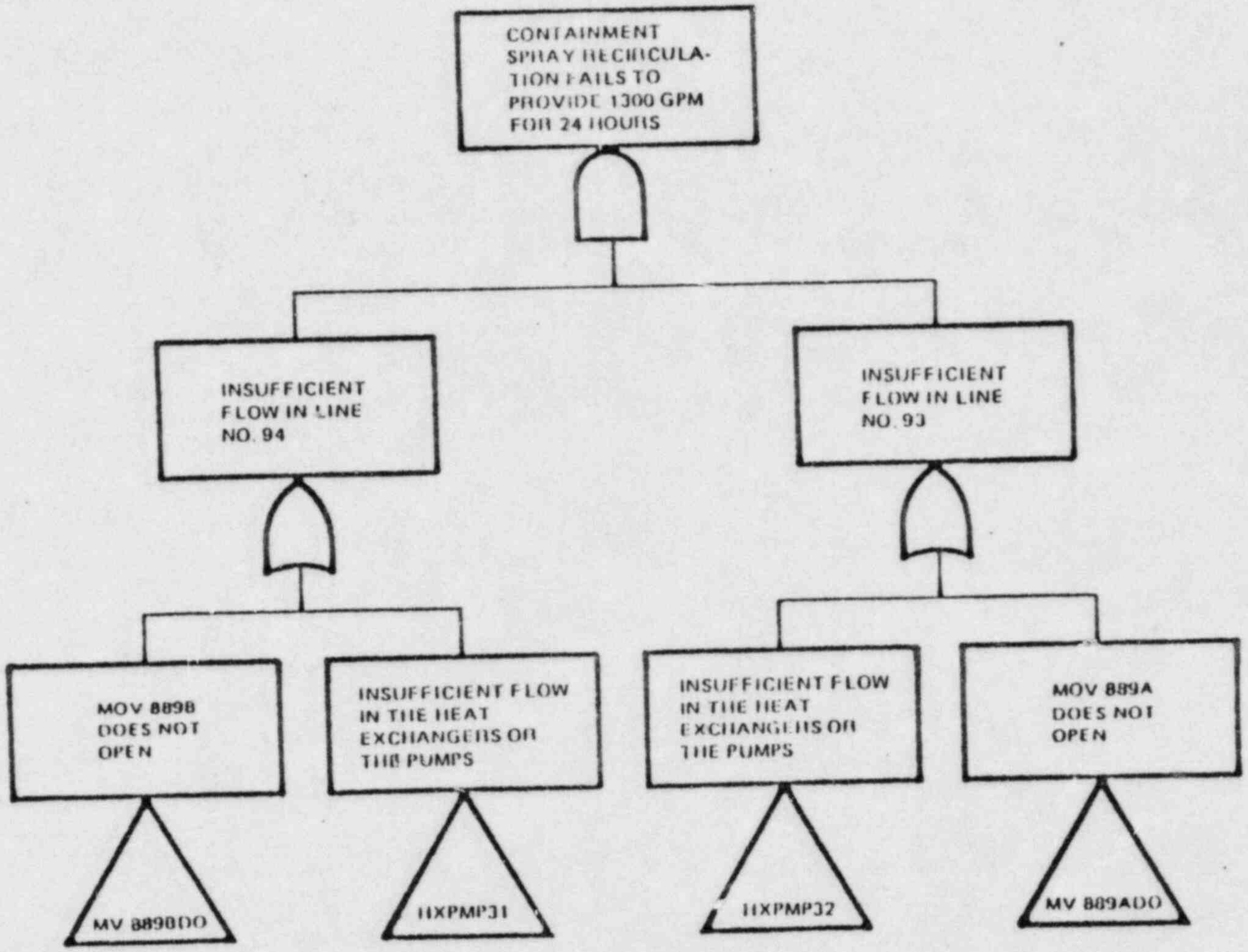


Figure 13. Top Structure of the Fault Tree for Containment Spray Recirculation

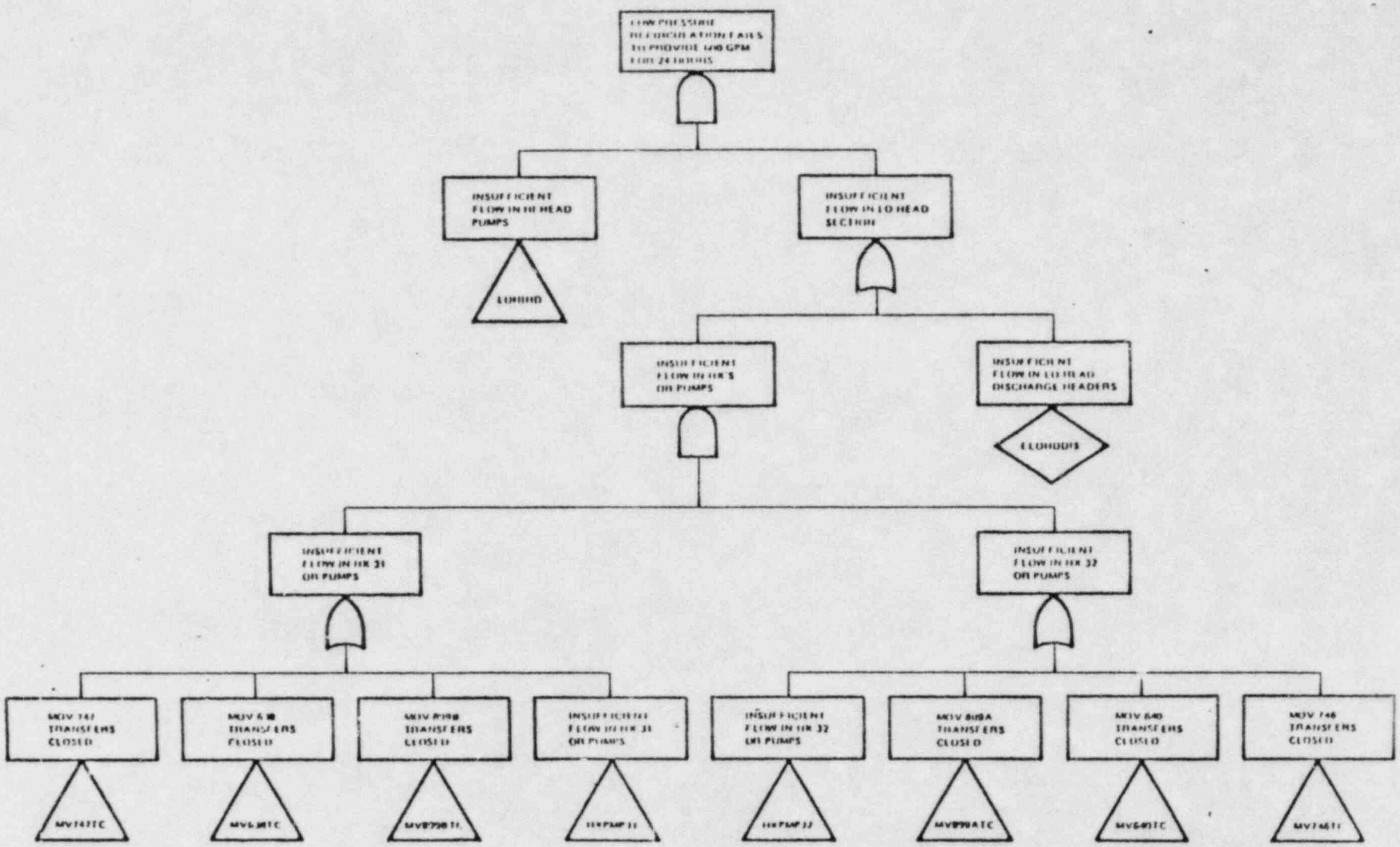


Figure 14. Top Structure of Fault Tree for Lo-Head Recirculation

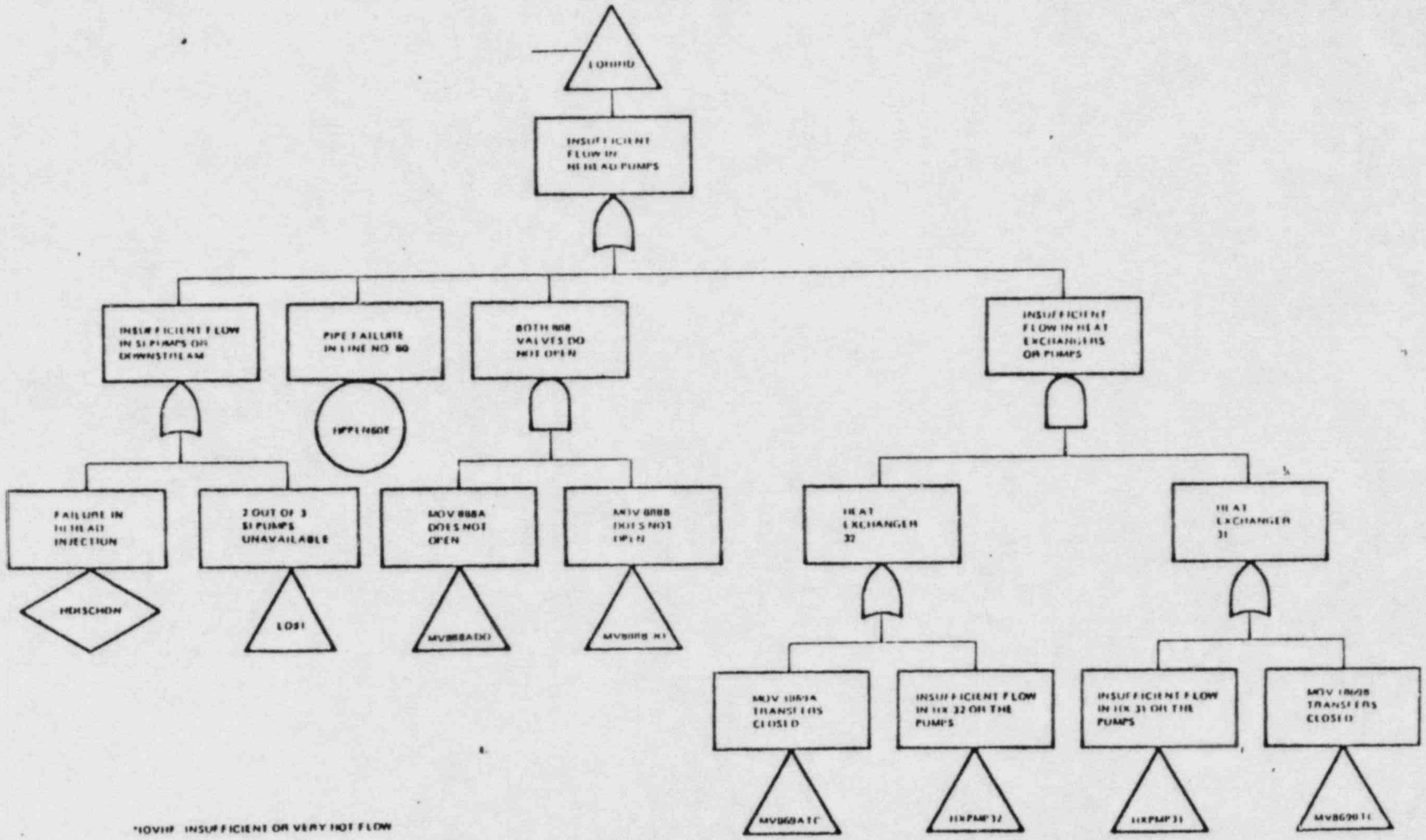


Figure 15. Fault Tree for Failures in Hi-Head Part of the System
(From Line #60 to SI Pump Discharge Headers)

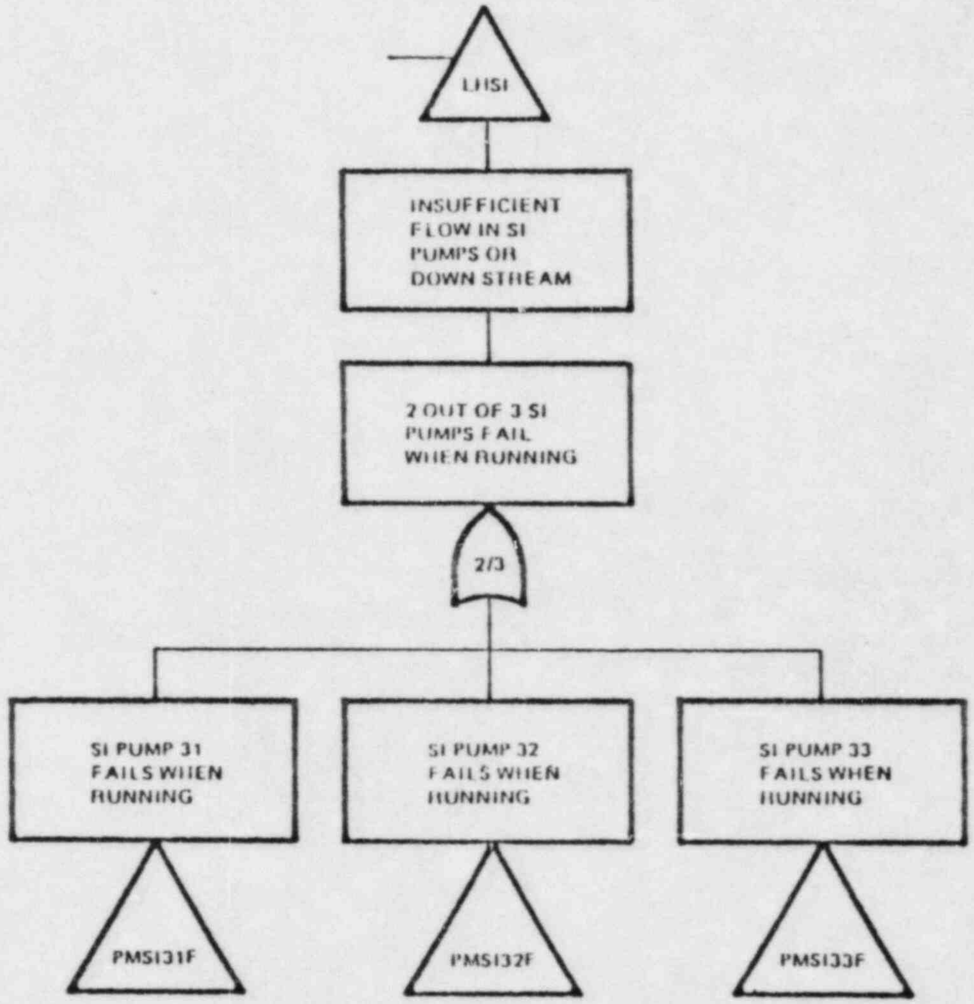


Figure 16. Fault Tree for the Failure of Two-Out-of-Three SI Pumps

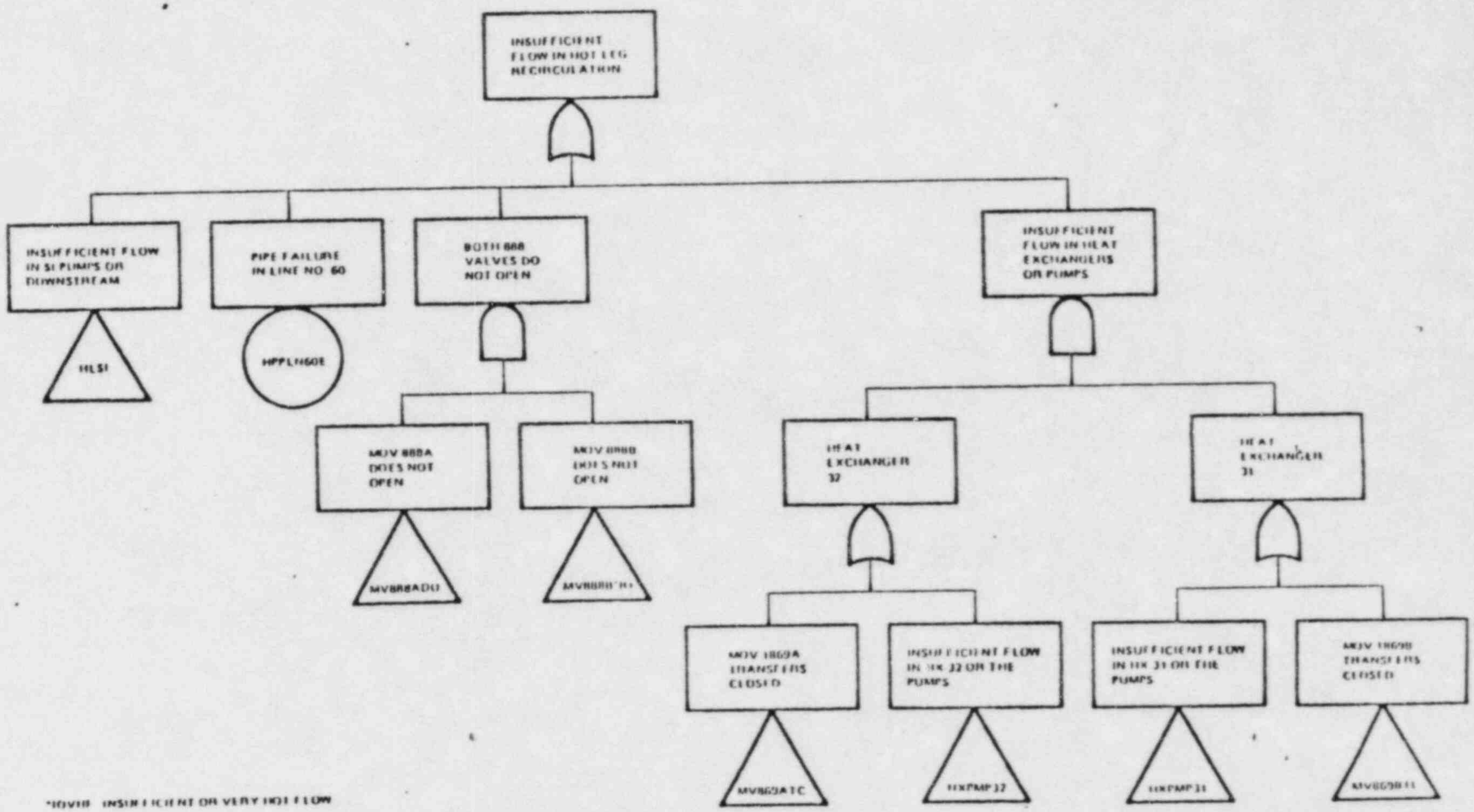


Figure 17. Top Structure of the Fault Tree for Hot Leg Recirculation

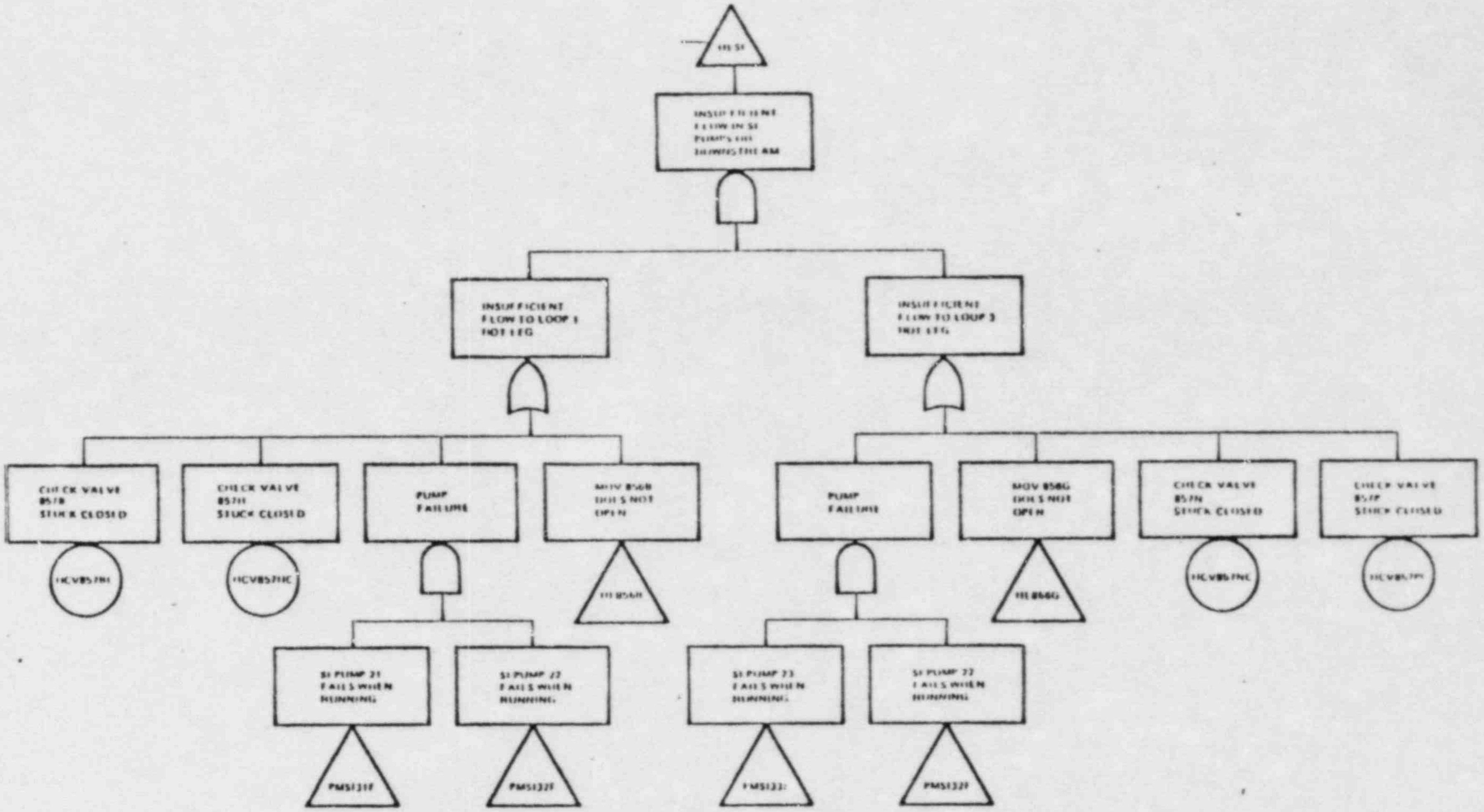


Figure 18. Fault Tree for Failures in SI Pumps on Downstream

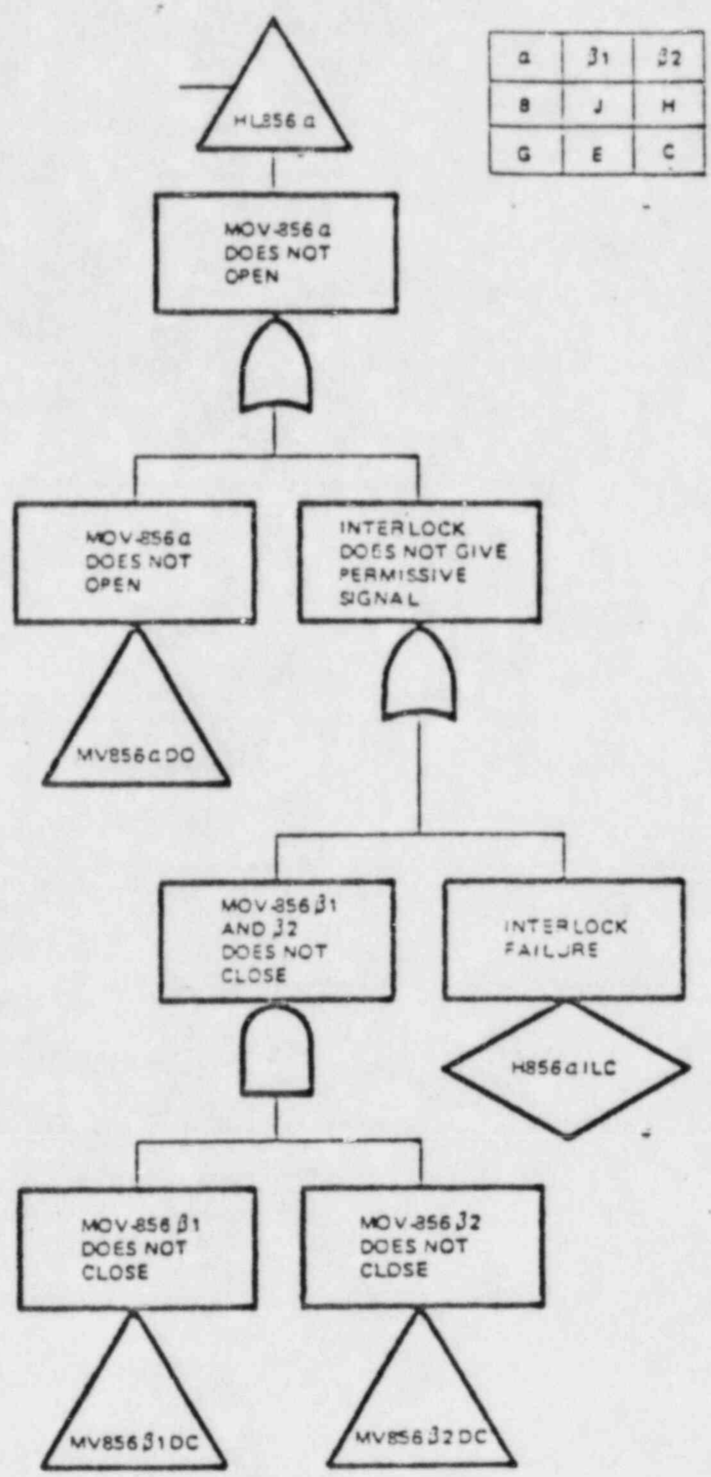
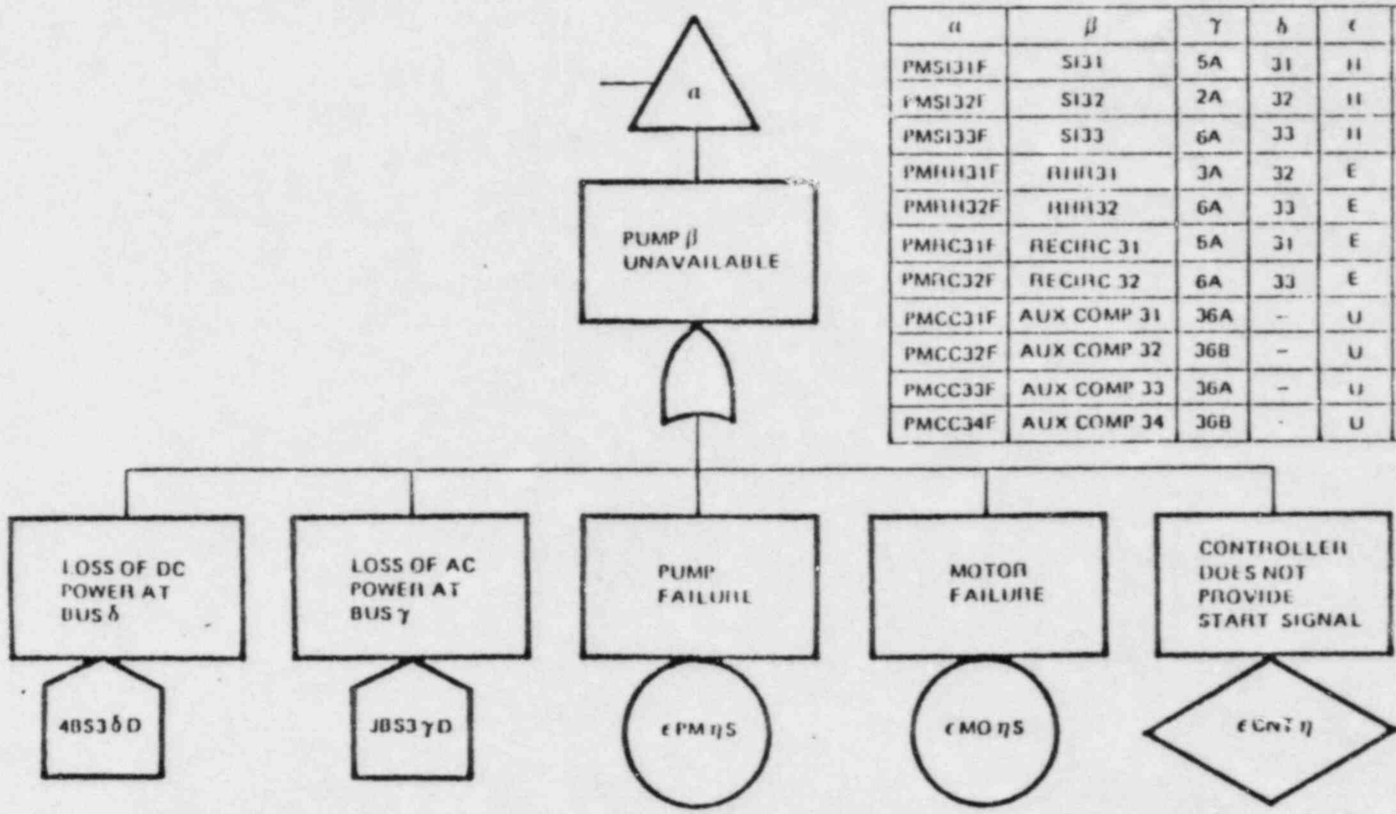
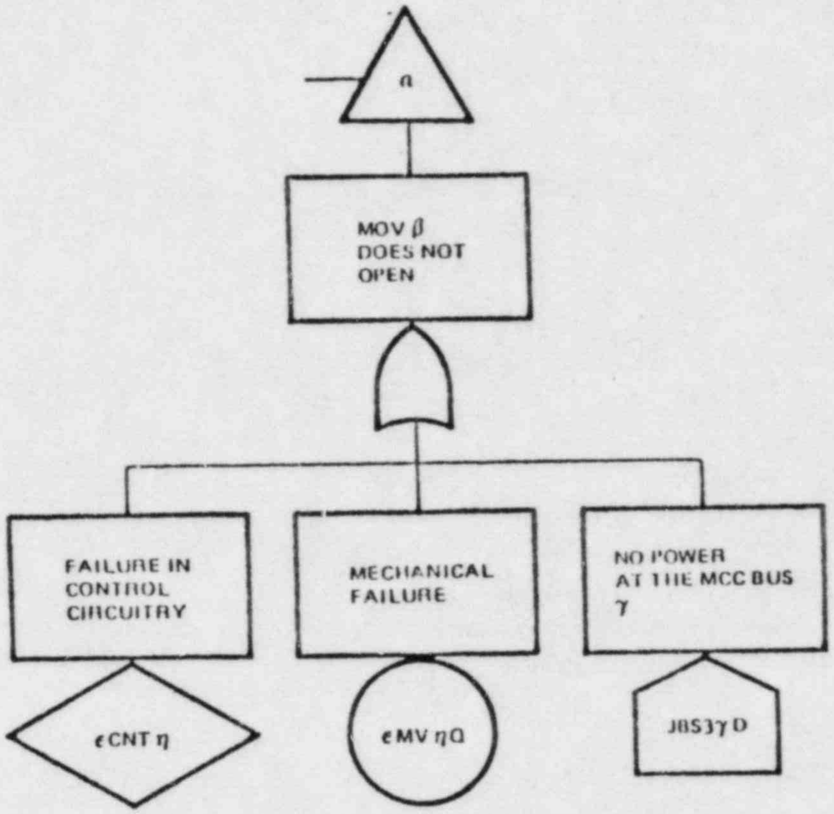


Figure 19. Fault Tree for Hot Leg Isolation MOVs Fail to Open



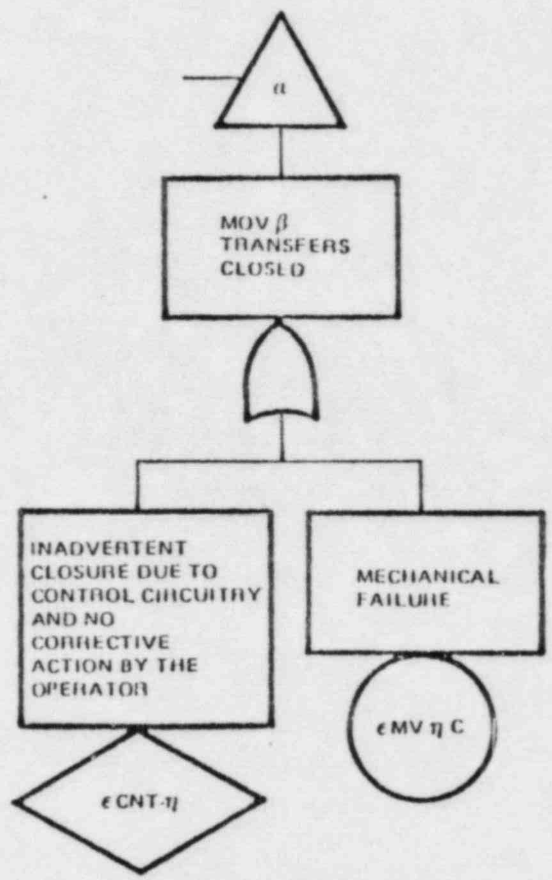
α	β	γ	δ	ε	η
PMSI31F	SI31	5A	31	H	SI31
PMSI32F	SI32	2A	32	H	SI32
PMSI33F	SI33	6A	33	H	SI33
PMRH31F	RHR31	3A	32	E	RH31
PMRH32F	RHR32	6A	33	E	RH32
PMRC31F	RECIRC 31	5A	31	E	RC31
PMRC32F	RECIRC 32	6A	33	E	RC32
PMCC31F	AUX COMP 31	36A	–	U	CC31
PMCC32F	AUX COMP 32	36B	–	U	CC32
PMCC33F	AUX COMP 33	36A	–	U	CC33
PMCC34F	AUX COMP 34	36B	-	U	CC34

Figure 20. Pump Failure



α	β	γ	ε	η
MV888ADO	888A	36A	H	888A
MV888BDO	888B	36B	H	888B
MV889ADO	889A	36A	C	889A
MV889BDO	889B	36B	C	889B
MV822ADO	822A	36A	U	822A
MV822BDO	822B	36B	U	822B
MV885ADO	885A	36A	E	885A
MV885BDO	885B	36B	E	885B
MV856BDO	856B	36B	H	856B
MV856FDO	856F	36A	H	856F
MV802ADO	1802A	36A	E	802A
MV802BDO	1802B	36B	E	802B
MV744DO	744	36A	E	-744

Figure 21. MOV Failure to Open



α	β	ε	η
MV745ATC	745A	E	746A
MV745BTC	745B	E	745B
MV744TC	744	E	744
MV1805TC	1805	E	1805
MV638TC	638	E	638
MV640TC	640	E	640
MV869ATC	1869A	H	869A
MV869BTC	1869B	H	869B
MV899ATC	899A	E	899A
MV899BTC	899B	E	899B
MV746TC	746	E	746
MV747TC	747	E	747

Figure 22. MOV Transfers Closed

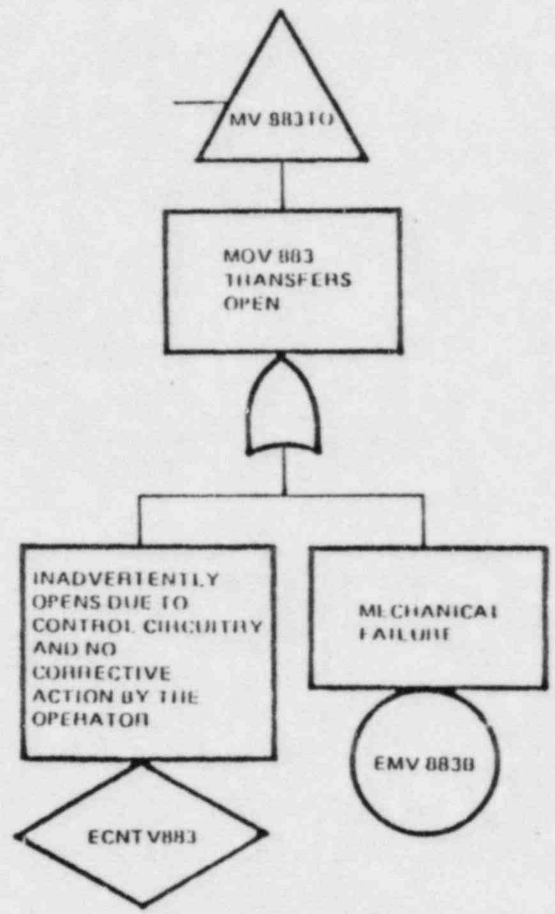
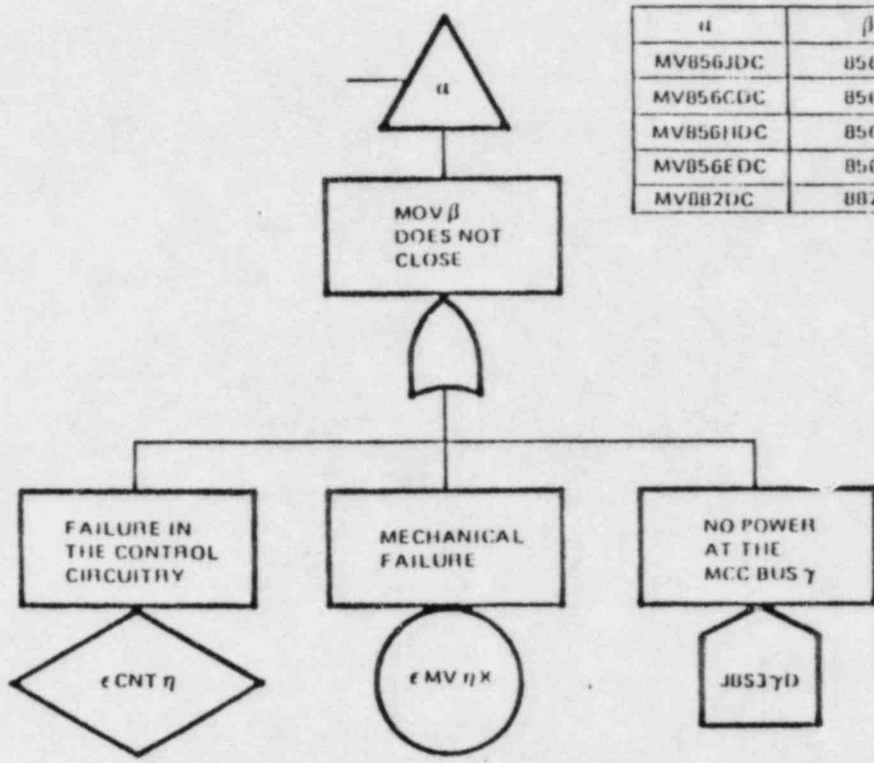


Figure 23. MOV Transfers Open



α	β	γ	ε	η
MV856JDC	856A	36A	H	856A
MV856CDC	856C	36A	H	856C
MV856HDC	856D	36B	H	856D
MV856EDC	856E	36B	H	856E
MV882DC	882	36B	E	882

Figure 24. MOV Fails to Open