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Byron Units 1 & 2 Braidwood Units 1 & 2 Auxiliary Feedwater System Reliability Analysis

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TABLE OF CONTENTS

TABLE OF CONTENTS - Continued

APPENDICES

LIST OF TABLES

LIST OF FIGURES

FOREWORD

GA-C16444

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BYRON/BRAIDWOOD NUCLEAR GENERATING STATONS

AFS RELIABILITY ANALYSIS

GA-C16444

1.0 Introduction

1.1 Objectives

The objectives of this study were to:

- Meet the requirements of the NRC generic letter dated March 10, 1980 (Ref. 8).
- Meet the acceptance criteria II.5.c. of NUREG-0800 (Ref. 5).

1.2 Background

The reliability characteristics of the four Byron/Braidwood (B/B) Auxiliary Feedwater Systems (AFSs) were evaluated in response to the NRC generic letter of March 10, 1980. NUREG-0611 provides the basis of qualitative comparison for the Byron/Braidwood AFS reliability with Westinghouse designed operating plants. NUREG-0800 provides the acceptable AFS quantitative range per demand as well as the methods and data to be used. Both qualitative and quantitative reliability results are presented in this study.

The Byron Unit 1 and 2 and the Braidwood Unit 1 and 2 AFSs are identical systems. The system evaluated in this study is the Byron Unit 1 AFS. The only difference identified between Byron Station and Braidwood Station is the reliability of the offsite power systems. The Braidwood offsite power system is considered to be more reliable for the reasons stated in section 4.1.2. Hence, to be conservative and to simplify the analysis a Byron AFS was chosen to be evaluated.

The Byron/Braidwood AFSs are redundant and diverse. The AFSs consist of three (3) trains; safety Trains A and B, and a non-safety Train C. Each train can supply 100% of the flow required for residual heat removal. Each pump has a different power supply. Train A and C pumps are electrically dependent. The Train B pump is electrically independent.

Trains A and B have two independent water supplies, the condensate storage tank and the essential service water system. The Train C water supply is the condenser hotwell. Trains A and B are automatically actuated. Train C is manually actuated. Trains A and B flows enter the steam generators (SGs) via the tempering flow lines. Train C flow enters the steam generators via either the main feedwater lines or the tempering flow lines. Trains A and B are tested on a monthly basis and following each maintenance outage. Train C is operated non-periodically on each plant start up and shutdown. Hence, considerable difference exists between the trains. The potential common cause failure areas is the check valves in the pump discharge lines.

The remainder of this report describes the Byron/Braidwood AFS reliability analysis assumptions, methodology and results.

1.3 Scope of Study

This study presents a qualitative comparison of the Byron/Braidwood AFS design to the operating Westinghouse designed plants using the methodology of NUREG-0611.

This study also presents a quantitative analysis of the AFS using methods and data presented in NUREG-0611 and NUREG-0635.

This quantitative method of analysis consists of two approaches. The detailed analysis was performed using Reliability Block Diagrams (RBD). The uncertainty analysis was performed using fault trees (FT). The results of each approach were compared to uncover data inconsistencies, modeling differences and unreasonable assumptions.

1.4 Criteria and Assumptions

The following analytical criteria, definitions and assumptions have been made:

A. The top event for this study is taken from NUREG-0611 which states: "The time interval of interest for all transient events considered is the availability of the auxiliary feedwater system during the period of time to boil the steam generator dry."

B. The 20 to 30 minutes boil dry time assumed in NUREG-0611 is used in this study.

C. The following initiating events were used in this study as required by NUREG-0611 and are assumed to occur on one unit only:
   - Event A: Loss of main feedwater (LMFW) with reactor trip (LMFW/RT)
   - Event B: LMFW coincident with loss of offsite power to both units (LMFW/LOOP)
   - Event C: LMFW coincident with loss of all AC power except for any derived from batteries (LMFW/LOAC)

D. Availability Criterion: Given that one of the postulated demand events occurs, unit AFS availability is defined as a success when at least one pump train starts and provides adequate feedwater to at least 2 of 4 steam generators in $\leq$ 20 minutes (dryout time). Repair and recovery was not included in this study.

E. Availability of AFS Power Sources: The following conditions are met with respect to the postulated demand events and the resulting AFS success.

1. LMFW: All AC and DC power available.
2. LMFW/LOOP: Diesel Generator 1A or 2A is available for Train A
3. LMFW/LOAC: DC and battery-backed AC available for Train B

F. The failure rate data base used for quantification was taken primarily from NUREG-0611. Additional data were taken from Reference 2. The component failure data determined the level of detail to which the analysis was taken.

G. Degraded Failures: A partially successful performance of any active or passive component was not considered. Each component and each operator action was assumed to be either successful or failed.

H. AFS Actuation and Control: For automatic operation during emergency shutdown conditions the Engineered Safety Feature (ESF) signal is initiated by any steam generator low-low level, safety injection and/or loss of offsite power. This starts AFS Trains A and B. The AFS Trains A, B, and C can also be actuated manually.

2.0 Summary of the AFS Reliability Study

The two objectives of this study were to evaluate the reliability of the Byron/Braidwood Auxiliary Feedwater Systems for three initiating events and to meet the requirements of the NRC generic letter dated March 10, 1980 and NUREG-0800. The results of these evaluations are presented. Findings stem from insights gained through the modeling and calculations indicates that the Byron/Braidwood AFS are well designed from the reliability viewpoint.

2.1 NUREG-0611 Method of Analysis (Qualitative)

The qualitative analysis of the AFS was achieved according to the qualitative criteria in NUREG-0611. Details of this comparison are presented in Table 4.2 and discussed in Section 4.2. The results are summarized in Figure 2.1.

2.2 Method of Quantitative Analysis

The quantitative analysis of the AFS complied with NUREG-0800 which stated: "An acceptable AFWS should have an unreliability in the range of 10^{-4} to 10^{-5} per demand on an analysis using methods and data presented in NUREG-0611 and NUREG-0635." Details are presented in Table 4.3 and discussed in Section 4.3. The results are summarized in Table 2.1.

The quantitative analysis was achieved using two methods. The first method used hand calculations based on point estimated reliability methodology. The second method used probability distributions in a fault tree code.

Insights into the impact of AFS reliability were first determined with event trees on a qualitative basis. Reliability Block Diagrams (RBDs) were used to study components in the AFS and provide first cut hand calculations to determine important contributors to unreliability. Next, a fault tree (FT) was developed and processed for the minimal cut sets. Then the STADIC computer code was used to calculate the probabilities and uncertainties for the fault trees under different initiating event conditions. Finally, the computer and hand calculations were compared, to assure that the quantitative results are reasonable and within the error spread as determined from the fault tree analysis. Details of these calculations are presented in Section 4.3.

2.3 Comparison of Quantitative Methods

The two assessment methods should give consistent results if the same assumptions are used in the logic of both RBDs and fault trees. The two methods can be made identical for simply defined systems. In this analysis both methods were employed to complement each other. The RBD and FT numerical unavailabilities were in close agreement. The RBD unavailability estimates were well within the error spread as determined from the FT estimates.

In the calculation of common cause factors a simplification was made in which the point estimates of Beta, a factor used in common-cause failure methodology (Ref. 9 and App.F), were 0.1 for intra train redundancy and 0.03 for inter train redundancy.

2.4 Findings

- The Byron/Braidwood (B/B) three train design is assessed to have high reliabilities (see Figure 2.1) based on the qualitative criteria described in NUREG 0611 for the three initiating events, (LMFW, LMFW/LOOP, and LMFW/LOAC). (Section 4.2)
- The B/B AFS meets the NUREG-0800 acceptable unreliability range of 10^{-4} to 10^{-5} per demand for the LMFW and LMFW/LOOP (see Table 2.1).
- Testing does not incapacitate the ESF trains due to the automatic opening of the ESF pump discharge test valve if an AFS requirement occurs.
- Low NPSH problems does not incapacitate the ESF pump train due to the automatic transfer to the standby water supply system (ESW - Essential Service Water).
- Inadvertent ESF pump maintenance valve closures due to human errors are minimized because of the automatic opening of the ESF pump discharge test valve and of the automatic transfer to the standby water supply system. Both automatic systems have remote manual overrides in the control room.
- Full flow testings of ESF pump trains and its associated valves from the condensate storage tank into the SGs at power operation during periodic testings and following maintenance outages will verify proper valve alignment, exercise check valves and test for valve plugging.
- The Byron/Braidwood Trains A and B are partly diverse and, therefore, resistive to some types of common cause failures. Train C is diverse from Trains A and B, but is dependent on off-site power availability. (Appendix F)

- The major component contributor to the ESF train unreliability is the pump startup and its local control circuit failure.

- The major contributors to the non-ESF train unreliability are the three manual operations (manual reset of Logic A, manual reset of Logic B and the manual start of Train C pump) required to start Train C.

- The major common cause component contributor to the B/B AFS unreliability indicated to be the pump discharge check valves.

- The major operational contributors to the B/B AFS unreliability (independent and common cause) indicated to be the normal "hardware/operator error" unreliability and the AFS unreliability during "maintenance" of a pump train. The point estimates indicated that the "maintenance" unreliabilities to be slightly greater than the "hardware/operator error" unreliabilities, however, the error spread (uncertainty) for each of these values determined from the fault tree analysis showed that these values were well within the error spread of the other.

- The "test" and "human error" operational contributors to the B/B AFS unreliabilities (independent and common cause) were calculated to be at least 2 orders ($<10^{-2}$) less than the "hardware/operator error" and "maintenance" operational contributors. Thus, the "test" and "human error" unreliabilities were determined to be insignificant in the total B/B AFS unreliability and were not estimated with the fault tree code.

- Automatic switching to the essential water service system on low suction pressure for Trains A and B does not significantly improve the AFS quantitative reliability. (Section 4.3)

2.5 Recommendations for the AFS Operation

- Supply the Train C auxiliary feedwater pump electric power from the bus fed by off-site power from the System Auxiliary Transformer (SAT) to eliminate bus transfer unreliability.

- Consider manual instead of automatic actuations of the Essential Service Water System (ESW). Spurious operation could introduce untreated water into the steam generators. Manual operation of ESW would prevent spurious automatic actuations.

Table 2.1

SUMMARY OF BYRON/BRAIDWOOD AFS UNRELIABILITY ESTIMATES

	INITIATING EVENT	POINT ESTIMATE FROM RBD (unavailability/demand)	MEDIAN ESTIMATE FROM FAULT TREE (unavailability/demand)
Statistical Independent	LMFW	3.4E-6	1.8E-6(7)*
	LOOP	9.2E-5	9.8E-5(4)*
	LOAC	1.1E-2	1.2E-2(3)*
Statistical Independent + Common Cause	LMFW	8.2E-6	1.2E-5(4)*
	LOOP	1.0E-4	1.5E-4(3)*
	LOAC	1.2E-2	1.2E-2(3)*

* Error spread = $Q_{95\%}/Q_{50\%}$ assuming log normal distribution

Significant Number to One Place

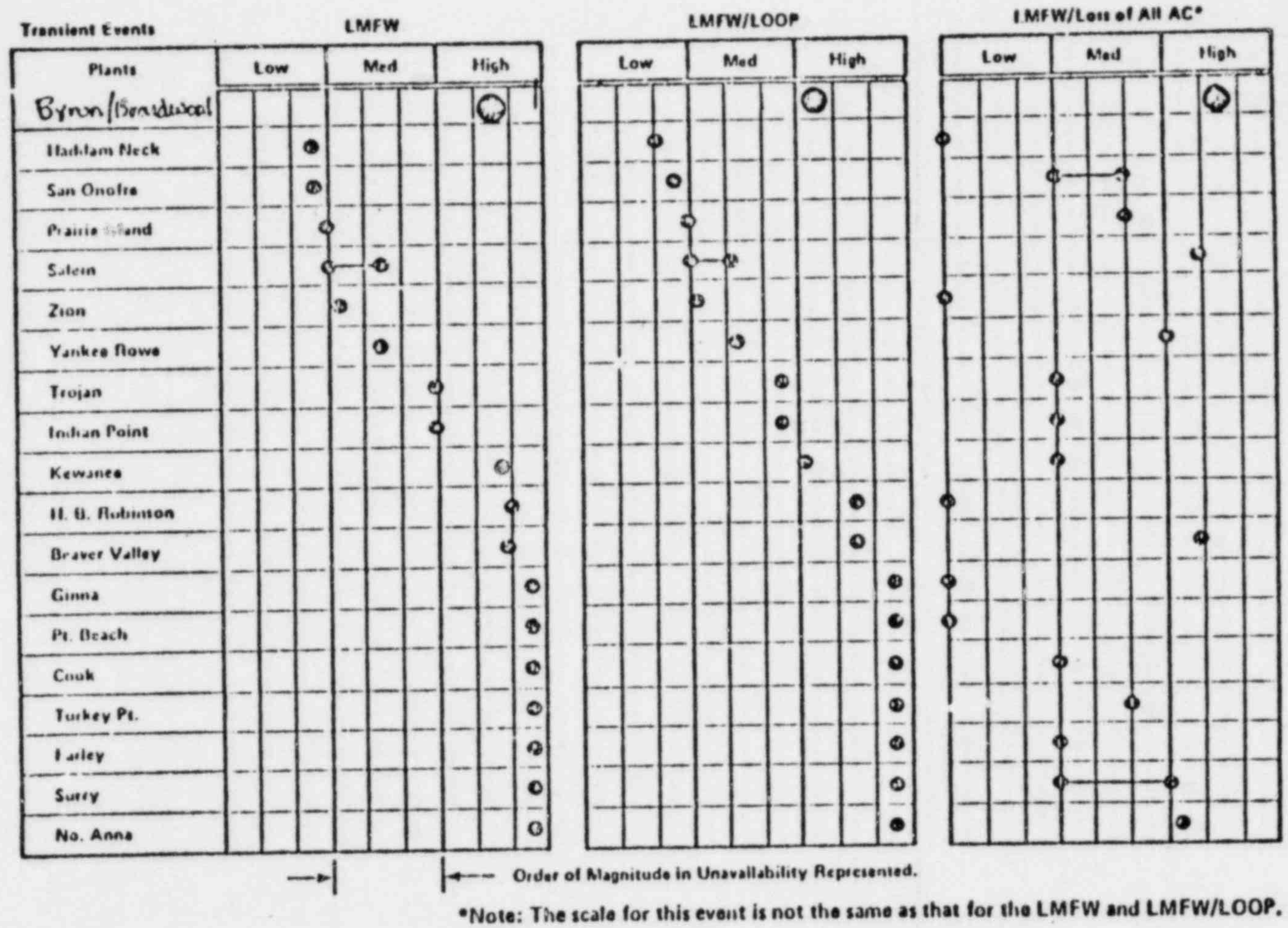

Figure 2.1 Comparison of This Byron/Braidwood Qualitative Reliability Assessment with Other Westinghouse AFS Using NUREG 0611

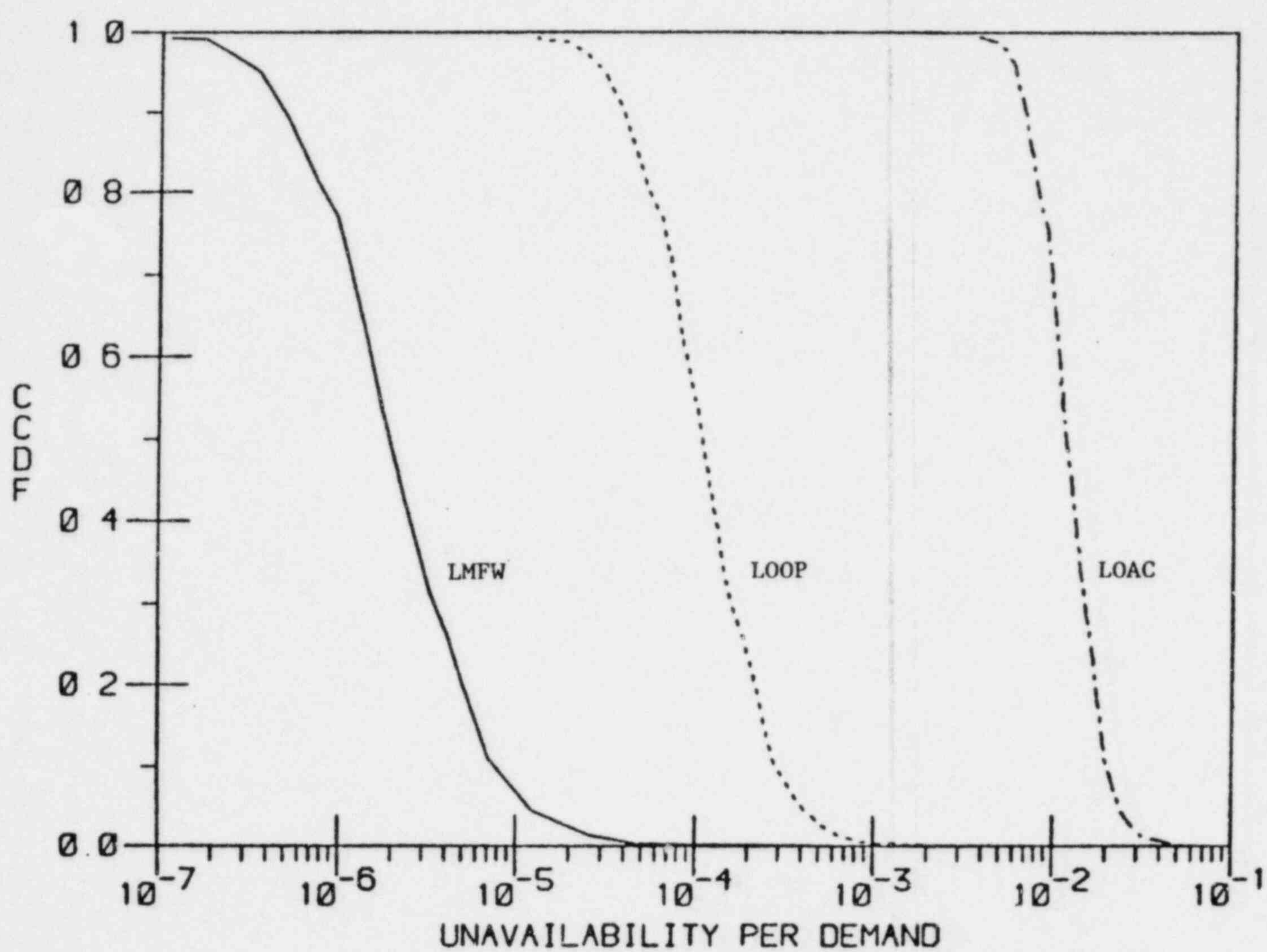

Figure 2.2 BYRON/BRAIDWOOD AFS UNRELIABILITY ERROR SPREAD

Statistical Independent Estimate

3.0 Auxiliary Feedwater System Description

3.1 General AFS Information

The function of the Auxiliary Feedwater System is to provide residual heat removal when the main feedwater (MFW) system is unavailable. The AFS consists of three 100% trains. Each train has the capacity to supply the steam generators with sufficient feedwater to cool down the unit safely to 350°F, the temperature at which the low pressure residual heat removal system can be utilized. One of the trains is used during start up and shutdown of the unit. A simplified drawing of the Bryon/Braidwood AFS is shown in Fig. 3.1.

Auxiliary feedwater is supplied by diverse means with two automatically initiated safety trains, Trains A and B, and one manually initiated non-safety train, Train C. ESF Bus 141, the bus that supplies the Train A motor driven auxiliary feedwater pump, is capable of being supplied from one of three sources: the system aux transformer (SAT 142-1); the diesel generator (DG 1A); or the Unit 2 ESF Bus 241. In the event of a LOOP event, Bus 141 automatically transfers to DG 1A. If DG 1A fails to start, the operator is able to close two breakers from the control room to feed Bus 141 from Bus 241, which still has power from the system aux transformer associated with that bus or from diesel generator 2A. The operator is capable of closing these breakers within the 20 minute steam generator boil dry time assumed in this analysis. Train B utilizes an ESF seismic Category I diesel-engine driven pump. This diesel-engine pump is AC power independent. Trains A and B are located in the Auxiliary Building.

Train C utilizes the start up feedpump, a non-ESF electric-motor driven pump. This train is also used during unit startup and normal unit shutdown from less than 10% power. It is also used in the hot standby mode. Train C is located in the Turbine Building.

3.2 System Operation

Successful unit cooldown can be achieved by supplying feedwater to any two of the four available steam generators. Safety analysis has shown that 160 gpm delivered to each of three steam generators or 240 gpm delivered to each of two steam generators is sufficient for residual heat removal. Each of the ESF trains, Trains A or B, has two times the minimum capacity. The non-ESF train, Train C, has approximately four times minimum capacity. Hence, any one of the three trains can supply the needed cooling water to the secondary side of the steam generators.

The Train A pump motor drive is powered from ESF Bus 141. The Train A AFS regulating valves are powered by 125 V DC ESF 131X4. The Train A AFS isolation valves are powered from 480 V AC ESF Bus 131. The AFS isolation valves are normally open and are not required to change position on AFS actuation.

The Train B pump diesel engine is supplied by its own 24 volt DC batteries. This diesel drive is self-contained and completely independent of AC power under emergency conditions. Train B AFS regulating valves are powered

by 125 V DC ESF Bus 112. Train B AFS isolation valves are powered by 480 V AC ESF Bus 132. The AFS isolation valves are normally open and are not required to change position on AFS actuation.

The Train C pump motor is powered from a non-ESF bus. This train is unavailable on loss of offsite power.

The ESF logic system will automatically start Trains A and B on three signals: lo-lo level in the secondary side of the steam generator; a safety injection signal; and a loss of offsite power signal. Manual start up capability from the control room backs up the automatic system start. Instrumentation and controls are also provided at the remote shutdown panel in the unlikely event that the control room must be evacuated. Train C is manually operated from the control room and provides a manual back up to Trains A and B.

The normal water supply for Trains A and B is the condensate storage tank. The alternate supply is the essential service water system. Train C takes a suction on the condenser hotwell via the condensate/condensate-booster pump.

The Train A and B pumps are protected against low suction pressure with a run inhibit signal. This condition is corrected by the automatic opening of essential service water (ESW) valves to the suction of the auxiliary feed pump. This occurs when a low suction pressure signal is received.[1] The automatic startup can be initiated within about 1 minute from the initiation of the Lo-Lo steam generator level signal. This is well within the limit of 30 minutes set by the inventory of secondary water already in the steam generators.

To prevent pump damage a recirculation line is provided on each AFS pump discharge which bypasses flow to the condensate storage tank or essential service water system for the ESF pumps and to the condenser hotwell for the non-ESF pump. Excessive recirculation flow is prevented by orifices in the piping, hence each of the pumps can supply the full feedwater requirement with full recirculation flow.

Monthly periodic tests are required for Trains A and B. Only one train is tested at a time, the other train remains in a normal line up. The air-operated discharge test valve is closed and the pump is warmed up on recirculation flow. The ESF logic start signals stated above will automatically open the discharge valve. Hence, the train under test is always available to supply auxiliary feedwater to the steam generators. The conclusion of the test requires the train valves to be aligned to the steam generator for a full flow test. This portion of the periodic test will identify any plugged or inadvertently closed valves. The same test is required following each maintenance or repair activity.

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[1]This action provides unprocessed water to the main steam generators. Section 4.3 shows that this action does not significantly improve AFS reliability, for the initiating events considered.

Train C operation is tested by normal use during startup and shutdown of the unit. It is always available except following loss of offsite power.

From the reliability viewpoint, the key components which contribute to the AFS unreliabilities are the electric and diesel drives and their controls. Valves in the water pathway have been contributors to system failure in other AFS but the normally opened valves, the application of check valves, and the monthly full flow tests reduce their contributions. A failure of the condensate water supply is not a major contributor because of the partly diverse valve train from the tank and the automatic backup water supply system. Maintenance outage of a train is also a contributor to AFS unreliability.

3.2.1 Water Pathway

3.2.1.1 Trains A and B

The normal water supply is the 500,000 gallon condensate storage tank. A minimum capacity of 200,000 gal is reserved for the Trains A and B. In addition to this normal water supply and the essential service water (ESW) system, the condensate tank from the other unit can be manually valved in by changing the position of one valve.

The auxiliary feedwater pump discharge is routed to the steam generators via the tempering flow lines. From the steam generator the steam is normally discharged to the condenser through the steam dump system. Should the condenser be unavailable, the steam is vented to atmosphere through the secondary relief valves. Either path provides for successful operation of the AFS, since the AFS function is to remove heat from the steam generators until either a restart condition or the residual heat removal system condition is reached.

The auxiliary feedwater flow to the steam generators is controlled from the control room. The control valves are throttled as the desired steam generator level is reached and the decay heat load diminishes during a cool down cycle. Depending on which trains, pumps, and steam generators are available, the operator can line up the appropriate valves to establish AFS flow paths. Any train can feed any of the four steam generators. In the unlikely event that the control room must be evacuated, the AFS valves and pumps can be operated at the remote shutdown panel.

When the AFS has cooled the plant down to 350°F, about 5 hours after the initiating event, the residual heat removal system can manually be placed in operation and the AFS trains are manually placed in standby condition.

3.2.1.2 Train C

The Train C water supply is the condenser hot well. The normal volume is approximately 100,000 gallons. Four 33% condensate/condensate booster pumps are available. Each condensate/condensate-booster pump is driven by one motor.

With off-site power available, the running pumps will remain operating and recirculating to the condenser, thus providing NPSH (net positive suction head) to the Train C pump. This pump is manually controlled from the control room. An ESF logic start of Trains A and B will automatically close the main feedwater valves used by Train C. To start Train C, the steam generator (SG) feedwater valves must be manually reset with pushbuttons, one for Logic Train A and one for Logic Train B.

3.2.2 Auxiliary Feedwater Drives

3.2.2.1 Diesel Driven Auxiliary Feedwater Pump

This 1250 HP diesel driven pump is designed to be independent of AC power under emergency conditions. It is automatically started by a self contained 24 Volt D.C., battery-powered, start system. When any of three emergency signals (e.g. the Lo-Lo steam generator level, safety injection, or loss of AC power) are received the diesel is started. The pump provides 840 gpm at a 3350 feet head. This Detroit Diesel has its own 500 gallon supply of fuel, intake and exhaust air ducts, internal lube oil pump, and water jacket cooling pump. An axial vane fan driven from the gear box circulates air over the engine to provide cooling during operation. The heated air is exhausted through passive building vents. When AC power is available, backup pumps are available for oil pressure, water jacket cooling and room air cooling. These backup systems help reduce engine wear during testing periods by providing prestartup oil pressure to the bearings and providing backup engine cooling.

3.2.2.2 ESF Motor Driven Auxiliary Feedwater Pump

The electric motor driven pump is used in most Pressurized Water Reactors (PWRs) as a diverse method of supplying auxiliary feedwater. In the B/B design the Train A pump is powered from the 4160 volt ESF Bus No. 141. This horizontal pump rated at 1250 HP provides 890 gpm at 3350 feet of head. This pump is functionally redundant to the diesel driven pump under all conditions except the loss of all AC power.

3.2.2.3 Non-ESF Motor Driven Auxiliary Feedwater Pump

The non-ESF electric motor driven pump is rated at 2000 HP and can provide 5300 gpm at 1200 feet of head. It is powered from a non-ESF 6.9 KV bus.

This electric motor driven pump has two requirements. Off-site power and at least one of the four condensate/condensate-booster pumps running to provide auxiliary feedwater to the four steam generators. The condensate/condensate-booster pumps also require off-site power. Commonwealth Edison's practice is to operate with ~50% of the house load on the unit auxiliary transformers (UATs) and 50% on the system auxiliary transformers (SATs)(FSAR pg. 8.3-2). On a turbine-generator trip, two condensate/condensate-booster pumps will continue to operate on the SATs. The other condensate/condensate-booster pumps will continue to run while the bus breakers automatically transfer from UAT to SAT.

3.2.3 Valving

3.2.3.1 Condensate Storage Tank Valves

The ESF AFW pumps are supplied from the Condensate Storage Tank via two separate lines, both of which are normally aligned to supply the ESF AFW system.

One line has a manual, locked open valve and a check valve in series. The other line has two manual, normally open valves in series. The lines combine downstream of these valves in the Turbine Building and this common line splits to supply the two ESF AFW pumps in the auxiliary building through a manual, locked open valve and a check valve in series in each pump supply line.

3.2.3.2 Auxiliary Feedwater Pump Suction Valves (Manual)

The manual suction valves to the Train A and B are locked open. In the case of low suction pressure the check valves in the suction line prevent backflow from the essential service water system to the condensate tank. The positioning of these valves are verified by the full flow testing procedure. Plugging or manually closing these valves are the most likely cause of loss of normal suction from the condensate storage tank.

3.2.3.3 Auxiliary Feedwater Supply Valves

Each train supplies all four steam generators. The separate Train A and Train B supply lines combine into a common header prior to entering the tempering flow lines at each steam generator. Each supply line has three valves; a check valve; a motor operated isolation valve; and a flow control valve. The control valves are air operated valves controlled from the control room or from the remote shutdown panel. The valves fail open on loss of air or loss of power to the solenoids. The control valves have an automatic setpoint controller which limits flow to 160 gpm to each steam generator when the pumps are running. The setpoint is monitored by the ESD (Engineered Safety Display) panel. Any controller output less than the setpoint value will initiate an alarm on the ESD panel.

3.2.3.4 Auxiliary Feedwater Backup Water Supply (Automatic)

The essential service water back up supply valves are normally closed, motor-operated valves. There are two valves in series to each pump suction. these valves are powered by ESF buses. A low pump suction pressure signal developed independently by each train in conjunction with a lo-lo SG level, SI, Loss of Power signals will automatically open these valves. They can also be opened from the control room or manually at the valve.

3.2.3.5 Train C Valves

The Train C flow path utilizes the normal main feedwater lineup. All the valves are to remain in operating position following a loss of main feedwater condition except for the main feedwater flow control valves. These valves must be reset and manually positioned from the control room for auxiliary feedwater flow from the Train C pump.

3.3 Inspection and Testing Requirements

The AFS trains are capable of being tested while the plant is in normal operation. A full flow test through the AFS valves allows the valve positions to be operationally tested. Discharge pressures and flow indications are provided locally and in the control room. Periodic testing will identify any "plugged" valve failures. During the first phase of the test procedure, the discharge test valves are closed and the auxiliary feedwater is recirculated back to the condensate storage tank. After the pump is tested, the discharge valves will be opened to allow full flow into the steam generators. These valves are designed to open on an ESF start signal for the AFS. Thus, the train is available during the test.

3.4 Instrumentation and Control

Control room instrumentation includes steam generator level indications, controls, hand switches, and position indicators for power operated valves.

The control start logic for the AFS, which is part of the Engineered Safety Features Actuation System, is an automatic two-of-four input signal with manual override.

The following main control room monitors are provided for purposes of AFS control:

- Input to ESD panel.
- AFS trip status light.
- Discharge presssure of each AFS pump.
- Auxiliary feedwater flow to each steam generator.
- Status lights for each regulator valve.
- Alarms for AFS diesel engine temperature, oil pressure, and speed.
- Status lights for AFS power operated valves.

The instrumentation and control system is designed such that undervoltage on two of the four instrument channels results in automatic initiation of the auxiliary feedwater Trains A and B.

3.5 Supporting Systems and Sources

The active components of the AFS are dependent upon diverse sources of electrical power. Lube oil and cooling subsystems are supplied internally from the diesel engine. All valves and controls in the same train are similarly matched to the same power source as its pump, and key devices can be manually or locally actuated as well. Four independent transmission lines supply the offsite power, and two dedicated diesel generators back up the onsite Class 1E power busses. In addition, the operator is able to close two breakers from the control room to feed each of these busses which still has power from the other Unit system aux transformer or from the other unit diesel generator. Up to 300,000 gallons of demineralized water can be made available to the AFS from the Unit 2 condensate storage tank by a manual cross tie valve.

3.6 Technical Specification Limitations

Technical Specifications require the availability of 200,000 gallons of water in the condensate storage tank for AFS use. Tank levels are alarmed and annunciated in the main control room.

A maximum of 72 hours out of service is allowed for maintenance or repair of an ESF AFW pump/train while the reactor is critical. If that time is exceeded, the reactor must be placed in hot shutdown within the next 12 hours. The 2A(1A) diesel generator is allowed to be inoperable for 7 days. If this time is exceeded, Unit 1(2) must be placed in HSD (hot shutdown).

3.7 Surveillance Requirements

1) Each auxiliary feedwater pump shall be demonstrated operable:

   A. At least once per 31 days by:

      (1) Verifying that each pump develops discharge pressure of at least 90% of the manufacturer pump performance curves.

      (2) Verifying that each valve (manual, power operated or automatic) in the flow path that is not locked, sealed, or otherwise secured in position, is in correct position.

   B. At least once per 18 months during shutdown by:

      (1) Verifying that AFS starts automatically upon receipt of an ESF test signal.

2) The condensate storage tank shall be demonstrated operable at least once per 12 hours by verifying that the contained water volume is within its limits when the tank is the supply source for the auxiliary feedwater pumps.

3) The essential service water system shall be demonstrated to be available whenever the condensate storage tank is inoperable.

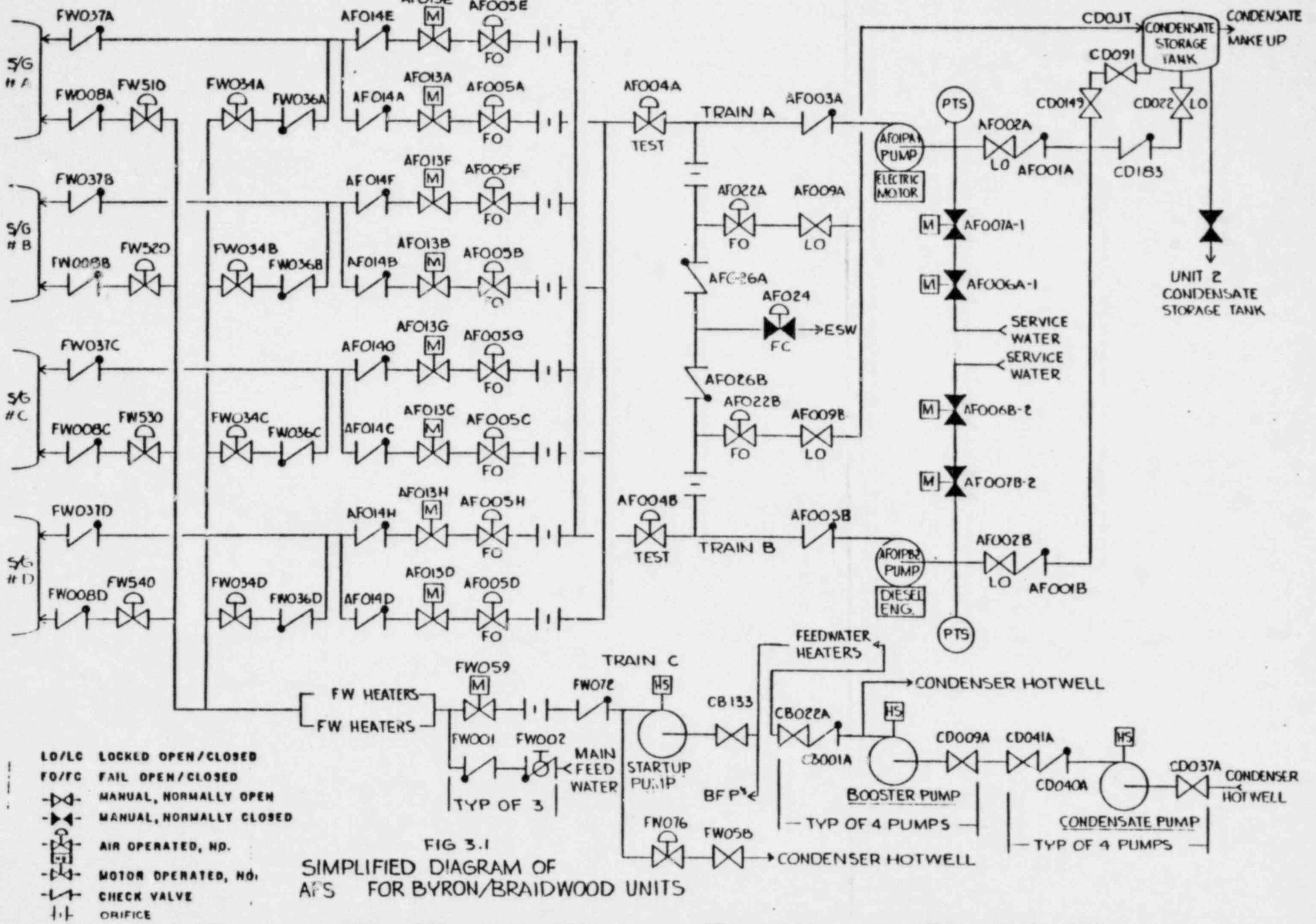


FIG 3.1
SIMPLIFIED DIAGRAM OF AFS FOR BYRON/BRAIDWOOD UNITS

4.0 Reliability Analysis

One of the most important parts of any reliability analysis is to define very carefully the boundaries of the analyzed system while retaining a perspective on the entire plant operation. In this analysis two methods were used. First, the components of the auxiliary feedwater system were defined in a reliability block diagram. This is a logic model which is based on the components needed to make the system work. The second approach is that of the event tree/fault tree analysis method. After studying the system to understand fully its operation, event trees were constructed to show the potential for various event sequences which involve the auxiliary feedwater system. The results of the event tree construction help to define the top events of fault trees. This important definition becomes the top block in a fault tree. Hence, by this process the failure conditions and component failures which lead to the top event can be defined. In the fault tree format the components can be in any system. RBDs and fault trees can be logically equivalent, if the boundary conditions are equivalent.

4.1 Event Tree Construction

Three initiating events are considered in the reliability evaluation as suggested in NUREG-0611. Accident scenarios stemming from these events are expected to dominate the plant risk for events using the AFS as shown in WASH-1400. These events are loss of the main feedwater (LMFW), loss of offsite power (LMFW/LOOP) and loss of all AC power (LMFW/LOAC). The AFS reliability has an impact on which scenario can be followed after the initiating event, but the purpose of this study is to assess only the AFS reliability under the major events listed above.

4.1.1 LMFW

Loss of main feedwater events are characterized by a reduction in steam generator water levels which results in a reactor trip, a turbine trip, and auxiliary feedwater actuation by the ESF protection system logic. Success of these actions are considered in events 1 and 2 in Figure 4.1 on the upper branches. Following reactor trip from a high initial power level, the power quickly falls to decay heat levels on the order of 6% to 3% of full power. Without auxiliary feedwater as shown in the lower branches of event 3, the steam generator water levels continue to decrease, progressively uncovering the steam generator tubes as decay heat is transferred and discharged in the form of steam preferably through the steam dump valves to the condenser or through the steam generator safety or power-operated relief valves to the atmosphere. As a result, the reactor coolant temperature increases as the residual heat in excess of that dissipated through the steam generators is absorbed. If this condition continues, the volume of reactor coolant expands and begins filling the pressurizer. Without the addition of sufficient auxiliary feedwater in about 30 minutes, further expansion will result in water being discharged through the pressurizer safety and/or relief valves into the containment and this is considered to be a failure of both the AFS and MFW. These sequences are shown with solid lines in Event 6.

If the temperature rise and the resulting volumetric expansion of the primary coolant are permitted to continue, and if the relief valves fail to reclose as shown in the lower branches of Event 7, the continuing loss of fluid from the primary coolant system may result in bulk boiling in the Reactor Coolant System and eventually in core uncovering, loss of natural circulation, and core damage. This condition can be avoided by recovery of the main feedwater or auxiliary feedwater within approximately one hour or successful closure of the relief valves. If such a situation were not recovered, the Emergency Core Cooling System could be used to supply primary coolant makeup water. After a longer time period, however, the primary coolant system pressure may exceed the shutoff head of the safety injection pumps, causing an insufficient supply of water. Hence, both success and failure of the ECCS is considered in Event 8. The timely introduction of the sufficient auxiliary feedwater is necessary to counteract the decrease in the steam generator water levels, which will reverse the rise in reactor coolant temperature, and prevent the pressurizer from filling to a solid water condition. AFS success is to establish stable hot standby conditions or prepare for restart. Subsequently, a decision may be made to proceed with plant cooldown if the problem cannot be satisfactorily corrected. The event tree of Figure 4.1 then provides the details of the potential accident sequences for later quantification. This evaluation is limited to reliability of the AFS in Event 3 and not the entire accident sequence.

4.1.2 Loss of the Offsite Power (LMFW/LOOP)

Loss of offsite power is an ESF actuation signal for the AFS. The reliability of the AFS is affected under this initiating event due to the unavailability of Train C (the non-ESF AFS train). The event tree of Figure 4.2 is a modification of Figure 4.1 which includes detailed consideration of the loss of offsite power. The difference here is in the recovery of the power supplies (not included in this analysis). The physical behavior of the plant is as described in Section 4.1.

As can be seen from Figures 4.3 and 4.4 there is a difference between the offsite power sources at the two stations. At Byron the offsite power system consists of a switchyard that is supplied from the Commonwealth Edison grid by four separate 345 kV lines. At Braidwood the system is supplied by six separate 345 kV lines. ESF Bus 141 supplies the 1A motor driven auxiliary feedwater pump. ESF Bus 141 is capable of being supplied from any one of three sources:

1. System Aux Transformer (SAT 142-1)

2. Diesel Generator 1A

3. Unit 2 ESF Bus 241.

During a LOOP event, ESF Bus 141 transfers automatically to 1A D/G. If 1A D/G fails to start, the operator is able to close two breakers from the control room to feed Bus 141 from Bus 241. Bus 241 receives its power from its associated SAT or from 2A D/G. Consideration for failure of 2A D/G has been included in the calculations. The operator is capable of closing the breaker from Bus 241 to Bus 141 within the 20 minute steam generator boil dry time assumed in this analysis.

4.1.3 Loss of All AC Power (LMFW/LOAC)

This event is a subset of the event tree in Figure 4.2. The main affect of this event is that the two diesel generator power supplies fail to supply the motor driven feedwater train. If the diesel generators supplying bus 141 cannot be recovered quickly, then the AFS depends on the diesel driven pump in Train B as the only operable source of auxiliary feedwater. Hence, for this initiating event diesel-driven pump reliability is the key factor. AFS response in this case, requires that the entire Train B cooling system be independent of AC power sources. The event tree of Figure 4.2 is still applicable except that loss of all AC power sources is considered in the fault trees.

4.2 Qualitative Reliability Analysis

A qualitative reliability comparison of the Bryon/Braidwood AFS with the results of those analyzed in NUREG 0611 indicates that the B/B system is among the higher reliability plants for all initiating events (IEs). Although the B/B AFS for the LMFW/LOOP is a two pump redundant system, the power sources to these pumps consists of three "power source" redundant systems. Since the power sources "fail to start" are the dominate failures, the B/B AFS for the LMFW/LOOP was qualitatively assessed into the lowest of the high reliability category range.

4.2.1 NUREG 0611 Comparative Reliability Analysis

The NUREG 0611 (Ref. 1) provides a qualitative reliability assessment of the various operating PWR AFSs. Qualitative criteria were used to classify the system reliability in classes of relative low, medium and high reliabilities for the three initiating events (IE). The criteria were presented in a narrative form on pages III-21 through III-23. These criteria are summarized here in Table 4.1. Table 4.2 shows the NUREG 0611 criteria and the Byron/Braidwood classifications and assessments. Figure 4.5 presents the comparison of the Byron/Braidwood AFS reliability characterization with other operating plants using a Westinghouse NSSS.

4.2.1.1 Interdependencies

The potential for dependencies between trains was reviewed during the reliability analysis from the qualitative viewpoint. Separation was adequate. No single point failures were found. Even in the test procedures an automatic start signal overrides the testing thus eliminating a potential human dependency. Inadvertent closure of the pump suction valve will not incapacitate the train.

The operating experience in Appendix A indicated that the greatest potential for dependencies between the Trains was the automatic start signal. However, in every case, the manual override start was successful. The B/B automatic AFS start signals are backed with manual overrides and thus this dependency is greatly minimized.

4.3 Quantitative Reliability Evaluation

The purpose of this analysis is to meet the quantitative reliability criteria of NUREG-0800 which states: An acceptable AFWS should have an unreliability in the range of 10^{-4} to 10^{-5} per demand based on an analysis using methods and data presented in NUREG-0611 and NUREG-0635. Data not given in NUREG-0611 and NUREG-0635 was supplemented with WASH 1400 data except for diesel generator "fail to start". This was assumed to be 10^{-2}/demand with an error factor of 3. This seemed to have been the value used in NUREG-0611 and NUREG-0635. NRC Safety and Licensing Branch agreed on the usage of this number.

The significant place of the quantitative results is basically to one place. If the numbers are rounded to one place, many numbers will appear to be the same. Thus, two place numbers are shown as a difference indicator. The 5% to 95% error spread as determined by the fault tree analysis will indicate the uncertainty of the results.

Two logic model types are utilized, each having strong points and weaknesses. First, the reliability block diagrams (RBD) logic model developed from questions such as: What is needed to make the system operate? What backups exist? What redundancies exist? This modeling technique requires knowledge of valve positions, changes of state, signal operations, etc., to properly model the system reliability characteristics. The weakness of the RBD logic modeling is that outside system interdependencies could be overlooked. For example, valve positions in other systems which impact flow in the AFS could be missed. Fault trees (FT) logic models are constructed to calculate the probability of the "top event". The top event should be carefully defined using event trees to define the boundaries of the fault tree analysis. For example, in the event tree of Figure 4.2 there is no special provision for onsite power (i.e. Diesels 1A,2A). Therefore, these items should be included in the fault tree. A drawback to fault trees is that so many conditions can be described that the reduction of the FT to its important contributors can be very difficult. To simplify this step, a minimal cut set computer code was employed to identify each set of failure conditions within the FT. These minimal cut sets helped in assessing the common cause failure potential between required components. After the minimal cut sets were developed, FT equations were written to describe the probabilities and associated uncertainties of the AFS unavailability. A computer code called STADIC can accept this FT equation along with data inputs for each component or supercomponent. Based upon this input a probability distribution for the top event was formulated. The component failure data determined the level of detail to which the analysis was taken.

4.3.1 Reliability Block Diagram Analysis

4.3.1.1 Assumptions

The RBD (Appendix B) for the Bryon/Braidwood AFS was developed assuming the need for the AFS from plant near full power. The RBD delineates the various success paths for starting the system on demand. It also shows the various components that were considered in the analysis and how they are inter-related to each other. The various types of redundancies (active, automatic standby, remote manual and local manual standbys) are symbolized.

The top train on RBD pages 1, 2, 3, and 4 shows the model for Train A with the ESF electric motor drive pump and the bottom train shows the model for Train B with the ESF diesel drive pump. These trains are identical except for the pump drives. The inter-relations between these trains are the common source of water supply, the condensate storage tank. However, each train has an independent, automatic switching capability to the ESW (emergency service water) system when low pressure occurs on the pump suction coincident with a Safeguards Actuation Signal, a Loss of off-site power, or a low-low SG level trip. The ESW is operable from the ESF electrical bus.

For the initiating events considered in this analysis, an automatic ESF AFS start signal was assumed. The ESF logic A signal actuates Train A and ESF logic B signal actuates Train B. Manual over-ride capabilities Trains A&B are available in the control room and the remote shutdown room.

AFW pump recirculation is only required when the flow is throttled, or stopped, to the SGs. During initial demand of the AFS when full flow is required to the SGs, the recirculation is not required. Each train has an automatic recirculation switchover from the condensate storage tank to the ESW system. The recirculation is used during pump testing for pump warmup before reopening the pump discharge test valve to provide full flow test into the SGs. By procedure, this same test will be used after each maintenance action on the train to assure complete train functioning.

Train A and Train B can independently supply AFW to each SG through the flow limiting orifice, flow control valve and a containment isolation valve. Cross flow between these trains is prevented by check valves in the tempering flow line at the SG and on the SG blowdown line and valves.

Train A is available for two of the three postulated initiating events (IE); loss of main feedwater (LMFW) with offsite power, and loss of main feedwater with loss of off-site power (LMFW/LOOP) (onsite power from Unit 1 and Unit 2).

Train B is available for all IEs, namely: LMFW, LMFW/LOOP and LMFW/LOAC (DC battery power, only).

Train C (10% full plant capacity) utilizes the normal condensate system and provides AFW through the main FW piping to the SGs. Therefore, Train C is available only for LMFW and requires remote manual startup from the control room. Train C utilizes the condensate hot well as the water source.

Assuming the plant is at power, three of the four (1/3 capacity) condensate/condensate booster pumps (one motor drives both pumps) will normally be operating. The fourth pump is on automatic standby. Two of the condensate/condensate booster pumps motors will be on SAT and two will be on UAT. With reactor/turbine trip, the UAT bus breakers will rapidly transfer (within 3 cycles) to the SAT. This will not affect the motor operation on these buses unless breaker transfer is not successful. The operating condensate/condensate booster pumps were assumed to continue to operate after a reactor/turbine trip. This requires that the condensate booster recirculation functions successfully. Otherwise, these pumps will be pumping against a shutoff head. In addition to the condensate booster pump recirculation, the two normally operating 50% capacity main FW pump recirculation valves are operable for added condensate recirculation. The standby 50% capacity main FW recirculation requires remote manual action before it can be placed into recirculation operation.

The normal condensate to the FW pump suction piping requires passing through several low pressure feedwater heaters. At least two flow paths are available, with a remote manual bypass line available around all LP FW heaters.

The startup FW pump is started from the control room. This pump motor is fed from the 6.9 kV Bus 159 and will be available after a reactor/turbine trip and the LMFW initiating event.

Startup FW pump recirculation was assumed to normally operate. With no flow on its discharge line, the recirculation valve will be fully open and allow recirculation flow. Thus, with condensate/condensate booster pump operating and recirculating, this pump will also be recirculating.

The startup FW pump is discharged directly into the main FW discharge piping. The main FW pump discharge check valve or stop-check valve must close in order to prevent backflow through the main FW pumps.

The feedwater from the FW pump discharge piping to the SG inlet must pass through the high pressure heaters. Two flow paths are available with a remote manual bypass line available around these heaters.

When the automatic AFS start signals, ESF logic A and logic B, are initiated, the FW control valves in the main FW lines and in the tempering flow lines to each SG will automatically close. In addition, a check valve in each of the above lines will also close. In order to return these lines to operation for Train C use, the operator must reset Logic trains A and B.

The preferred path is to use the main FW lines to the SG. A redundant path using the tempering flow lines is also available to each SG. The Train C main FW line discharge to each SG is independent of Trains A and B. The Train C tempering flow line paths are the same as Trains A and B.

4.3.1.2 Reliability Block Diagram Quantitative Analysis

The RBD model shown in Appendix B for the Byron/Braidwood AFS was manually quantified using the data from Appendix A. The failure probability calculated is for the AFS fail to start and to provide AFW to 2 steam generators (SGs). Failure probabilities were estimated for three initiating events (IE). Two quantitative estimates were performed assuming statistical independence of the various trains and common cause on similar or identical redundant paths. Each block in the RBD was assigned a failure rate. These failure rates were used to calculate the overall failure probability, or unavailability of the AFS.

Each initiating event (IE) was divided into the following:

- Hardware/Operator Error - this assumed that the total AFS is available and is the failure probability that the AFS fail to start and provide FW to 2 SGs.

- Test - This assumes that one ESF train is being tested when the IE occurs. During the first 15 to 20 minutes of testing when the discharge test valve is closed to warm up the pump in the recirculation mode, a demand for the AFS would automatically open this valve. After warm up, the discharge test valve is opened as part of the test. The pump then provides full auxiliary feedwater flow to the SGs. For this analysis, the "warm up" test mode was considered. The pump discharge valve is designed to open on ESF logic signal to start the AFS flow to the SG's and thus the unreliability of these components were used. Since the pump would be running and continue to run, the failure rate of the pump to start was assumed to be zero.

- Maintenance - This assumed the IE occurred during the time a train was out for maintenance. The train would not be available for AFS operation and thus, the failure probability of this train is 1.

- Human Error - This assumed plant personnel failed to reopen valves after pump testing or maintenance operation or inadvertently a closure of these valves. In the Byron/Braidwood design and procedure, this type of error appears to be greatly minimized because of automatic opening to the discharge test valve and automatic switching to the ESW. In addition, after each maintenance action on the AFS train, it will use the same test procedure as the monthly periodical test which includes a full flow test into the SGs.

The test, maintenance and human error outage contribution utilized the data in Ref. 1. Fault trees for test, maintenance and human error were developed and shown in Appendix D. Portions of the RBD model were used as inputs to estimate AFS failure probability as applicable to these

trees. The sum of the failure probabilities for hardware, test, maintenance, and human error became the estimate for the AFS fail to start and provide AFW to ≥2 SGs on demand.

4.3.1.2.1 Statistical Independent Estimate

The statistical independent estimate assumes that all redundant components are truly independent. The results are shown on Table 4.3. The NUREG-0800 acceptable unreliability range of 10^{-4} to 10^{-5} per demand was met for the LMFW and the LOOP initiating events (IEs), 3.4E-6 and 9.2E-5, respectively. The results show that the greatest contributor to AFS unreliability is in the maintenance outage portion with the hardware/operator error portion a relatively close second. The test and human error portions are shown to be at least 2 orders of magnitude (10^{-2}) less than the others, thus, are insignificant contributors. This is due to the automatic valve action which keeps these trains available during test and many human error problems. The LOAC IE was estimated to be 1.1E-2 per demand.

Due to a concern of an inadvertent automatic initiation of the ESW, a separate analysis assuming a remote manual backup using two valves in-line was calculated. These results are also shown on Table 4.4 for comparison with the previous results. A slight increase in the failure probabilities was noted. However, the summation, or the unavailability per demand, was essentially unchanged. Thus, use of manual actuation for ESW will not impact the overall AFS quantitative reliability for the three initiating events.

4.3.1.2.2 Common Cause Estimate

The common cause estimate assumes that redundant components are not truly independent. This estimate assumes that some commonality exists between redundant components, or trains, i.e., same maintenance personnel, same procedure, same manufacturer, same environment (humidity, temperature, earthquake, etc.), same design, etc.

In order to quickly estimate the common cause effect, a generic Beta Factor of 0.03 for inter-train redundancy and 0.1 for intra-train redundancy was used. The electric motor driven pump and diesel driven pump were assumed to be diverse. Using these assumptions, the results are shown on Table 4.3. The NUREG-0800 acceptable unreliability range of 10^{-4} to 10^{-5} was met for the LMFW and LOOP IEs, 8.2E-6 and 1.0E-4, respectively. In most cases the table shows that the hardware/operator error contribute to the greatest unreliability with the maintenance outage a relatively close second. Again, the test and human error portions were found to be insignificant contributors to AFS unreliability. Hence, this AFS design and procedure has done an outstanding job of reducing the test and human error contributions which have impacted many other AFSs in the past. The LOAC IE was estimated to be 1.2E-2 per demand.

4.3.1.2.3 Summary of Dominant Failure Modes

The dominant failure modes for each initiating event have been assessed by review of the dominant contributors to unreliability from the RBD in Appendix B.

LMFW with Off-site Power Available

Automatic start with manual backup except for Train C.

For both independent and common cause estimates, the dominant component failures are the failure of the pumps to start and its local control circuit failure in Trains A and B and the operator error in manually starting Train C. For maintenance outage portion of the $\overline{A}$, the dominant failure modes are the failure to start and its local control circuit failure the 2 pumps when both auto-start trains (Trains A and B) are available, or either Train A or B pump fail to start and its local control circuit failure and the operator errors in manually starting Train C. The results are shown on Table 4.3

The test and human error portions of the $\overline{A}$ were insignificant and thus did not contribute to the overall AFS failure.

LMFW with LOOP

Automatic start with manual backup

For the independent estimate, the dominant component failures are the failure of the pumps to start and its local control circuit failure in Trains A and B. For maintenance outage portion of the $\overline{A}$, the dominant failures are the failure to start and its local control circuit failure of the pumps. Two auxiliary power supplies (Unit 1 and Unit 2 diesel generators) are available to Train A motor drive auxiliary feedwater pump via Bus 141. The redundant power supplies to this pump contributed a minor portion of the fail to start unreliability.

The test and human error portions of the $\overline{A}$ were insignificant and thus did not contribute to the overall AFS failure.

LMFW with LOAC

Auto-start with manual backup

For the independent and common cause estimates, the dominant component failures for the hardware/operator error $\overline{A}$ the diesel pump fail to start and its local control circuit failure in Train B, the only train available for this initiating event (IE). For the maintenance outage portion of the $\overline{A}$, the dominant failure is when Train B is out and no train is available for this IE. This does not consider recovery of the offsite power and main feedwater within 20 minutes.

The test and human error portions of the $\overline{A}$ were insignificant and thus did not contribute to the overall AFS failure.

4.3.2 Fault Tree Quantification

In addition to the RBD analysis a fault tree analysis was undertaken to quantify the uncertainty range and provide independent check on the impact of the modeling assumptions. Three initiating events were considered:

- Loss of main feedwater (LMFW)
- Loss of offsite power (LMFW/LOOP)
- Loss of AC power (LMFW/LOAC)

4.3.2.1 Methods

The fault trees were developed to consider faults within each train which could cause failure to supply auxiliary feedwater to the steam generators within 20 minutes after an initiating event. The analysis considered hardware/operator error and maintenance failures only, since the RBD analysis showed testing and human error failures to have insignificant contributions. In most cases data were taken from Ref. 1 and 2. Probability distributions and uncertainty ranges were taken from Ref. 2. A more detailed discussion of the method of determining minimal cut sets and quantifying the failure probability of the system including uncertainty considerations is given in Appendix G.

Common cause failures were considered on a case-by-case basis. Two types of common cause failures were included; first, those within a train where redundant components are found, and second, those between trains where redundant components are found. A third type of common cause failure, that of external faults which impact the AFS, was not considered as its effect on the overall system reliability is minimal and was not included in the NUREG-0611 and NUREG-0635 study. Examples of the third type are common faults which block the steam generator output steam flow and piping faults which cause the flow to bypass the steam generators. The common cause failures were considered as explained in Appendix F with Beta factors which represent the ratio of the common cause failures to independent and common cause failures as measured by data from redundant systems.

Each train could be out for maintenance during a 72 hour period while the plant operation continues. During this period, the AFS consists of two trains. After 72 hours, the plant must be shutdown according to the technical specifications. NUREG-0611 (Appendix A, Table A.I.1) suggest that the maintenance outage contribution calculation be performed as follows:

$$Q_{MAINT.} \approx \frac{0.22(\text{No.hrs/maint.hrs})}{720}$$

The pump range on duration time is given as one-half hour to 72 hours, with a mean act time of 19 hour, thus,

$$Q_{MAINT} \approx \frac{0.22(19)}{720} = 0.0058$$

4.3.2.2 Fault Tree Estimates

The fault tree (FT) results are shown on Table 4.3 and the uncertainty curves (error spread) are shown on Figure 4.6 for the statistical independent estimates and on Figure 4.7 for the independent plus common cause estimates. In most cases, the FT results were slightly higher than those estimated by the RBD, however, all RBD estimates were well within the error spread as determined by the FT analysis. Data input to the FT are shown on Table A.III.1.

For the LMFW initiating event, the FT median values are well within the NUREG-0800 acceptable range of 10^{-4} to 10^{-5}, 2E-6(6)* or 9.8E-5(4)* for independent and common cause.

For the LOOP initiating event, the FT median value for the independent estimate of or 9.8E-5(4)* is in the NUREG-0800 acceptable range, but the independent plus common cause estimate of 1.5E-4(3)* is on the border line or the NUREG-0800 acceptable range for a one significant number.

Maintenance outage contributed about 60% of the AFS unreliability when only independent failures are considered and 30% to 45% when common cause failures are included.

4.3.2.3 Simplified Fault Tree (FT)

A simplified master FT was developed incorporating only the components which dominated the overall unreliability. For the B/B AFS, the hardware/operator error portion and the maintenance outage portion were the dominant contributors. With the master FT (Figure 4.8) and Maintenance FT (Figure 4.9), a relative easy point estimate of the B/B AFS unreliability may be calculated.

The master FT represents the LMFW IE hardware unreliability per demand. For the other IE hardware unreliabilities, portions of this FT are used as applicable.

Portions of the master FT are also used for the maintenance unreliability per demand. Assuming one train is out for maintenance, the unreliability is calculated for the balance of the system using the master FT and the result inserted into the appropriate portion of the maintenance FT. The completed maintenance FT is the estimate of the AFS unreliability due to maintenance outage.

The sum of the hardware/operator error and maintenance outage unreliabilities is the point estimate of the B/B AFS unreliability.

*Error Spread

Table 4.1 Criteria for NUREG 0611 Reliability Comparison - Ref. 1

LMFW and LOOP	AC Blackout
Low Reliability	**Low Reliability**
. Manual actuation*	. AC dependencies-turbine lube pumps*
. Minimum redundancy - 2 pump	
. Single point failure	
. No time limit on train outage	
Medium Reliability	**Low to Medium Reliability**
. Auto start with manual backup	. AC dependencies - valves with local manual control*
. Single point failure*	
. No time limit on train outage	. No time limit on train outage
. Water-hammer concerns	
. System interactions (safety and non-safety)	
. Human interactions	
. tests not staggered	
. test by same personnel and same shift	
. Testing incapacities more than one train	
High Reliability	**High Reliability**
. High redundancy	. No identifiable AC power dependencies
. Auto start with manual backup	. Auto start with manual backup
. No observed single point failure	
. Human interactions	
. Tests staggered and different shifts	
. Testing incapacitates only one train	
. Time limit on train outage	

*Dominant contributor.

Table 4.2 NUREG 0611 Qualitative Reliability Analysis

IE	NUREG ASSESS. CRITERIA	NUREG CRITERIA	BYRON/BRAIDWOOD REMARK AND ASSESSMENT
LMFW	High	. High redundancy	. Three trains
		. Auto start with manual backup.	. Two trains-auto start with manual backup; third train - manual start.
		. No observed single point failure.	. Comply
		. Human interactions . Test staggered and different shifts. . Maintenance valve inadvertently left closed.	. Exceeds criteria. Testing does not incapacitate ESF train. Maintenance suction valve inadvertently left closed does not incapacitate ESF train.
		. Testing incapacitates only one train.	. Exceed criteria. Testing does not incapacitate ESF train.
		. Time limit on train outage.	. Tech Spec requirement on train outage. Qualitative Assessment: Med/High range
LOOP	Low	. Minimum redundancy (2 pump)	. 2 Pump system, but motor pump has backup DG from other Unit, thus assess into Med range.
	High	. Same as LMFW except minimum redundancy.	. Same as LMFW except one criteria assess in Med range. Qualitative Assessment: Lo/High range.
LOAC	High	. No identifiable AC power dependencies.	. Complies
		. Auto start with manual backup.	. Complies Qualitative Assessment: Med/High range.

Table 4.3

BYRON/BRAIDWOOD AFS UNRELIABILITY ESTIMATES

Method		Initiating Event	Unavailability Per Demand				
			Hardware & Oper Error	Test	Maint.	Human Error	TOTAL
Statistical Independent	RBD(a)	LMFW	1.0E-6	1.8E-9	2.4E-6	2.9E-10	3.4E-6
		LOOP	2.9E-5	1.0E-7	6.3E-5	2.6E-9	9.2E-5
		LOAC	5.5E-3	1.5E-5	5.8E-3	2.9E-7	1.1E-2
	Fault Tree(b)	LMFW	5.6E-7(10)*	-	1.2E-6(6)*	-	1.8E-6(7)*
		LOOP	3.2E-5(6)*	-	6.2E-5(4)*	-	9.8E-5(4)*
		LOAC	5.2E-3(3)*	-	5.4E-3(3)*	-	1.2E-2(3)*
Stat. Indep. + Common Cause	RBD (a)	LMFW	4.9E-6	1.4E-8	3.3E-6	2.1E-8	8.2E-6
		LOOP	3.5E-5	1.4E-7	6.3E-5	1.7E-8	1.0E-4
		LOAC	5.6E-3	2.1E-5	5.9E-3	6.6E-7	1.2E-2
	Fault Tree (b)	LMFW	7.5E-6(6)*	-	3.5E-6(5)*	-	1.2E-5(4)*
		LOOP	6.8E-5(4)*	-	6.6E-5(4)*	-	1.5E-4(3)*
		LOAC	5.2E-3(3)*	-	5.4E-3(3)*	-	1.2E-2(3)*

(a) Point Estimate
(b) Median Estimate
- Not Estimated
* Error Spread = $Q_{95\%}/Q_{50\%}$ assuming log normal distribution
Significant Number to One Place

Table 4.4

BYRON/BRAIDWOOD AFS UNRELIABILITY ESTIMATES

Method		Initiating Event	Unavailability Per Demand				
			Hardware & Oper Error	Test	Maint.	Human Error	TOTAL
Statistical Independent	RBD (1)	LMFW	1.0E-6	1.8E-9	2.4E-6	2.9E-10	3.4E-6
		LOOP	2.9E-5	1.0E-7	6.3E-5	2.6E-9	9.2E-5
		LOAC	5.5E-3	1.5E-5	5.8E-3	2.9E-7	1.1E-2
	RBD(2)	LMFW	1.0E-6	1.8E-9	2.4E-6	3.4E-10	3.4E-6
		LOOP	2.9E-5	1.0E-7	6.3E-5	4.2E-9	9.2E-5
		LOAC	5.5E-3	1.5E-5	5.9E-3	2.9E-7	1.1E-2

(1) Assumed as designed case: Automatic switchin of ESW to Trains A & B water supply system.

(2) Assumed: Only remote manual switchin of ESW to Trains A & B water supply system.

Significant Number to One Place

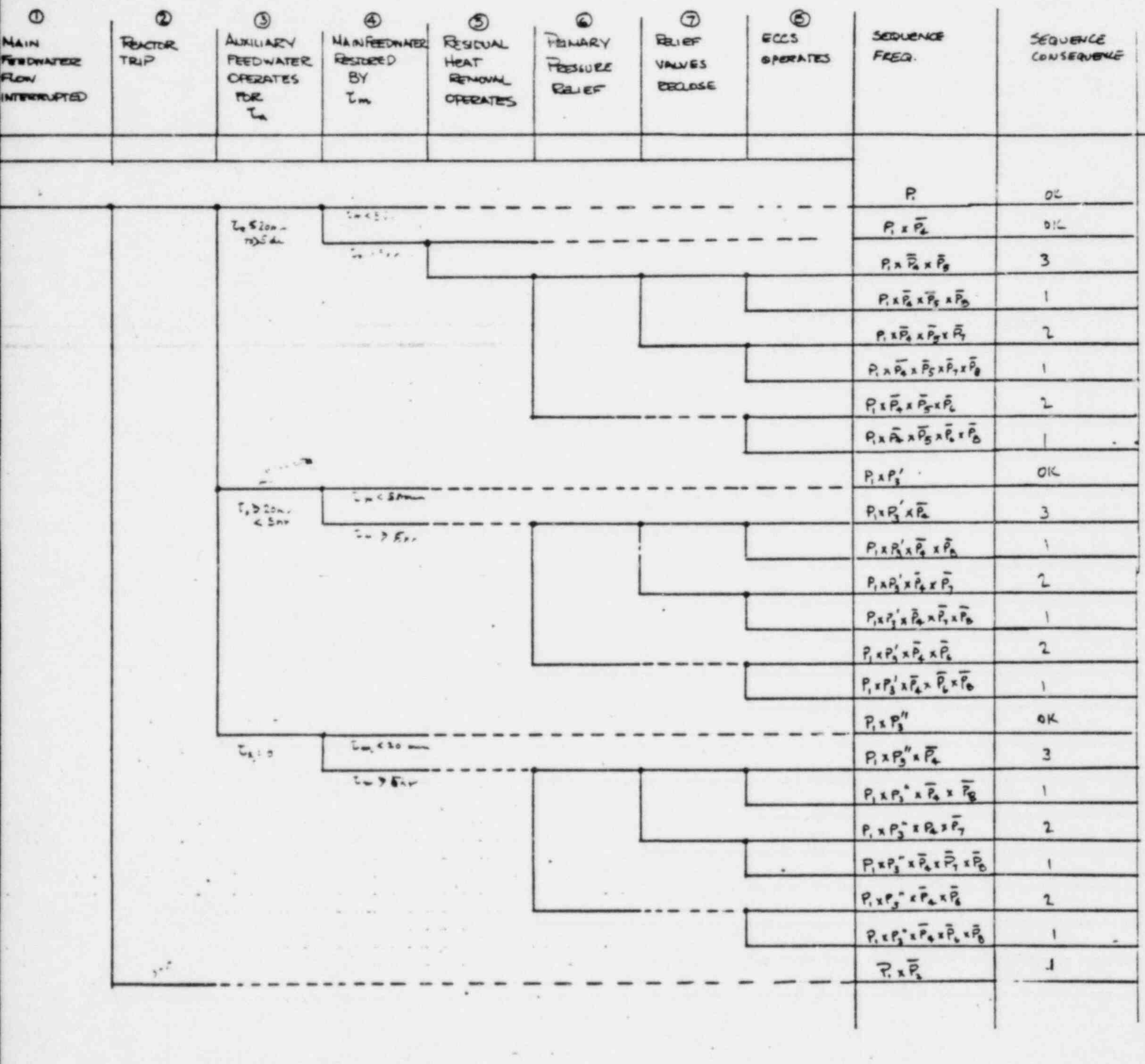


Figure 4.1 Event Tree for LMFW Events with Electric Power

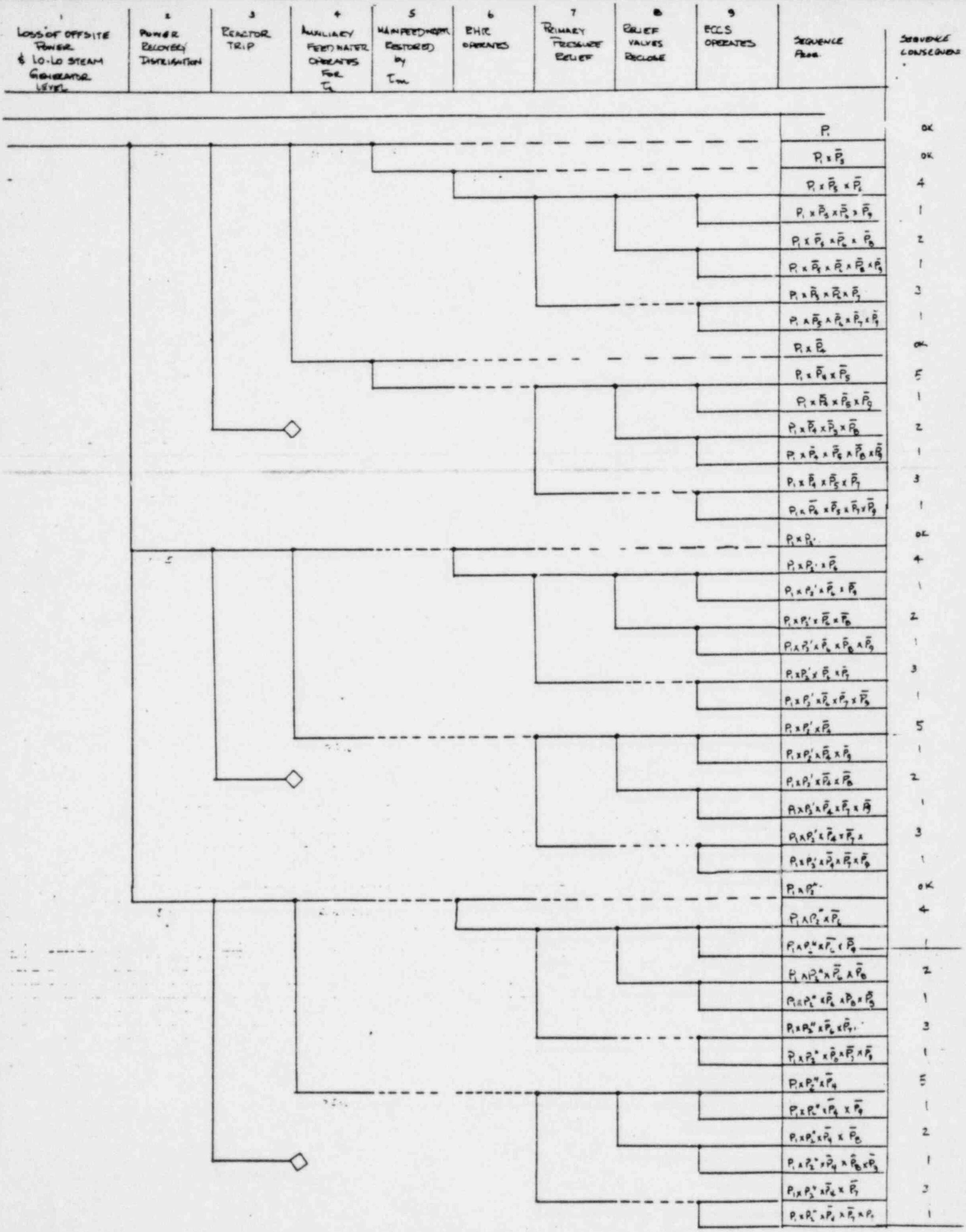
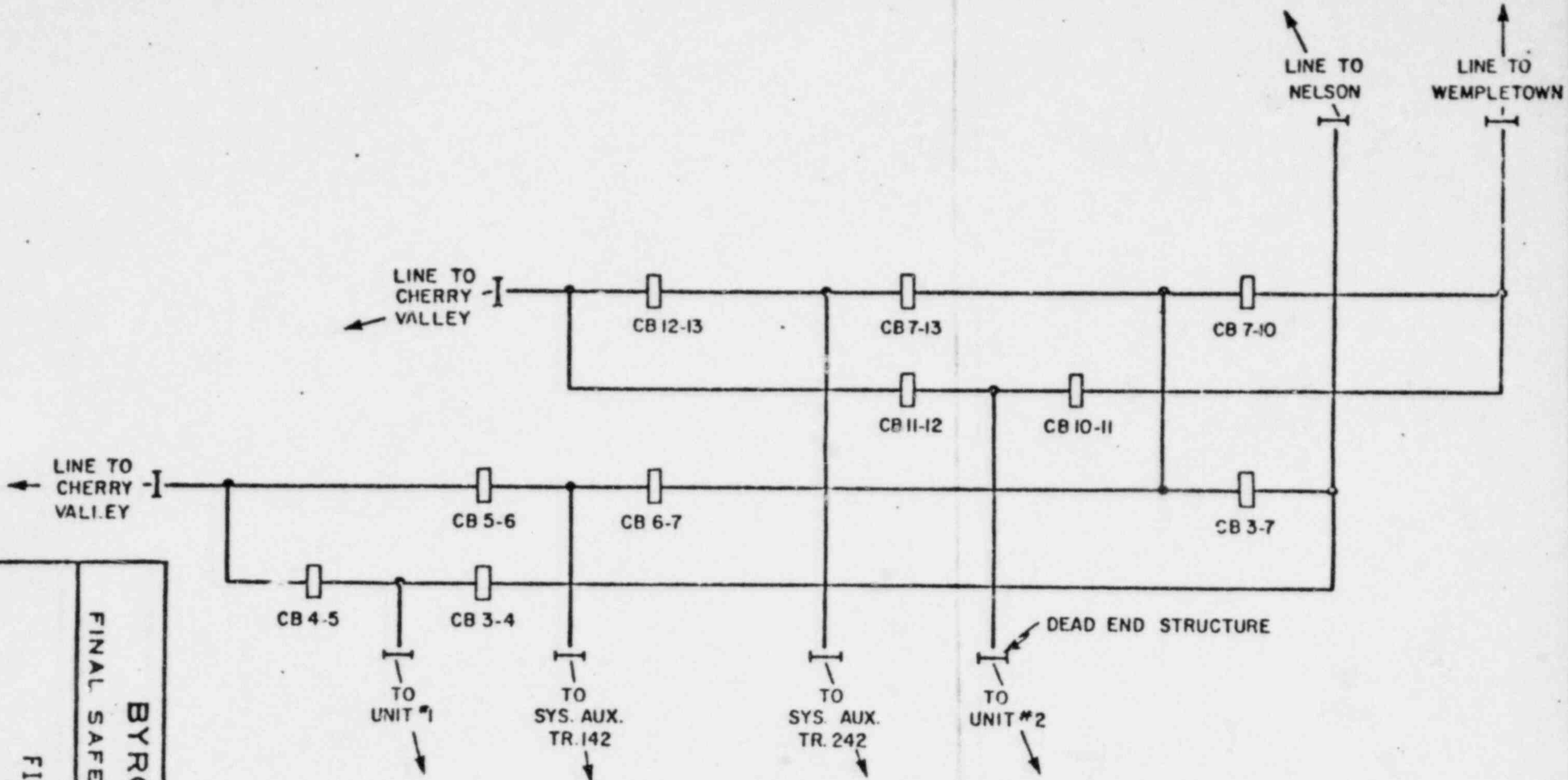


Figure 4.2 Event Tree for LMFW/LOOP and LMFW/LOAC Events

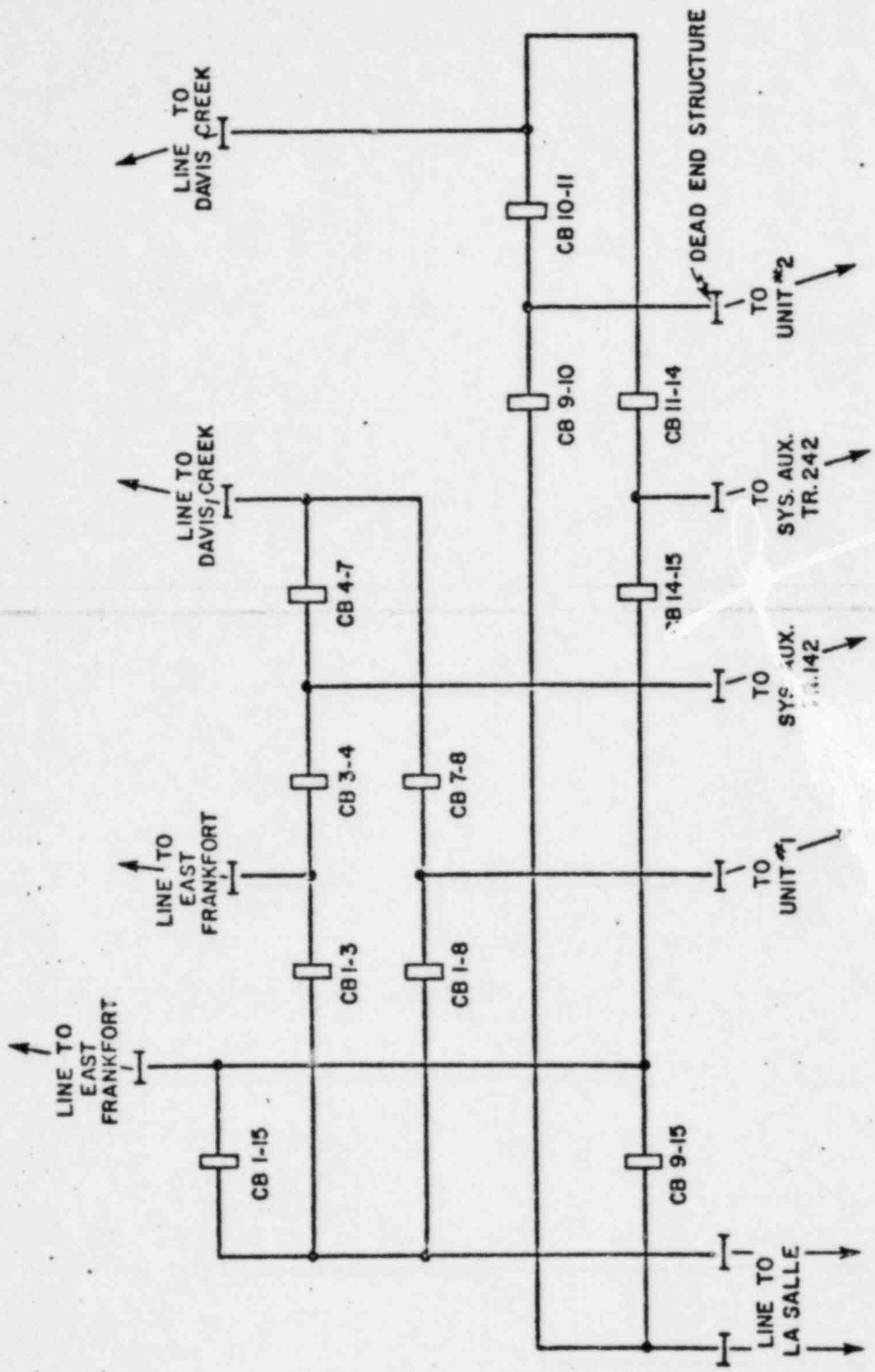


BYRON STATION

FINAL SAFETY ANALYSIS REPORT

FIGURE 4.3

345-kV SWITCHYARD BUS ARRANGEMENT



BRAIDWOOD STATION

FINAL SAFETY ANALYSIS REPORT

FIGURE 4.4

345-kV SWITCHYARD BUS ARRANGEMENT

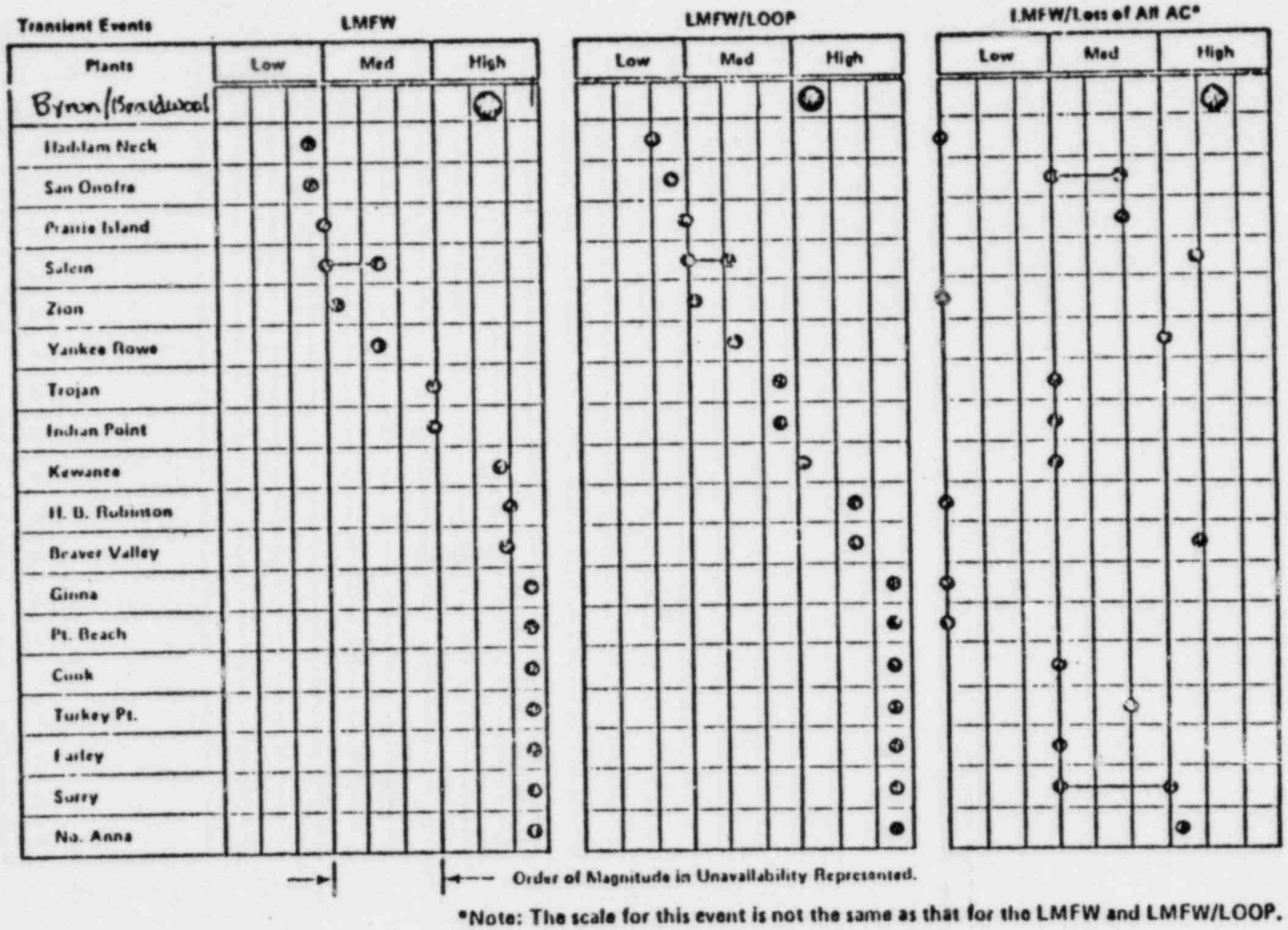


Figure 4.5 Comparison of This Byron/Braidwood Qualitative Reliability Assessment with Other Westinghouse AFS Using NUREG 0611

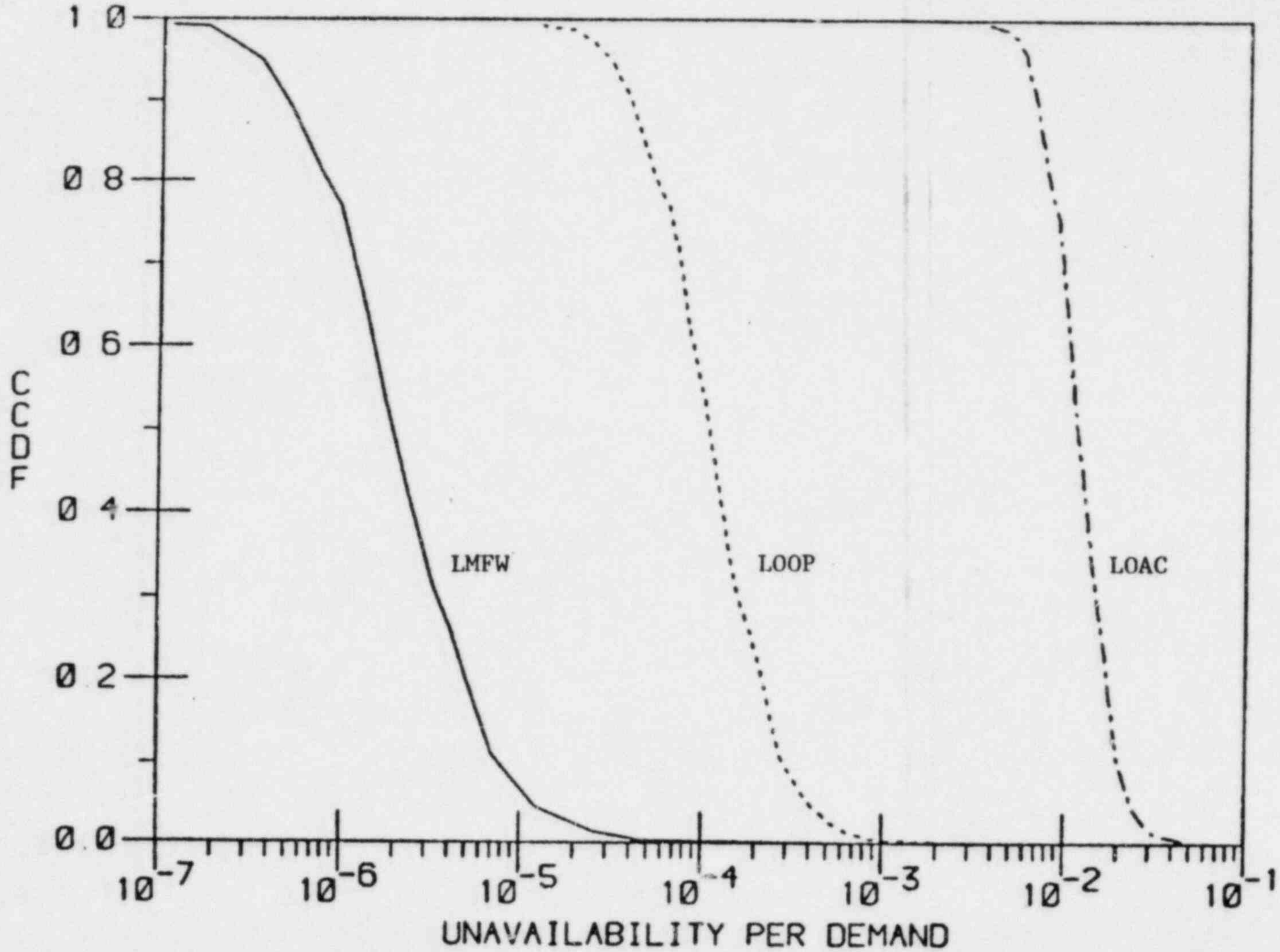


Figure 4.6 BYRON/BRAIDWOOD AFS UNRELIABILITY ERROR SPREAD

Statistical Independent Estimate

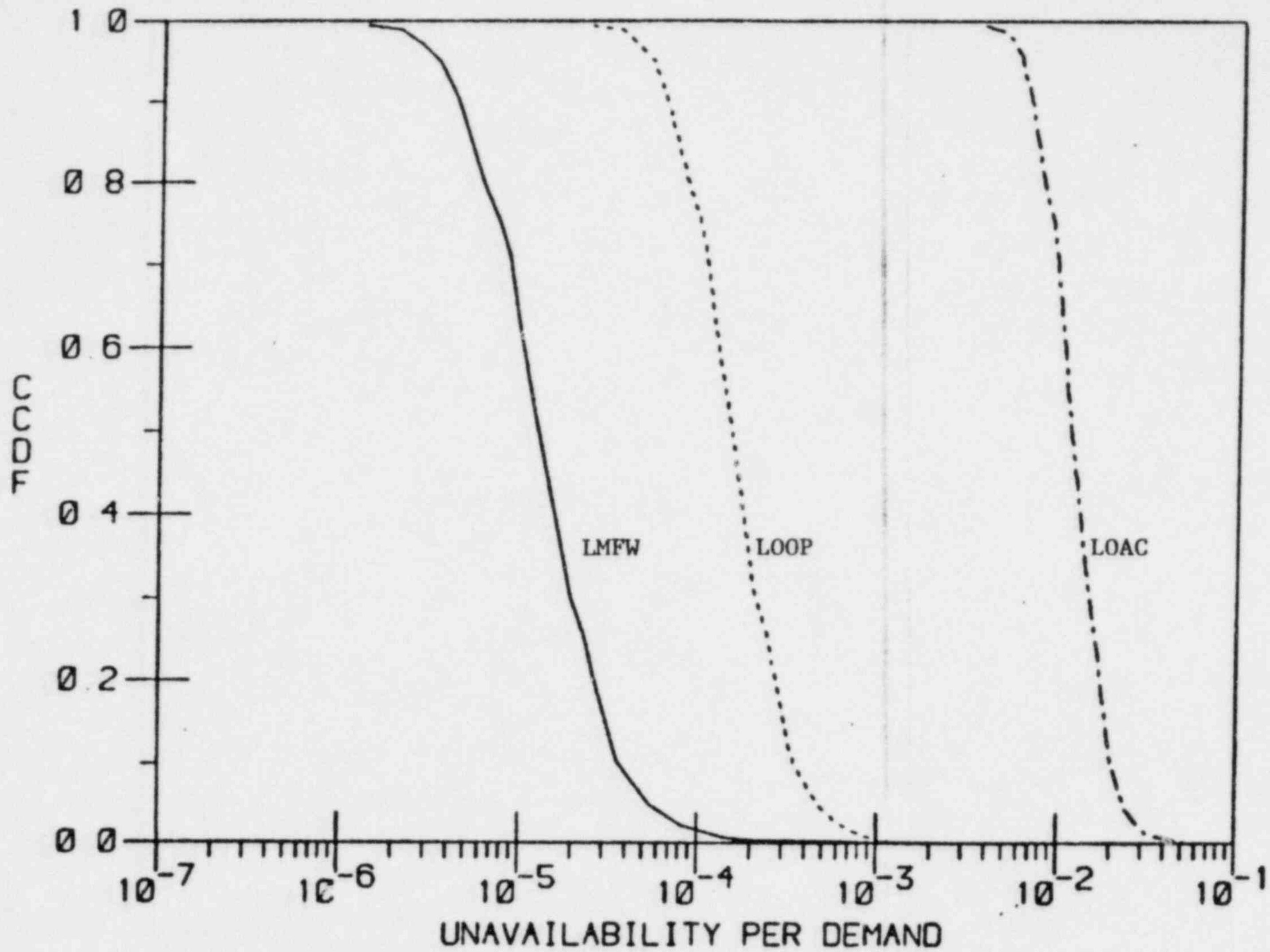


Figure 4.7 BYRON/BRAIDWOOD AFS UNRELIABILITY ERROR SPREAD
Statistical Independent + Common Cause Estimate

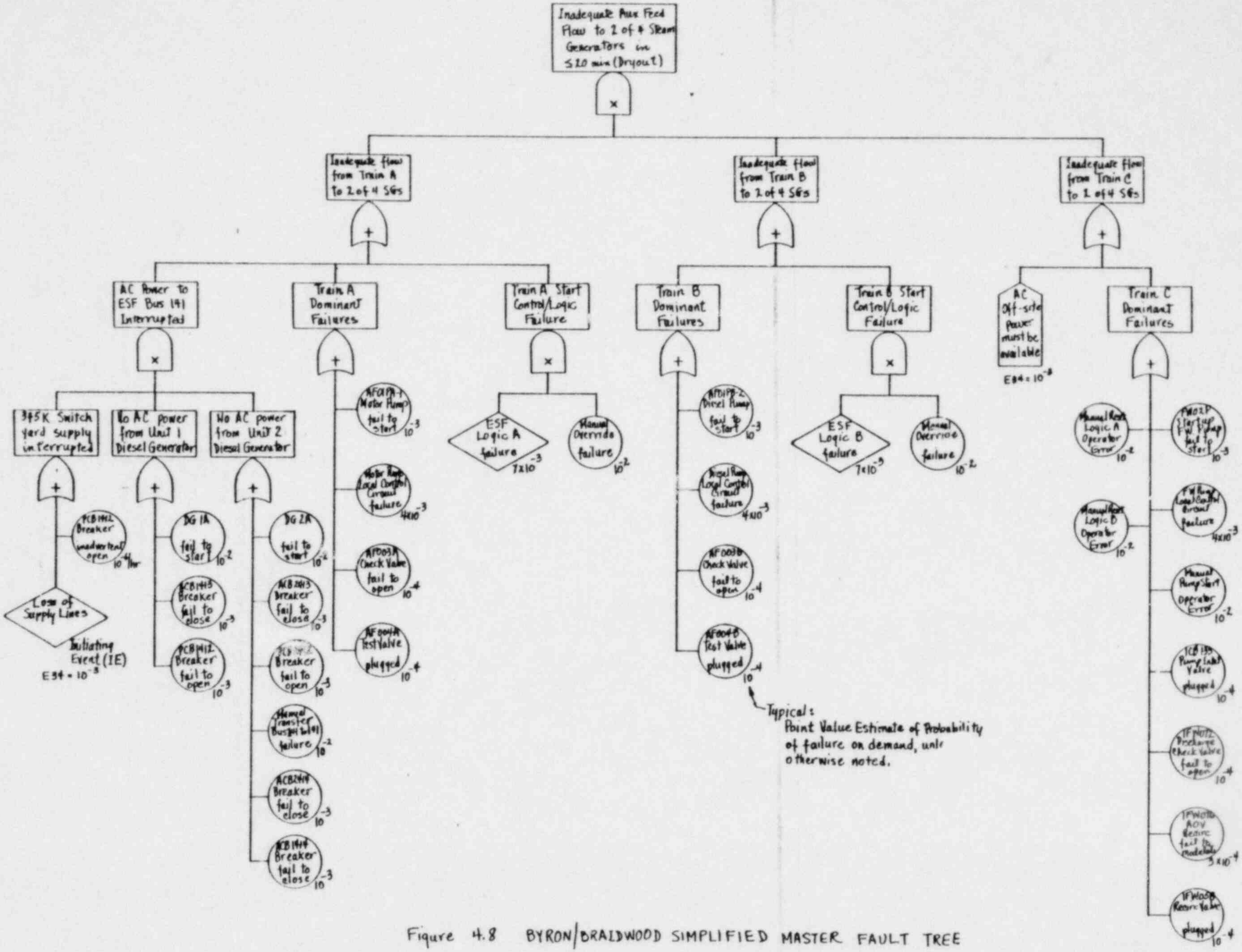


Figure 4.8 BYRON/BRAIDWOOD SIMPLIFIED MASTER FAULT TREE

Dominant failure components, only. Use for quick point estimate calculations.

Note: This total fault tree represents the LMFW IE Hardware/Operator Error Unreliability per demand.

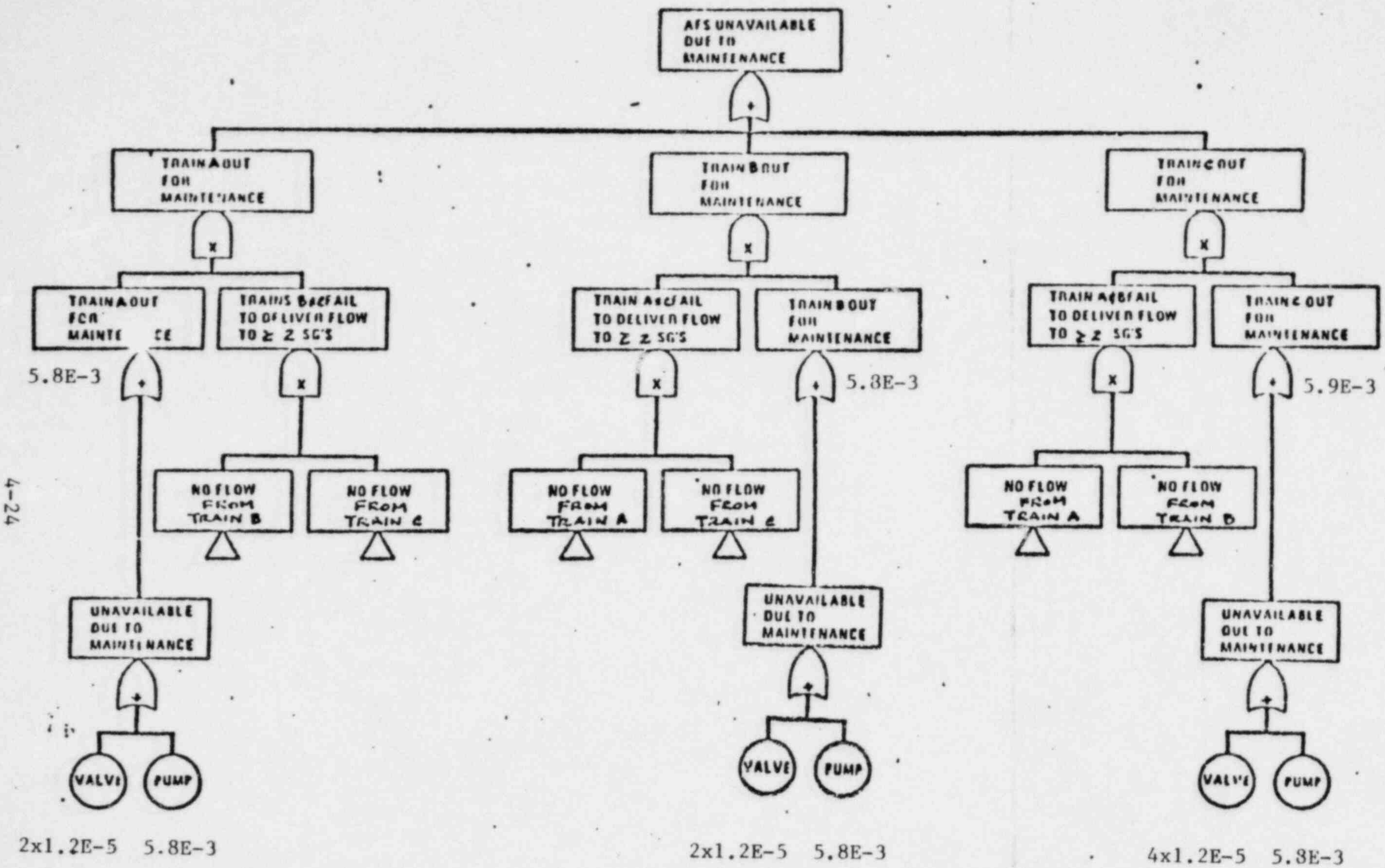


Fig. 4.9 Maintenance Fault Tree

5.0 References

1. NUREG-0611 "Generic Evaluation of Feedwater Transients and Small Break Loss of Coolant Accidents in Westinghouse Designed Operating Plants". Jan . 1980.

2. WASH-1400 (NUREG-75/014) Reactor Safety Study an Assessment of Accident Risks in U.S. Commercial Nuclear Plants, 1975.

3. Atwood, C. L., "Common Cause and Individual Failure and Fault Rates for Licensee Event Reports of Pumps at U.S. Commercial Nuclear Power Plants", EGG-EA-5289, (Draft), November, 1980.

4. Byron/Braidwood FSAR Chapters 8, 10, 15.

5. NUREG-0800 Standard Review Plan 10.4.9 Auxiliary Feedwater System (PWR), Rev. 2 - July 1981.

6. Common Cause Failure Experience in Nuclear Plant Auxiliary Feedwater Systems for Reliability Analysis (WARD-SR-3045-4) Topical report by G. E. Edison.

7. A study of operating data at the Trojan Nuclear Generating Station. General Atomic Report by T. Taniguchi, 1981.

8. NRC letter of March 10, 1980.

9. "Common Cause Failure Considerations in Predicting Cooling System Reliability , K. N. Fleming and G. W. Hannaman, IEEE Transactions on Reliability , Volume R-25, No. 3, August,1976.

10. "MOCUS - A Computer Program to Obtain Minimal Sets from Fault Tree", J. B. Fussell, et. al, Aerojet Nuclear Company, National Reactor Testing Station, Idaho Falls, Idaho, August 1974.

11. "STADIC-II, A Computer Program for Combining Distributions: Users Manual", P. Koch, et. al, GA-A16227, to be published.

12. "Palo Verde Nuclear Generating Station Auxiliary Feedwater System Reliability Analysis." Arizona Nuclear Power Project. Docket No. 50528-8102250251, Feb. 10, 1981.

13. "Defenses Against Common-mode Failures in Redundant Systems" by J. Bourne, et. al. SRD R196, System Reliability Service, Jan. 1981.

APPENDIX A

DATA BASE

APPENDIX A

DATA BASE

A I. Basic Reliability Data - Used for the Byron/Braidwood Analyses

The basic reliability data (failure rates) utilized for the quantitative analysis were taken from Ref. 1 (NUREG 0611) and are repeated here in Table A.I.1. When the required data were not given in Ref. 1, then Ref. 2 (WASH-1400) was utilized and these data are repeated here in Table A.I.2. The diesel generator "fail to start" used in this analysis was 10^{-2}/demand with an error factor of 3. This was the value indicated to have been used in the NUREG-0611 and NUREG-0635 studies. NRC Safety and Licensing Branch agreed on the usage of this number. Ref. 1 was also utilized for the test and maintenance outage contributions, human acts and error failure data and the frequency of occurrence for the various initiating events.

A special investigation was undertaken to search for data on the diesel driven auxiliary feedwater pump. A first cut sample was reviewed from Ref. 3 and this was updated from Trojan AFS experience. The results are that (1) the diesel driven pump, after correction of early problems has achieved a reliability equivalent to turbine driven pumps, and (2) the diesel pump is more reliable than diesel-generator start data by about a factor of three, as compared to WASH-1400.

A II. AFW Pump Data:

A II.1 AFWS Data From Ref. 3

A review of data sources showed that the generic base presented in Ref. 1 for pumps does not differentiate between the type of drives. Most AFW pumps are either electric-motor- or steam-turbine-driven. Ref. 3, which is a study of LER (Licensee Event Report) pump failures, listed a table of PWR plant data with the number of the various AFW pump type, critical hours, calendar months, etc.. Ref. 3 also had a listing of the PWR AFW pump problems from LERs. The AFW pump problems were divided into the following categories as required by the model, or various components and classifications:

- Fail to start or Fail to run after start.
    - Motor drive
    - Turbine drive
    - Diesel drive
    - Auto/Manual start circuit
    - Human/Operator error

To estimate a failure rate from that data the system demand cycles were first determined by assuming one test per pump per month plus three AFS start requirements per reactor year. This first-cut comparison is summarized in Table A II.1.1.

In this first cut analysis the diesel drive AFW pump appears to have a very high failure rate, both demand and run. Therefore, additional investigation was undertaken to more accurately understand the nature of the failures and the demand and run frequency estimates. This indepth investigation is discussed in Section A II.2.

A II.2 Trojan Nuclear Power AFS Experience

The Reference 3 listing of AFS drives showed that the only diesel driven auxiliary feedwater pump with any experience was at the Trojan Nuclear Power Plant. Trojan utilizes their AFS for normal startup and shutdown operations.[2]

Thus, the numbers of AFS starts were underestimated in Section A II.1, causing the failure rate of the AFS diesel pump to be high. The Graybooks (through March 1981) and the annual operation reports for the years 1975, 1976, and 1977 were used to estimate the numbers of starts and runs that the Trojan AFS had experienced.

From initial criticality (12/15/75) through 2/29/76, Trojan was experiencing many problems with both the turbine and diesel drive pumps. Docket 50344-250 summarizes the major equipment changes and modifications to improve the reliability of the AFS. These changes and modifications occur between 2/29/76 through 3/21/76. The data were analyzed in two parts, before corrective actions (CA) and after CA. The AFS components and its failure modes, estimated numbers of starts and runs, and estimated time to restore the system are presented in Tables A II.2.2.

Tables A II.2.1 summarizes the data and provides estimates of the failure rates for different modes of failure, including both before corrective action and after corrective action. After CA, the diesel pump and its controls was estimated to be 5.2×10^{-3}/demand. Including a human factor "fail to start", the diesel pump would be estimated to be $\sim 1.0 \times 10^{-2}$/demand. Reference 2 (WASH-1400) diesel/generator fail to start is assessed at 3×10^{-2} with an error factor of 3. Thus, the Trojan diesel AFW pump failure rate per demand appears to be less than that of Ref. 2 diesel/generator. Including the before and after data for the pump and its controls without operator error, the failure rate per demand would be

2Conversations with the plant operating personnel.

assessed at 7/254 = 0.029 or with operator error at 8/254 = 0.031. In both cases, these assessments are practically the same as that for diesel/generators in Ref. 2.

The Trojan experience on both the diesel pump and its controls (without human factor) fail to start on demand of 0.0052 and the turbine drive and its controls of 0.0063 are practically the same. The turbine drive and its controls from Section A II was assessed at 0.0068. Thus, from this data, it can be concluded that diesel pump fail to start failure rate is at least as good as for the turbine pumps, and about a factor of 3 better than the diesel generator start failure rate.

Table A.I.1 Recommended Data from NUREG 0611

BASIC DATA USED FOR PURPOSES OF CONDUCTING
A COMPARATIVE ASSESSMENT OF EXISTING
AFWS DESIGNS & THEIR POTENTIAL RELIABILITIES

Component (Hardware) Failure Data	Point Value Estimate of Probability of* Failure on Demand
a. Valves:	
Manual Valves (plugged)	$\sim 1 \times 10^{-4}$
Check Valves	$\sim 1 \times 10^{-4}$
Motor Operated Valves	
. Mechanical Components	$\sim 1 \times 10^{-3}$
. Plugging Contribution	$\sim 1 \times 10^{-4}$
. Control Circuit (local to Valve)	
w/quarterly tests	$\sim 6 \times 10^{-3}$
w/monthly tests	$\sim 2 \times 10^{-3}$
Piston Actuated Valves	
. MOV-Mechanical Components	$\sim 3 \times 10^{-4}$
. SOV-Mechanical Components	$\sim 1 \times 10^{-3}$
. Control Circuit (Note: Use MOV Failure Rate if Valve is not Fail Safe)	ε**
b. Pumps: (1 Pump)	
. Mechanical Components	$\sim 1 \times 10^{-3}$
. Control Circuit (Local to Pump - applies to Electrical Pumps)	
w/Quarterly tests	$\sim 7 \times 10^{-3}$
w/Monthly tests	$\sim 4 \times 10^{-3}$
c. Actuation Logic (Assumes at least 1 of 2 logic)	$\sim 7 \times 10^{-3}$/train

*Error factors of 3-10 (up and down) about such valves are not unexpected for basic data uncertainties.

**ε represents a number so small in magnitude that it may be neglected for basis of this study.

Table A.I.1 (cont.)

II. TEST & MAINTENANCE OUTAGE CONTRIBUTIONS:

a. Calculational Approach

1. Test Outage

$$Q_{TEST} \approx \frac{(\#hrs/test)\ (\#tests/year)}{\#hrs/year}$$

2. Maintenance Outage

$$Q_{MAINT.} \approx \frac{0.22\ (\#hrs/maint.\ act)}{720}$$

b. Data Tables for Test & Maint. Outages*

SUMMARY OF TEST ACT DURATION

Component	Range on Test Act Duration Time, hr	Calculated Mean Test Act Duration Time, t_D, hr
Pumps	0.25 - 4	1.4
Valves	0.25 - 2	0.86
Diesels	0.25 - 4	1.4
Instrumentation	0.25 - 4	1.4

LOG-NORMAL MODELED MAINTENANCE ACT DURATION

Component	Range On Duration Time, hr	Mean Act Duration Time, hr
Pumps	1/2 - 24	7
	1/2 - 72	19
Valves	1/2 - 24	7
Diesels	2 - 72	21
Instrumentation	1/4 - 24	6

* Note: These data tables were taken from the Reactor Safety Study (WASH-1400)[2] for purposes of this AFW system assessment. Where the plant technical specifications placed limits on the outage duration(s) allowed for AFW system trains, this tech spec limit was used to estimate the mean duration times for maintenance ACPS. In general, it was found that the outages allowed for maintenance dominated those contributions to AFW system unavailability from outages due to testing.

Table A.I.1 (cont.)

III. <u>Human Acts & Errors - Failure Data</u>:

	Estimated Human Error/Failure Probabilities Modifying Factors & Situations					
	With Valve Position Indication in Control Room		With Local Walk-Around & Double Check Procedures		W/O Either	
	Point Value Est	Est. on Error Factor	Point Value Est	Est. on Error Factor	Point Value Estimate	Est On Error Factor
a. Acts & Errors of A Pre-Accident Nature						
1. Valves Mispositioned During Test/Maint						
(a) Specific Single Valve Wrongly Selected out of A Population of Valves During Conduct of a Test or Maintenance Act (X No. of Valves in Population at Choice)	$\frac{1}{20} = 10^{-2} = \frac{1}{X}$	20	$\frac{1}{2} = 10^{-2} = \frac{1}{X}$	10	$10^{-2} = \frac{1}{X}$	10
(b) Inadvertently Leaves Correct Valve in Wrong Position	$N5 \times 10^{-4}$	20	$N5 \times 10^{-3}$	10	$N10^{-2}$	10
2. More than one valve is affected (coupled errors)	$N1 \times 10^{-4}$	20	$N1 \times 10^{-3}$	10	$N3 \times 10^{-3}$	10
3. Miscalibration of Sensors/Electrical Relays						
(a) One Sensor/Relay Affected	-	-	$N5 \times 10^{-3}$	10	$N10^{-2}$	10
(b) More than one Sensor/Relay Affected	-	-	$N1 \times 10^{-3}$	10	$N3 \times 20^{-3}$	10

Table A.I.1 (cont.)

	Time Actuation Needed	Estimated Failure Prob. for Primary Operator to Actuate AFWS	Estimated Failure Prob. of other (Backup) Control Rm. Operator to Actuate AFWS	Overall Estimate of Failure Probability	Estimated Error Factor on Overall Probability
b. <u>Acts & Errors of a Post-Accident Nature</u>					
1. Manual Actuation of AFW system from Control Room					
(a) Considering "Dedicated" Operator to Actuate AFW system and Possible Backup Actuation of AFWS	N5 min.	N2 x 10^{-3}	-	N2 x 10^{-3}	10
	N15 min.	N1 x 10^{-3}	N0.5 (mod. dep.)	N5 x 10^{-4}	10
	N30 min.	N5 x 10^{-4}	N.25 (low dep.)	N10^{-4}	10
(a) Considering "Non-Dedicated" Operator to Actuate AFW system and Possible Backup Acutation of AFW system	N5 min.	N5 x 10^{-2}	-	N5 x 10^{-2}	10
	N15 min.	N1 x 10^{-2}	N0.5 (mod. dep.)	N5 x 10^{-3}	10
	N30 min.	N5 x 10^{-3}	N.25 (low dep.)	N10^{-3}	10

Table A.I.2 - Data Table From WASH 1400 (Ref. 2)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Pumps (includes driver):	Failure to start on Demand, Q_d [(a)]:	3×10^{-4} - 3×10^{-3}/d	1×10^{-3}/d	3
	Failure to run, given start, λ_o (normal environments):	3×10^{-6} - 3×10^{-4}/hr	3×10^{-5}/hr	10
	Failure to run, given start, λ_o (extreme, post accident environments inside containment):	1×10^{-4} - 1×10^{-2}/hr	1×10^{-3}/hr	10
	Failure to run, given start, λ_o (post accident, after environmental recovery):	3×10^{-5} - 3×10^{-3}/hr	3×10^{-4}/hr	10
Valves Motor Operated:	Failure to operate, Q_d (includes driver) [(b)]:	3×10^{-4} - 3×10^{-3}/d	1×10^{-3}/d	3
	Failure to remain open, Q_d (plug) [(c)]:	3×10^{-5} - 3×10^{-4}/d	1×10^{-4}/d	3
	λ_s:	1×10^{-7} - 1×10^{-6}/hr	3×10^{-7}/hr	3
	Rupture, λ_s:	1×10^{-9} - 1×10^{-7}/hr	1×10^{-8}/hr	10

Table A.I.2 (Continued)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Solenoid Operated:	Failure to operate, Q_d (d):	3×10^{-4} - 3×10^{-3}/d	1×10^{-3}/d	3
	Failure to remain open, Q_d(plug):	3×10^{-5} - 3×10^{-4}/d	1×10^{-4}/d	3
	Rupture, λ_s:	1×10^{-9} - 1×10^{-7}/hr	1×10^{-8}/hr	10
Air-Fluid Operated:	Failure to operate, Q_d (a):	1×10^{-4} - 1×10^{-3}/d	3×10^{-4}/d	3
	Failure to remain open, Q_d (plug):	3×10^{-5} - 3×10^{-4}/d	1×10^{-4}/d	3
	λ_s:	1×10^{-7} - 1×10^{-6}/hr	3×10^{-7}/hr	3
	Rupture, λ_s:	1×10^{-9} - 1×10^{-7}/hr	1×10^{-8}/hr	10
Check Valves:	Failure to open, Q_d:	3×10^{-5} - 3×10^{-4}/d	1×10^{-4}/d	3
	Internal leak, λ_o (severe):	1×10^{-7} - 1×10^{-6}/hr	3×10^{-7}/hr	3
	Rupture, λ_s:	1×10^{-9} - 1×10^{-7}/hr	1×10^{-8}/hr	10
Vacuum Valve:	Failure to operate, Q_d:	1×10^{-5} - 1×10^{-4}/d	3×10^{-5}/d	3
Manual Valve:	Failure to remain open, Q_d (plug):	3×10^{-5} - 3×10^{-4}/d	1×10^{-4}/d	3
	Rupture, λ_s:	1×10^{-9} - 1×10^{-7}/hr	1×10^{-8}/hr	10
Relief Valves:	Failure to open, Q_d:	3×10^{-6} - 3×10^{-5}/d	1×10^{-5}/d	3
	Premature open, λ_o:	3×10^{-6} - 3×10^{-5}/hr	1×10^{-5}/hr	3

Table A.I.2 (Continued)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Test Valves, Flow Meters, Orifices:	Failure to remain open, Q_d (plug):	$1x10^{-4}$ - $1x10^{-3}$/d	$3x10^{-4}$/d	3
	Rupture, λ_s:	$1x10^{-9}$ - $1x10^{-7}$/hr	$1x10^{-8}$/hr	10
Pipes				
Pipe ≤ 3" dia per section:	Rupture/Plug, λ_s, λ_o:	$3x10^{-11}$ - $3x10^{-8}$/hr	$1x10^{-9}$/hr	30
Pipe > 3" dia per section:	Rupture/Plug, λ_s, λ_o:	$3x10^{-12}$ - $3x10^{-9}$/hr	$1x10^{-10}$/hr	30
Clutch, mechanical:	Failure to operate, Q_d (d):	$1x10^{-4}$ - $1x10^{-3}$/d	$3x10^{-4}$/d	3
Scram Rods (Single):	Failure to insert:	$3x10^{-5}$ - $3x10^{-4}$/d	$1x10^{-4}$/d	3

(a) Demand probabilities are based on the presence of proper input control signals. For turbine driven pumps the effect of failures of valves, sensors and other auxiliary hardware may result in significantly higher overall failure rates for turbine driven pump systems.

(b) Demand probabilities are based on presence of proper input control signals.

(c) Plug probabilities are given in demand probability, and per hour rates, since phenomena are generally time dependent, but plugged condition may only be detected upon a demand of the system.

(d) Demand probabilities are based on presence of proper input control signals.

Table A.I.3 - Data Table From WASH 1400 (Ref. 2)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Clutch, Electrical:	Failure to operate, Q_d[(a)]:	$1x10^{-4}$ - $1x10^{-3}$/d	$3x10^{-4}$/d	3
	Premature dis-engagement, λ_o:	$1x10^{-7}$ - $1x10^{-5}$/hr	$1x10^{-6}$/hr	10
Motors, Electric:	Failure to start, Q_d[(a)]:	$1x10^{-4}$ - $1x10^{-3}$/d	$3x10^{-4}$/d	3
	Failure to run, given start, λ_o (normal environ-ment):	$3x10^{-6}$ - $3x10^{-5}$/hr	$1x10^{-5}$/hr	3
	Failure to run, given start, λ_o (extreme environ-ment):	$1x10^{-4}$ - $1x10^{-2}$/hr	$1x10^{-3}$/hr	10
Relays:	Failure to energize, Q_d[(a)]:	$3x10^{-5}$ - $3x10^{-4}$/d	$1x10^{-4}$/d	3
	Failure of NO contacts to close, given energized, λ_o:	$1x10^{-7}$ - $1x10^{-6}$/hr	$3x10^{-7}$/hr	3
	Failure of NC contacts by Opening, given not energized, λ_o:	$3x10^{-8}$ - $3x10^{-7}$/hr	$1x10^{-7}$/hr	3
	Short across NO/NC contact, λ_o:	$1x10^{-9}$ - $1x10^{-7}$/hr	$1x10^{-8}$/hr	10
	Coil open, λ_o:	$1x10^{-8}$ - $1x10^{-6}$	$1x10^{-7}$/hr	10
	Coil Short to power, λ_o:	$1x10^{-9}$ - $1x10^{-7}$/hr	$1x10^{-8}$/hr	10

Table A.I.3 (Continued)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Circuit Breakers:	Failure to transfer, Q_d (a):	$3x10^{-4}$ - $3x10^{-3}$/d	$1x10^{-3}$/d	3
	Premature transfer, λ_o:	$3x10^{-7}$ - $3x10^{-6}$/hr	$1x10^{-6}$/hr	3
Switches				
Limit:	Failure to operate, Q_d:	$1x10^{-4}$ - $1x10^{-3}$/d	$3x10^{-4}$/d	3
Torque:	Failure to operate, Q_d:	$3x10^{-5}$ - $3x10^{-4}$/d	$1x10^{-4}$/d	3
Pressure:	Failure to operate, Q_d:	$3x10^{-5}$ - $3x10^{-4}$/d	$1x10^{-4}$/d	3
Manual:	Failure to transfer, Q_d:	$3x10^{-6}$ - $3x10^{-5}$/d	$1x10^{-5}$/d	3
Switch Contacts:	Failure of NO contacts to close given switch operation, λ_o:	$1x10^{-8}$ - $1x10^{-6}$/hr	$1x10^{-7}$/hr	10
	Failure of NC by opening, given no switch operation, λ_o:	$3x10^{-9}$ - $3x10^{-7}$/hr	$3x10^{-8}$/hr	10
	Short across NO/NC contact, λ_o:	$1x10^{-9}$ - $1x10^{-7}$/hr	$1x10^{-8}$/hr	10
Battery Power Systems (wet cell):	Failure to provide proper output, λ_s:	$1x10^{-6}$ - $1x10^{-5}$/hr	$3x10^{-6}$/hr	3

Table A.I.3 (Continued)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Transformers:	Open Circuit primary or secondary, λ_o:	3×10^{-7} - 3×10^{-6}/hr	1×10^{-6}/hr	3
	Short primary to secondary, λ_o:	3×10^{-7} - 3×10^{-6}/hr	1×10^{-6}/hr	3
Solid State Devices, Hi power Applications (diodes, transistors, etc.):	Fails to function, λ_o:	3×10^{-7} - 3×10^{-5}/hr	3×10^{-6}/hr	10
	Fails shorted, λ_o:	1×10^{-7} - 1×10^{-5}/hr	1×10^{-6}/hr	10
Solid State Devices, Low power Applications:	Fails to function, λ_o:	1×10^{-7} - 1×10^{-5}/hr	1×10^{-6}/hr	10
	Fails shorted:	1×10^{-8} - 1×10^{-6}/hr	1×10^{-7}/hr	10
Diesels (Complete plant):	Failure to start, Q_d:	1×10^{-2} - 1×10^{-1}/d	3×10^{-2}/d	3
	Failure to run, emergency conditions, given start, λ_o:	3×10^{-4} - 3×10^{-2}/hr	3×10^{-3}/hr	10
Diesels (Engine only):	Failure to run, emergency conditions, given start, λ_o:	3×10^{-5} - 3×10^{-3}/hr	3×10^{-4}/hr	10

Table A.I.3 (Continued)

Components	Failure Mode	Assessed Range	Computational Median	Error Factor
Instrumentation - General (Includes transmitter, amplifier and output device):	Failure to operate, λ_o:	$1x10^{-7}$ - $1x10^{-5}$/hr	$1x10^{-6}$/hr	10
	Shift in calibration, λ_o:	$3x10^{-6}$ - $3x10^{-4}$/hr	$3x10^{-5}$/hr	10
Fuses:	Failure to open, Q_d:	$3x10^{-6}$ - $3x10^{-5}$/d	$1x10^{-5}$/d	3
	Premature open, λ_o:	$3x10^{-7}$ - $3x10^{-6}$/hr	$1x10^{-6}$/hr	3
Wires (Typical circuits, several joints):	Open circuit, λ_o:	$1x10^{-6}$ - $1x10^{-5}$	$3x10^{-6}$/hr	3
	Short to ground, λ_o:	$3x10^{-8}$ - $3x10^{-6}$/hr	$3x10^{-7}$/hr	10
	Short to power, λ_o:	$1x10^{-9}$ - $1x10^{-7}$/hr	$1x10^{-8}$/hr	10
Terminal Boards:	Open connection, λ_o:	$1x10^{-8}$ - $1x10^{-6}$/hr	$1x10^{-7}$/hr	10
	Short to adjacent circuit, λ_o:	$1x10^{-9}$ - $1x10^{-7}$	$1x10^{-8}$/hr	10

(a) Demand probabilities are based on presence of proper input control signals.

TABLE A II.1.1

FIRST CUT AFS Component Estimated Failure Rates from Ref. 3 Data

Pump Type	(1) Est. No. of Starts	Fail To Start (Cause)	Start Failure Rate Per Demand	Est. No. of Runs (Cause)	Fail to Run	Run Failure Fraction	Run Failure Rate Per Hour
Pump and its Controls							
Turbine	2803	19(2)	.0068	2745	13	.0047	$5x10^{-4}$
Motor	3132	2	.00064	3067	5	.0016	$2x10^{-4}$
Diesel	35	4	.11	25	5	.2	$2x10^{-2}$
Auto Start Circuit							
Turbine	560	9cc*(3)	.016				
Motor	626	3(4)	.0048				
Diesel	7	1	.14				

NOTES:

(1) Assumed one test per month per train plus 3 AFS requirements per reactor year.
(2) 3 Pumps fail to start during test. 1 pump had control problems and 2 pumps had excessive tight packing.
(3) 3 pumps fail to autostart. Manual started 3 pumps O.K. Fuses not installed. 7 days after initial criticality and before on-line.
(4) 2 electric drive pump fail to autostart due to defective switches. Turbine drive pump started O.K.

*cc - Common cause failure.

TABLE A II.1.1 (cont'd)

FIRST CUT AFS Component Estimated Failure Rates from Ref. 3 Data

Pump Type	Est. No. of Starts (1)	Fail To Start (Cause)	Start Failure Rate Per Demand	Est. No. of Runs (Cause)	Fail to Run	Run Failure Fraction	Run Failure Rate Per Hour
Miscellaneous							
Turbine	2803	2 (e) (e)	.00071	2745	4 (b)(b) (2)(b) (h)(g)	.0015	
Motor	3132	3 (c)(d) (e)	.00096	3067	7 (f)(h) (2)(f) (h)(2) (f)(h) (3)(h)(3)	.0023	
Diesel	35	1(a)	.029	25	0	>.04	

Outage Causes

(a) Inadequate procedure, (b) No. 3 SG FW reg bypass valve recirculating (Haddem Neck unique).,(c) pump motor breaker, (d) 480V bus breaker, (e) unknown, (f) air in suction header, (g) recirculator line and orifice redesign, (h) plugged strainer during plant startup.

Notes

(1) Assumed 1 test per month per train plus 3 AFS requirements per reactor year.
(2) During startup, AFW pumps flow reduced due to startup-strainers plugged.
(3) During test, 2 motor-drive pumps lost suction due to air in the section header.

TABLE A II.1.1 (cont'd)

FIRST CUT AFS Component Estimated Failure Rates from Ref. 3 Data

Pump Type	(1) Est. No. of Starts	Fail To Start (Cause)	Start Failure Rate Per Demand	Est. No. of Runs (Cause)	Fail to Run	Run Failure Fraction	Run Failure Rate Per Hour
			OPERATOR ERROR				
Turbine and its control	2803	8	.0029	2745	0		
Motor & its control	3132	4 (3)	.0013	3067	0		
Diesel & its control	35	2	.057	25	0		
Auto start turbine	560	1 cc*(2)	.0018				
Auto start motor	626	0	>.0016				
Auto start diesel	7	1 cc*(2)	.14				

Notes

(1) Assumed 1 test per month per train plus 3 AFS requirements per reactor year.

(2) All pumps fail to auto start, manual start one pump O.K.. Mislogged leads in auto-start circuitry.

(3) During monthly test, two electric drive pumps failed to start until third manual attempt. Auxiliary oil pump not energized.

*Common cause failure.

Table A II.2.1

TROJAN NUCLEAR POWER PLANT AFS EXPERIENCE FROM OPERATIONAL REPORTS

Pump Type	Est. No. Starts	Fail To Start	Start Failure Rate/ Demand	Est. No. of Runs	Fail to Run	Run Failure Rate/ Demand
			Pump and Its Controls Before CA (Corrective Actions)			
Diesel	51	6	.12	42	2	.048
Turbine	25	2	.08	25	2	.08
			After CA			
Diesel	194	1	.0052	190	5	.026
Turbine	159	1	.0063	157	1	.0064
			Auto Start Circuit Before CA			
Logic B	9	0	<.11			
Logic A	9	0	<.11			
			After CA			
Logic B	28	1	.036			
Logic A	28	0	<.036			

*cc = common cause

Table A II.2.1 (Cont'd)

TROJAN NUCLEAR POWER PLANT AFS EXPERIENCE FROM OPERATIONAL REPORTS

Pump Type	(1) Est. No. Starts	Fail To Start	Start Failure Rate/ Demand	Est. No. of Runs	Fail to Run	Run Failure Rate/ Demand
			Operator Error Before CA			
Diesel Auto Start	9	1 cc*(1)	.11			
Turbine Auto Start	9	1 cc*(1)	.11			
			After CA			
Diesel Auto Start	28	1 cc(2)	.036			
Turbine Auto Start	28	1 cc(2)	.036			
			After CA			
Diesel & Its Controls	194	1	.0052	190	0	.0052
			Miscellaneous before CA			
Diesel	51	1(3)	.020			
Turbine	51	0	.020			
			After CA			
Diesel	194	0	.0052	190	0	.0052
Turbine	159	0	.0063	157	0	.0064

(1) Mislogged lifted leads (manual start O.K.)
(2) Wiring error (Manual start O.K.)
(3) Procedure inadequate.

Table A II.2.2 EVENT SUMMARY (Cont'd)

Component Type: Diesel Driven AFW Pump and its Controls

Date	Time to Restore	Cause
		Failure Mode: Fail to start on demand.
12/19/75	>20m, <5h	Special sequence required after each engine shutdown to reset fuel racks and control circuitry.
12/24/75	<20m	Fail to reset fuel rocks.
1/9/76	5h	Misaligned governor.
1/23/76	<20m	Low lube oil press., cold start, 2nd start O.K.
1/24/76	<20m	Same
1/24/76	<20m	Same
2/29/76	2m	Cold start, overspeed trip, local manual start. (Turbine drive pump declared inoperable 2 days before.)

12/75 - 2/76 Operational starts: 48 plant startup and shutdowns.
POT-5-1: 3 at 1 per month

2/29/76 - 3/21/76 Corrective Actions and Verification Tests (Docket 50344-250)

Date	Time to Restore	Cause
12/17/77	>20m, <5h	Speed microswitch, out of adjustment.
9/3/80	>20m, <5h	No details-fail to start during test.

3/76 - 2/81 Operational starts: 86 plant startups and shutdowns.

Verification Tests: 48 POT-5-1: 60 at 1 per month

Table A II.2.2 EVENT SUMMARY

Component Type: Diesel Driven AFW Pump and its Controls

Date	Time to Restore	Cause
		Failure Mode: Fail to run after starting.
12/24/75	>20m, <5h	Fail to set current limiter on speed controller.
1/4/76	1.1h	Speed signal lead vibrated loose.
2/14/76	>20m, <5h	Jacket cooling water setpoint changed.

12/75-2/76 Operational runs: 39 plant startups and shutdowns.
POT-5-1: 3 at 1 per month

2/29/76 - 3/21/76 Corrective Actions and Verification Tests (Docket 50344-250)

Date	Time to Restore	Cause
3/28/76	<20m	Insufficient margin on overspeed setpoint.
9/2/76	>5h, ~7days	Loose adjustment spring in jacket temp. sensing device.
9/9/76	Same	Same
3/24/77	145h	Broken crank shaft.
2/7/80	>20m,<5h	Broken cooling water hose.

3/76-2/81 Operational runs: 83 plant startups and shutdowns.

Verification Tests: 48 POT-5-1: 59 at 1 per month

Table A II.2-2 EVENT SUMMARY (Cont'd)

Component Type: Diesel Driven AFW Pump and its Controls

Date	Time to Restore	Cause
		Component Type: AFS auto start system. Failure Mode: Fail to initiate auto start signal.
1/16/76	<20m (>5h repair)	Mislogged lifted leads in auto start circuitry. Both diesel and turbine pumps fail to start. Manually started one of the pumps (cc)*.
		12/77 - 2/76 Auto starts: 9
2/29/76 - 3/25/76		No change indicated in auto start system (Docket 50344-250)
9/3/76	<20m (<5h repair)	Blown fuse in diesel pump auto start circuitry. Manual start O.K.
10/3/80	<20m (>5h repair)	Wiring error, both diesel and turbine pumps fail to auto start. Assumed manual start O.K. (cc)*.
10/11/80 circuitry	<20m (5h repair)	Blown fuse in diesel pump auto start Assumed manual start O.K.
		3/76 - 2/81 Auto starts: 28

*Common cause.

Table A II.2-2 EVENT SUMMARY (Cont'd)

Component Type: Diesel Driven AFW Pump and its Controls

Date	Time to Restore	Cause
		Component Type: AFW Pumps **Failure Mode : Declared Inoperable**
1/13/76	24.4 (16.0 repair)	Turbine-steam leak
2/27/76	~25 days*	Turbine-governor oil problem.
3/29/76 - 3/2/76	Corrective Actions and Verification Tests (Docket 50344-250)	
12/17/77	>20m, <5h	Turbine - could not be reset for auto start, limit switch failure.
12/28/78	>20m, <5h	Diesel - fuel oil leak
4/15/79	>20m, <5h	Diesel - fuel line crack
		Component Type: AFW Isolation Valve **Failure Mode : Stuck partially open.**
11/17/77	>5 h	AFWIV between diesel pump and "B" SG stuck partially open (90%). Damaged sealing gasket allowed water to leak into main operator.

*2 days later on 2/29/76, diesel pump pump fail to auto start. Remote manual start failed. Local manual start OK after resetting overspeed trip. Started in about 2 minutes after initial failure.

Table A.III.1

Fault Tree Dat Input

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E1	ESF Logic A fail[illegible]	7.0E-3	3	1	
E2	M[illegible] override failure for control logic A	1.0E-2	10	1	
E3	ESF Logic B failure	7.0E-3	3	1	
E4	Manual override failure for control logic B	1.0E-2	10	1	
E5A, E6A	2 inch blowdown valves to SG-A fail to close	1.0E-4	3	1	
E5B, E6B	2 inch blowdown valves to SG-B fail to close	1.0E-4	3	1	
E5C, E6C	2 inch blowdown valves to SG-C fail to close	1.0E-4	3	1	
E5D, E6D	2 inch blowndown valves to SG-D fail to close	1.0E-4	3	1	
E7	6 inch blowdown valve to 4 SG's	1.0E-4	3	1	
E8A	Check valve (FW037A) fails to close	1.0E-4	3	1	
E8B	Check valve (FW037B) fails to close	1.0E-4	3	1	
E8C	Check valve (FW037C) fails to close	1.0E-4	3	1	
E8D	Check valve (FW037D) fails to close	1.0E-4	3	1	
E9A	Check valve (FW09A) plugged	1.0E-4	3	1	
E9B	Check valve (FW09B) plugged	1.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile.

Table A.III.1

Fault Tree Data Input

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E9C	Check valve (FW09C) plugged	1.0E-4	3	1	
E9D	Check valve (FW09D) plugged	1.0E-4	3	1	
E10A	Check valve (FW008A) fails to open	1.0E-4	3	1	
E10B	Check valve (FW008B) fails to open	1.0E-4	3	1	
E10C	Check valve (FW008C) fails to open	1.0E-4	3	1	
E10D	Check valve (FW008D) fails to open	1.0E-4	3	1	
E11A	Flow controller (FC2A) failure	(3.1E-5)	10	2	
E11B	Flow controller (FC2B) failure	(3.1E-5)	10	2	
E11C	Flow controller (FC2C) failure	(3.1E-5)	10	2	
E11D	Flow controller (FC2D) failure	(3.1E-5)	10	2	
E12A	Air operated valve (FW510) fails to open	(3.0E-4)	3	1	
E12B	Air operated valve (FW520) fails to open	(3.0E-4)	3	1	
E12C	Air operated valve (FW530) fails to open	(3.0E-4)	3	1	
E12D	Air operated valve (FW540) fails to open	(3.0E-4)	3	1	

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*Error Factor = Ratio of 95th to 50th percentile.

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E13A	Manual valve (FW055A) plugged	1.0E-4	3	1	
E13B	Manual valve (FW055B) plugged	1.0E-4	3	1	
E13C	Manual valve (FW055C) plugged	1.0E-4	3	1	
E13D	Manual valve (FW055D) plugged	1.0E-4	3	1	
E14	Manual reset for logic A failure	1.0E-2	10	1	
E15	Manual reset for logic B failure	1.0E-2	10	1	
E16A	Train A check valve (AF014A) to SG-A fails to open	1.0E-4	3	1	
E16B	Train A check valve (AF014B) to SG-B fails to open	1.0E-4	3	1	
E16C	Train A check valve (AF014C) to SG-C fails to open	1.0E-4	3	1	
E16D	Train A check valve (AF014D) to SG-D fails to open	1.0E-4	3	1	
E17A	Train A MOV (AF013A) to SG-A plugged	1.0E-4	3	1	
E17B	Train A MOV (AF013B) to SG-B plugged	1.0E-4	3	1	
E17C	Train A MOV (AF013C) to SG-C plugged	1.0E-4	3	1	
E17D	Train A MOV (AF013D) to SG-D plugged	1.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile.

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E18A	Train A AOV (AF005A) to SG-A plugged	1.0E-4	3	1	
E18B	Train A AOV (AF005B) to SG-B plugged	1.0E-4	3	1	
E18C	Train A AOV (AF005C) to SG-C plugged	1.0E-4	3	1	
E18D	Train A AOV (AF005D) to SG-D plugged	1.0E-4	3	1	
E19A	Train A flow limiting orifice (AF011) to SG-A plugged	3.0E-4	3	1	
E19B	Train A flow limiting orifice (AF013) to SG-B plugged	3.0E-4	3	1	
E19C	Train A flow limiting orifice (AF015) to SG-C plugged	3.0E-4	3	1	
E19D	Train A flow limiting orifice (AF017) to SG-D plugged	3.0E-4	3	1	
E20A	Train B check valve (AF014E) to SG-A fails to open	1.0E-4	3	1	
E20B	Train B check valve (AF014F) to SG-B fails to open	1.0E-4	3	1	
E20C	Train B check valve (AF014G) to SG-C fails to open	1.0E-4	3	1	
E20D	Train B check valve (AF014H) to SG-D fails to open	1.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E21A	Train B MOV (AF013E) to SG-A plugged	1.0E-4	3	1	
E21B	Train B MOV (AF013F) to SG-B plugged	1.0E-4	3	1	
E21C	Train B MOV (AF013G) to SG-C plugged	1.0E-4	3	1	
E21D	Train B MOV (AF013H) to SG-D plugged	1.0E-4	3	1	
E22A	Train B AOV (AF005E) to SG-A plugged	1.0E-4	3	1	
E22B	Train B AOV (AF005F) to SG-B plugged	1.0E-4	3	1	
E22C	Train B AOV (AF005G) to SG-C plugged	1.0E-4	3	1	
E22D	Train B AOV (AF005H) to SG-D plugged	1.0E-4	3	1	
E23A	Train B flow limiting orifice (AF012) to SG-A plugged	3.0E-4	3	2	
E23B	Train B flow limiting orifice (AF014) to SG-B plugged	3.0E-4	3	2	
E23C	Train B flow limiting orifice (AF016) to SG-C plugged	3.0E-4	3	2	
E23D	Train B flow limiting orifice (AF018) to SG-D plugged	3.0E-4	3	2	
E24A	Train C check valve (FW036A) to SG-A fails to open	1.0E-4	3	1	
E24B	Train C check valve (FW036B) to SG-B fails to open	1.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E24C	Train C check valve (FW036C) to SG-C fails to open	1.0E-4	3	1	
E24D	Train C check valve (FW036D) to SG-D fails to open	1.0E-4	3	1	
E25A	Train C AOV (FW035A) to SG-A fails to operate	3.0E-4	3	1	
E25B	Train C AOV (FW035B) to SG-B fails to operate	3.0E-4	3	1	
E25C	Train C AOV (FW035C) to SG-C fails to operate	3.0E-4	3	1	
E25D	Train C AOV (FW035D) to SG-D fails to operate	3.0E-4	3	1	
E26A	Train C flow controller (FC15A) to SG-A fails	(3.1E-5)	10	2	
E26B	Train C flow controller (FC15B) to SG-B fails	(3.1E-5)	10	2	
E26C	Train C flow controller (FC15C) to SG-C fails	(3.1E-5)	10	2	
E26D	Train C flow controller (FC15D) to SG-D fails	(3.1E-5)	10	2	
E27A	Train C AOV (FW034A) to SG-A fails to operate	3.0E-4	3	1	
E27B	Train C AOV (FW034B) to SG-B fails to operate	3.0E-4	3	1	
E27C	Train C AOV (FW034C) to SG-C fails to operate	3.0E-4	3	1	
E27D	Train C AOV (FW034D) to SG-D fails to operate	3.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E28A	Train C manual valve (FW33A) to SG-A plugged	1.0E-4	3	1	
E28B	Train C manual valve (FW33B) to SG-B plugged	1.0E-4	3	1	
E28C	Train C manual valve (FW33C) to SG-C plugged	1.0E-4	3	1	
E28D	Train C manual valve (FW33D) to SG-D plugged	1.0E-4	3	1	
E29	Train A discharge valve (AF004A) plugged	1.0E-4	3	1	
E30	Train A check valve (AF003A) fails to open	1.0E-4	3	1	
E31	Train A motor pump (AF10PA-1) fails to start	1.0E-3	3	1	
E32	Train A motor pump local control circuit fails	4.0E-3	3	1	
E33	Train A breaker (PCB1412) inadvertently opened	(1.0E-6)	3	2	
E34	Loss of AC supply lines on reactor trip	1.0E-3	10	-	Engineering judgment
E35	Unit 1 diesel generator (DG-1A) fails to start	1.0E-2	3	1	NRC Safety & Licensing Branch agreed.
E36	ACB14B breaker fails to close	1.0E-3	3	2	
E37	PCB1412 breaker fails to open	1.0E-3	3	2	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E38	Unit 2 diesel generator (DG2A) fails to start	1.0E-2	3	1	Same as E35
E39	ACB2413 breaker fails to close	1.0E-3	3	2	
E40	PCB2412 breaker fails to open	1.0E-3	3	2	
E41	Operator fails to manually transfer BUS 241 to 141	1.0E-2	10	1	
E42	ACB2414 breaker fails to close	1.0E-3	3	2	
E43	ACB1414 breaker fails to close	1.0E-3	3	2	
E44	Manual valve (AF002A) plugged	1.0E-4	3	1	
E45	Check valve (AF001A) fails to open	1.0E-4	3	1	
E46	Recirculation orifice and valves plugged	(5.0E-4)	3	2	Not required on demand
E47	MOV (AF007A-1) fails to open	1.0E-3	3	1	
E48	MOV (AF007A-1) level control circuit fails	6.0E-3	3	1	
E49	MOV (AF006A-1) fails to open	1.0E-3	3	1	
E50	MOV (AF006A-1) level control circuit fails	6.0E-3	3	1	
E51	ESW recirculation failure to switch (train A)	4.8E-3	3	RBD	Not required on demand
E52	ESW train A fails	(1.0E-6)	3	2	
E53	Train A discharge valve (AF004A) inadvertently closed	7.0E-6	3	1&2	Human error
E54	Manual override for motor pump (AF10PA-1) fails	1.0E-2	10	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E55	Automatic ESW and recirculation transfer circuits (for Train A) fail	8.0E-3	3	RBD	Not required on demand
E56	Manual overrides for ESW supply to Train A fail	1.0E-2	10	1	
E57	Train A discharge valve (AF004A) fails to open	3.0E-4	3	1	
E58	Train A discharge valve (AF004A) local circuit fails	2.0E-3	3	1	
E59	Train A discharge valve (AF004A) manual override fails	1.0E-2	10	1	
E60	Train B discharge valve (AF004B) plugged	1.0E-4	3	1	
E61	Train B check valve (AF003B) fails to open	1.0E-4	3	1	
E62	Train B diesel pump (AF01PB-2) fails to start	1.0E-3	3	1	
E63	Diesel pump local control circuit fails	4.0E-3	3	1	
E64	CST manual valve to Train B (AF002B) plugged	1.0E-4	3	1	
E65	CST check valve to Train B (AF001B) fails to open	1.0E-4	3	1	
E66	CST recirculation orifice and valves to Train B plugged	5.0E-4	3	2	Not required on demand
E67	ESW MOV (AF007B-2) to Train B fails to open	1.0E-3	3	1	
E68	ESW MOV (AF007B-2) local control circuit fails	6.0E-3	3	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E69	ESW MOV (AF006B-2) to Train B fails to open	1.0E-3	3	1	
E70	ESW MOV (AF006B-2) local control circuit fails	6.0E-3	3	1	
E71	ESW recirculation failure to switch (Train B)	4.8E-3	3	RBD	Not required on demand
E72	ESW Train B fails	(1.0E-6)	3	2	
E73	Discharge valve (AF004B) inadvertently closed	7.0E-6	3	1&2	Human error
E74	Diesel pump manual override fails	1.0E-2	10	1	
E75	Automatic ESW and recirculation transfer circuits to Train B fail	8.0E-3	3	RBD	Not required on demand
E76	ESW (control logic) manual override (for Train B) fails	1.0E-2	10	1	
E77	Train B discharge valve (AF004B) fails to open	3.0E-4	3	1	
E78	Discharge valve (AF004B) local circuit fails	2.0E-3	3	1	
E79	Manual override for discharge valve (AF004B) fails	1.0E-2	10	1	
E80	Condensate storage tank rupture	1.0E-6	3	2	
E81	Condensate storage tank manual valve (CD022) plugged	1.0E-4	3	1	
E82	Condensate storage check valve (CD183) fails to open	1.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E83	Condensate storage tank manual valve (CD149) plugged	1.0E-4	3	1	
E84	Condensate storage tank manual valve (CD091) plugged	1.0E-4	3	1	
E85	Condenser hotwell rupture	1.0E-6	3	2	
E86	Train C startup FW pump (FW02P) fails to start	1.0E-3	3	1	
E87	Train C pump control cicruit fails	4.0E-3	3	1	
E88	Operator fails to manually start pump (Train C)	1.0E-2	3	1	
E89	Train C pump recirculation circuit and valves fail	4.3E-4	3	RBD	
E90	Boiler feedwater pump motor driven stop check valve (FW002A) fails to stay closed	1.0E-6	3		Engineering judgement
E91	Boiler feedwater pump check valve (FW001A) fails to stay closed	1.0E-6	3		-
E92	Boiler feedwater turbine driven stop check valve (FW02B) fails to close	1.0E-4	3	1	
E93	Boiler feedwater check valve (FW4001B) fails to close	1.0E-4	3	1	
E94	FW002C stop check valve fails to close	1.0E-4	3	1	
E95	FW001C check valve fails to close	1.0E-4	3	1	

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E96	Condensate booster pump 1A fails to keep running	(3.0E-5)	10	2	Running failure
E97	Condensate booster pump 1A control circuit fails	(3.1E-5)	10	2	Running failure
E98	Pump 1A strainers plugged	1.0E-4	3	2	
E99	Pump 1A recirculation circuit and valves fail	6.0E-4	3	RBD	
E100	Condensate pump 1B fails to keep running	(3.0E-5)	10	2	Running failure
E101	Pump 1B control circuit fails to keep running	(3.1E-5)	10	2	
E102	Pump 1B strainers plugged	1.0E-4	3	1	
E103	Pump 1B recirculation circuit and valves fail	6.0E-4	3	RBD	
E104	Condensate pump 1C fails tc keep running	(3.0E-5)	10	2	Running failure
E105	Condensate pump 1C control circuit fails to keep running	(3.1E-5)	10	2	Running failure
E106	Condensate pump 1C strainers plugged	1.0E-4	3	2	
E107	Condensate pump 1C recirculation circuit and valves fail	6.0E-4	3	RBD	

----

*Error Factor = Ratio of 95th to 50th percentile

Table A.III.1 (Continued)

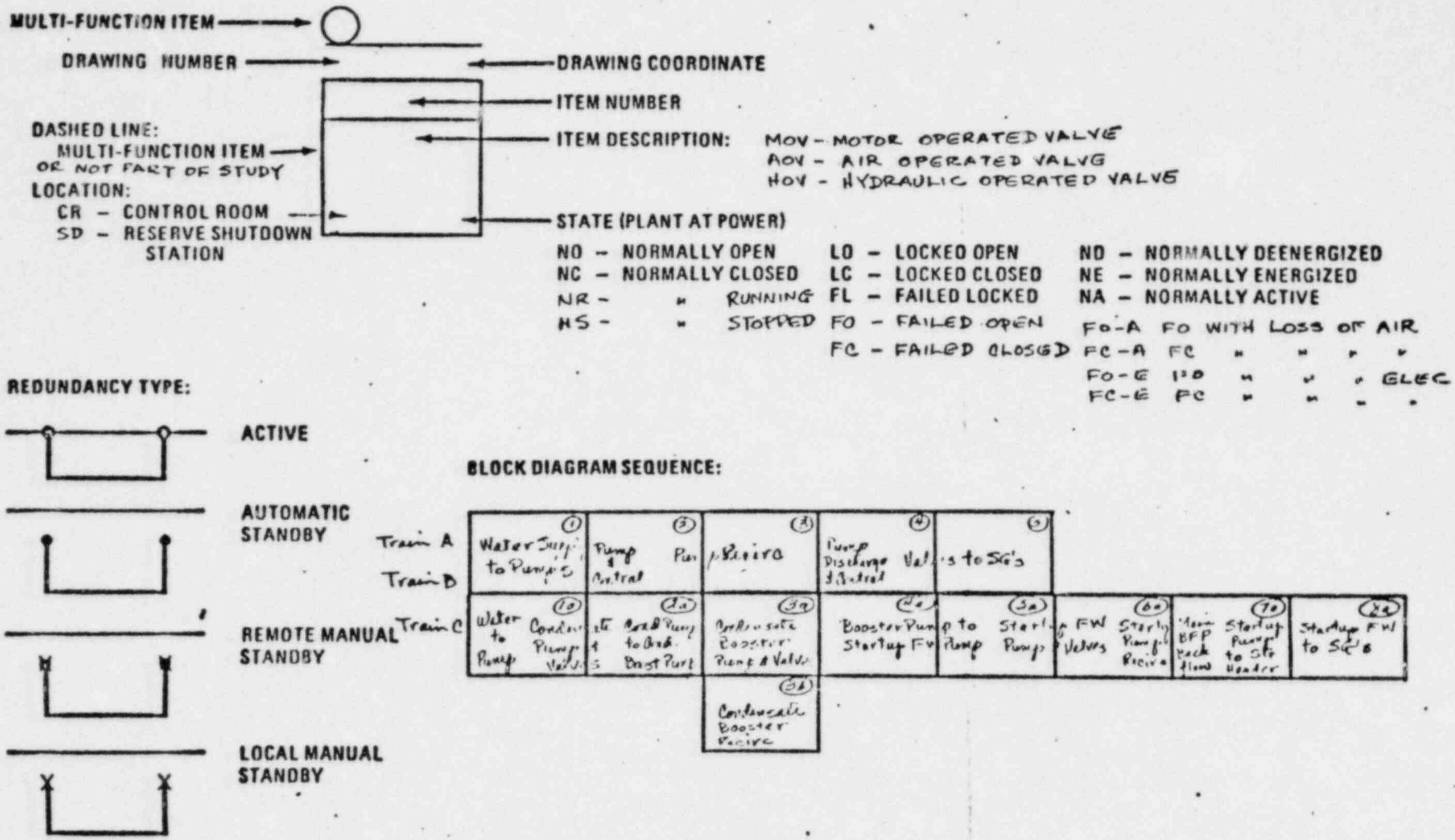
Event No.	Description	Failure Probability Per Demand (Per Hour)	Error Factor*	Ref.	Comments
E108	Condensate pump 1D fails to start	1.0E-3	3	1	
E109	Condensate pump 1D control circuit fails	4.0E-3	3	1	
E110	Condensate pump 1D strainers plugged	1.0E-4	3	2	
E111	Condensate pump 1D recirculation circuit and va[illegible]es fail	6.0E-4	3	RBD	
E112	Condensate pump 1D auto and manual start circuit fails	1.0E-6	10	2	
QM	Probability of equipment failure due to maintenance	5.8E-3	3	1	Maintenance outage
Beta Factors					
B_1	Intra-system (valves, circuit breakers, pumps)	.10	3	9	
B_2	Inter-system (valves, ESF signal, pumps)	.03	3	9	

*Error Factor = Ratio of 95th to 50th percentile

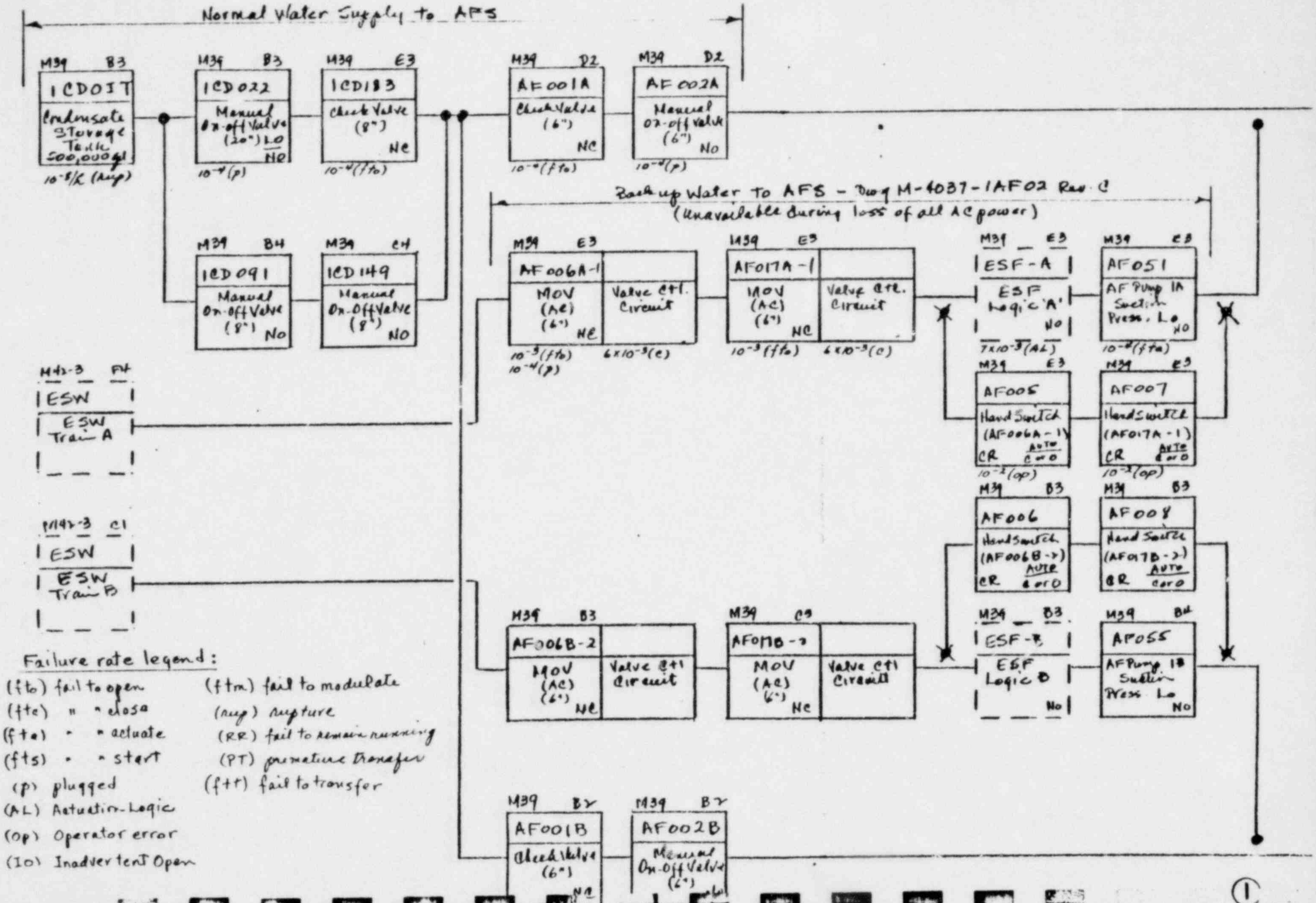
APPENDIX B

AFS RELIABILITY BLOCK DIAGRAM

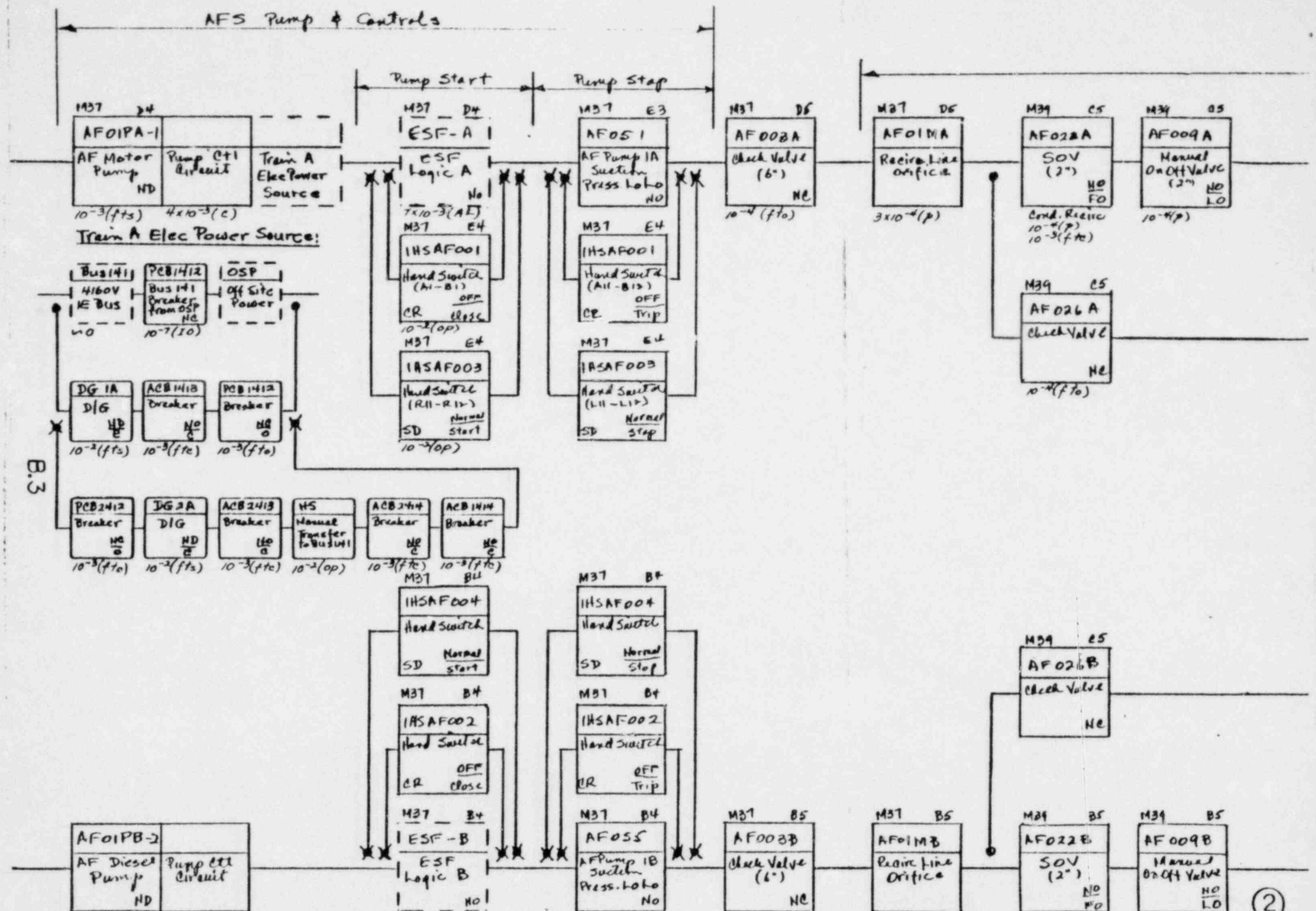
B.1



AFS RELIABILITY BLOCK DIAGRAM

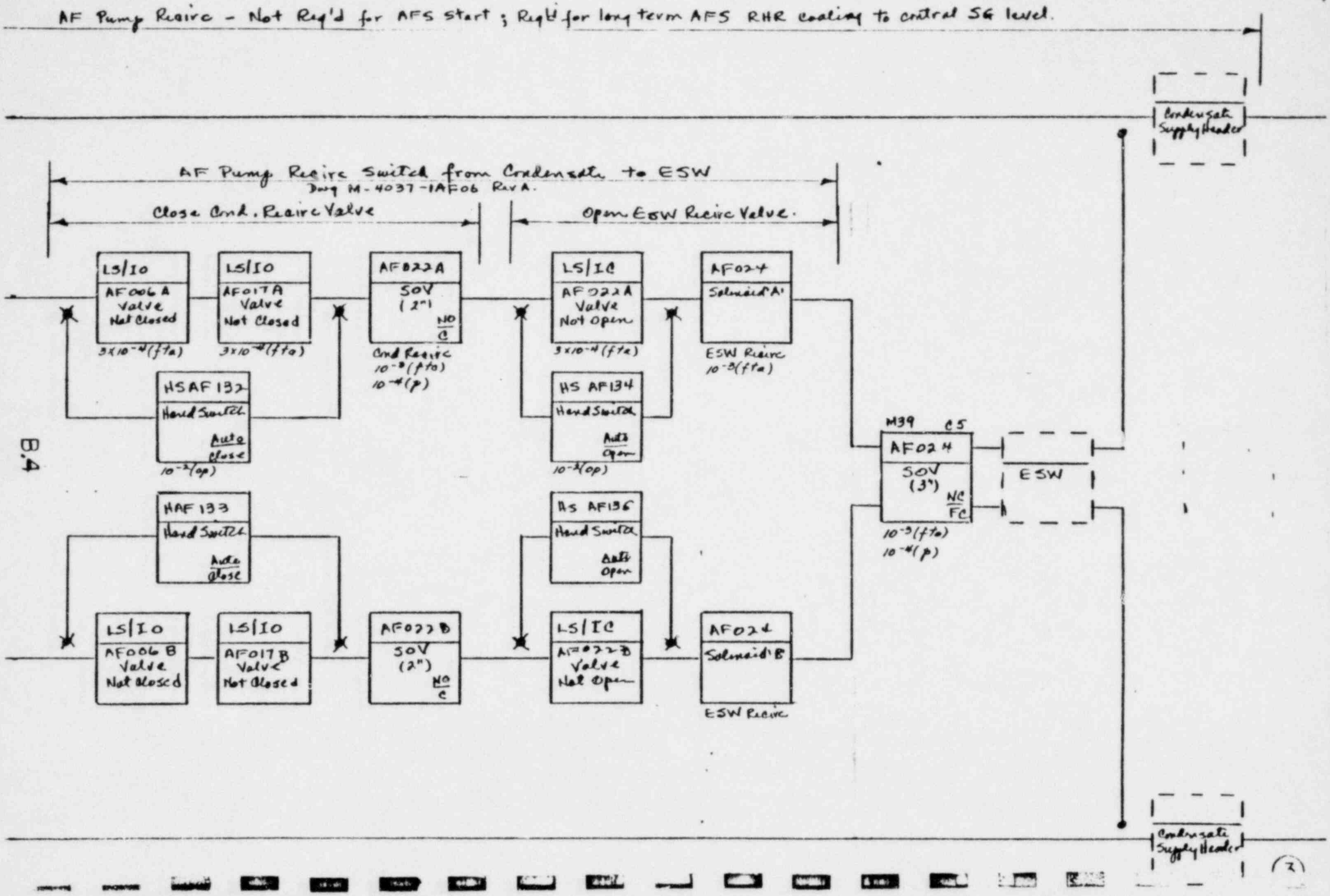

Normal Water Supply to AFS
M39 B3
1CD01T
Condensate Storage Tank 500,000 gal
10-5/h (rup)
M39 B3
1CD022
Manual On-off Valve (20") LO NO
10-4 (p)
M39 E3
1CD183
Check Valve (8") NC
10-4 (fto)
M39 D2
AF001A
Check Valve (6") NC
10-4 (fto)
M39 D2
AF002A
Manual On-off Valve (6") NO
10-4 (p)
M39 B4
1CD091
Manual On-off Valve (8") NO
M39 C4
1CD149
Manual On-Off Valve (8") NO
Backup Water To AFS - Dwg M-4037-1AF02 Rev. C
(Unavailable during loss of all AC power)
M39 E3
AF006A-1
MOV (AC) (6") NC
Valve Ctl. Circuit
10-3 (fto)
10-4 (p)
6x10-3 (c)
M39 E3
AF017A-1
MOV (AC) (6") NC
Valve Ctl. Circuit
10-3 (fto)
6x10-3 (c)
M39 E3
ESF-A
ESF Logic 'A' NO
7x10-3 (AL)
M39 E3
AF051
AF Pump 1A Suction Press. Lo NO
10-3 (fta)
M39 E3
AF005
Hand Switch (AF006A-1)
CR AUTO C-O-O
10-2 (op)
M39 E3
AF007
Hand Switch (AF017A-1)
CR AUTO C-O-O
10-2 (op)
M42-3 F4
ESW
ESW Train A
M42-3 C1
ESW
ESW Train B
M39 B3
AF006
Hand Switch (AF006B-2)
CR AUTO C-O-O
M39 B3
AF008
Hand Switch (AF017B-2)
CR AUTO C-O-O
M39 B3
AF006B-2
MOV (AC) (6") NC
Valve Ctl Circuit
M39 C3
AF017B-2
MOV (AC) (6") NC
Valve Ctl Circuit
M39 B3
ESF-B
ESF Logic B NO
M39 B4
AF055
AF Pump 1B Suction Press. Lo NO
Failure rate legend:
(fto) fail to open
(ftc) " " close
(fta) " " actuate
(fts) " " start
(p) plugged
(AL) Actuation Logic
(op) Operator error
(IO) Inadvertent Open
(ftm) fail to modulate
(rup) rupture
(RR) fail to remain running
(PT) premature transfer
(ftt) fail to transfer
M39 B2
AF001B
Check Valve (6") NC
M39 B2
AF002B
Manual On-Off Valve (6") NO

B.2



AFS Pump & Controls
Pump Start
Pump Stop
AF01PA-1
AF Motor Pump
ND
Pump Ctl Circuit
Train A Elec Power Source
10⁻³(fts)
4x10⁻³(c)
ESF-A
ESF Logic A
No
7x10⁻³(AE)
AF051
AF Pump 1A Suction Press Lo-Lo
NO
AF003A
Check Valve (6")
NC
10⁻⁴(fto)
AF01MA
Recirc Line Orifice
3x10⁻⁴(p)
AF022A
SOV (2")
NO FO
Cond. Recirc
10⁻⁴(p)
10⁻³(ftc)
AF009A
Manual On Off Valve (2")
NO LO
10⁻⁴(p)
Train A Elec Power Source:
Bus141
4160V 1E Bus
NO
PCB1412
Bus 141 Breaker from OSP
NC
10⁻⁷(10)
OSP
Off Site Power
1HSAF001
Hand Switch (A11-B11)
OFF Close
CR
10⁻²(op)
1HSAF001
Hand Switch (A11-B12)
OFF Trip
CR
AF026A
Check Valve
NC
10⁻⁴(fto)
DG 1A
D/G
ND
10⁻²(fts)
ACB1418
Breaker
NO
10⁻³(ftc)
PCB1412
Breaker
NO
10⁻³(fto)
1ASAF003
Hand Switch (R11-R12)
SD
Normal Start
10⁻²(op)
1ASAF003
Hand Switch (L11-L12)
SD
Normal Stop
PCB2412
Breaker
NO
10⁻³(fto)
DG 2A
D/G
ND
10⁻²(fts)
ACB2413
Breaker
NO
10⁻³(ftc)
HS
Manual Transfer to Bus141
10⁻²(op)
ACB2414
Breaker
NC
10⁻³(ftc)
ACB1414
Breaker
NC
10⁻³(ftc)
1HSAF004
Hand Switch
SD
Normal Start
1HSAF004
Hand Switch
SD
Normal Stop
AF026B
Check Valve
NC
1HSAF002
Hand Switch
CR
OFF Close
1HSAF002
Hand Switch
CR
OFF Trip
AF01PB-2
AF Diesel Pump
ND
Pump Ctl Circuit
ESF-B
ESF Logic B
NO
AF055
AF Pump 1B Suction Press. Lo-Lo
No
AF003B
Check Valve (6")
NC
AF01MB
Recirc Line Orifice
AF022B
SOV (2")
NO FO
AF009B
Manual On Off Valve
NO LO
M37 D4
M37 E3
M37 D6
M37 E4
M37 B4
M37 B5
M39 C5
M39 B5

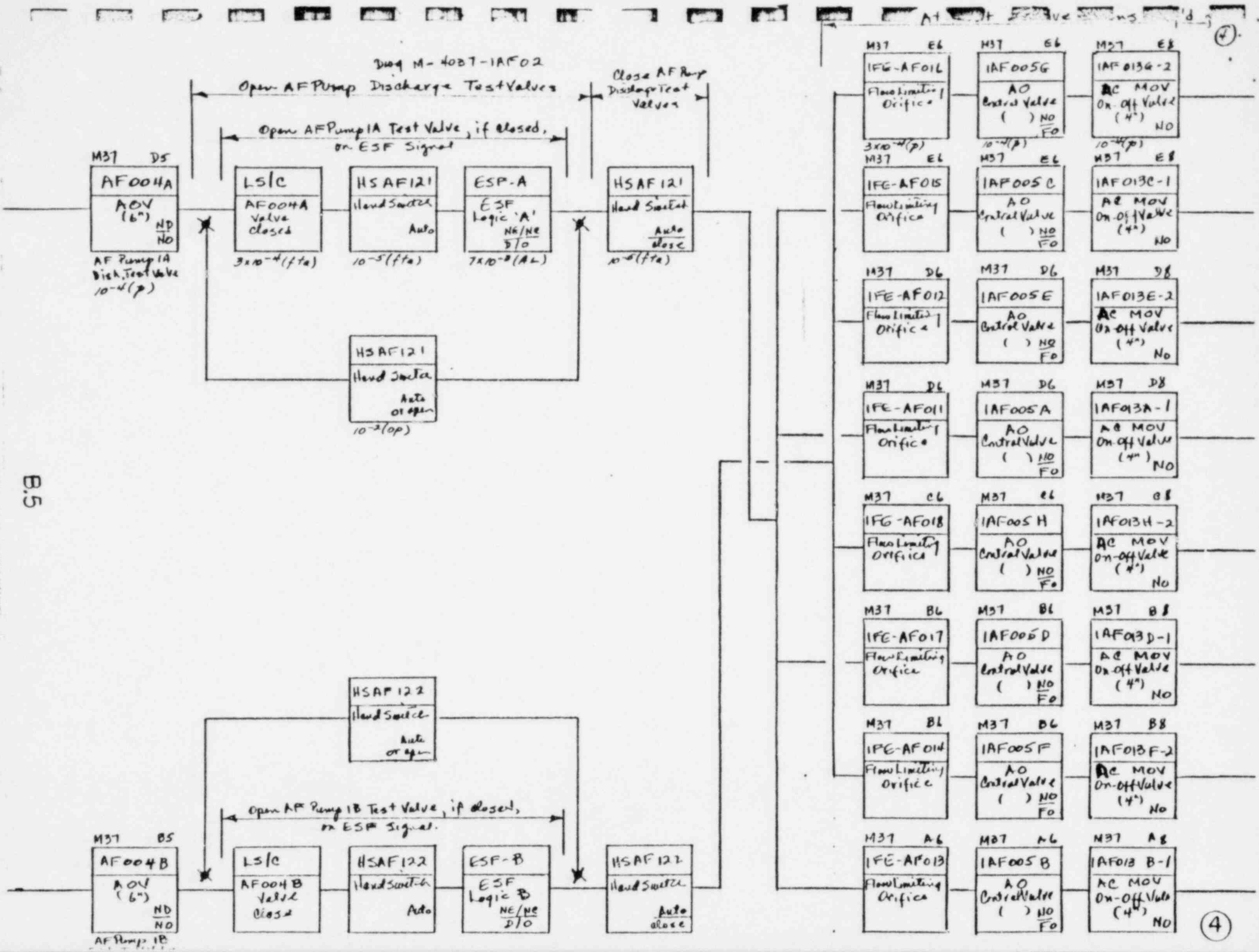
B.3



AF Pump Recirc - Not Req'd for AFS start ; Req'd for long term AFS RHR cooling to control SG level.
Condensate Supply Header
AF Pump Recirc Switch from Condensate to ESW
Dwg M-4037-1AF06 Rev A.
Close Cnd. Recirc Valve
Open ESW Recirc Valve.
LS/IO
AF006 A
Valve
Not Closed
3x10^-4 (fto)
LS/IO
AF017A
Valve
Not Closed
3x10^-4 (fto)
AF022A
SOV
(2")
NO
C
Cnd Recirc
10^-3 (fto)
10^-4 (p)
LS/IC
AF022A
Valve
Not Open
3x10^-4 (fto)
AF024
Solenoid 'A'
ESW Recirc
10^-3 (fto)
HSAF132
Hand Switch
Auto
Close
10^-2 (op)
HS AF134
Hand Switch
Auto
Open
10^-2 (op)
M39
C5
AF024
SOV
(3")
NC
FC
10^-3 (fto)
10^-4 (p)
ESW
HAF133
Hand Switch
Auto
Close
HS AF136
Hand Switch
Auto
Open
LS/IO
AF006 B
Valve
Not Closed
LS/IO
AF017 B
Valve
Not Closed
AF022B
SOV
(2")
NO
C
LS/IC
AF022B
Valve
Not Open
AF024
Solenoid 'B'
ESW Recirc
Condensate Supply Header

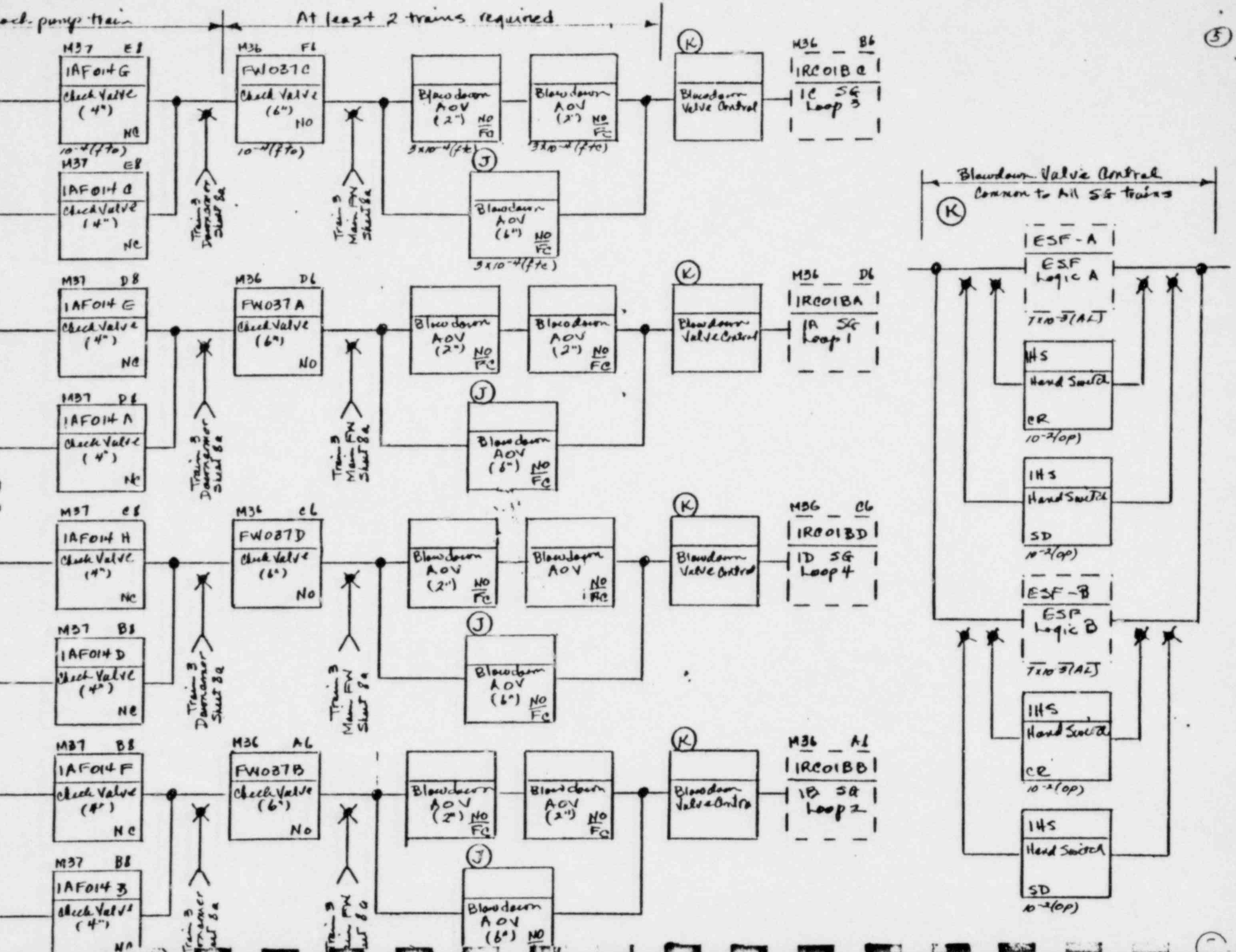
B.4

B.5

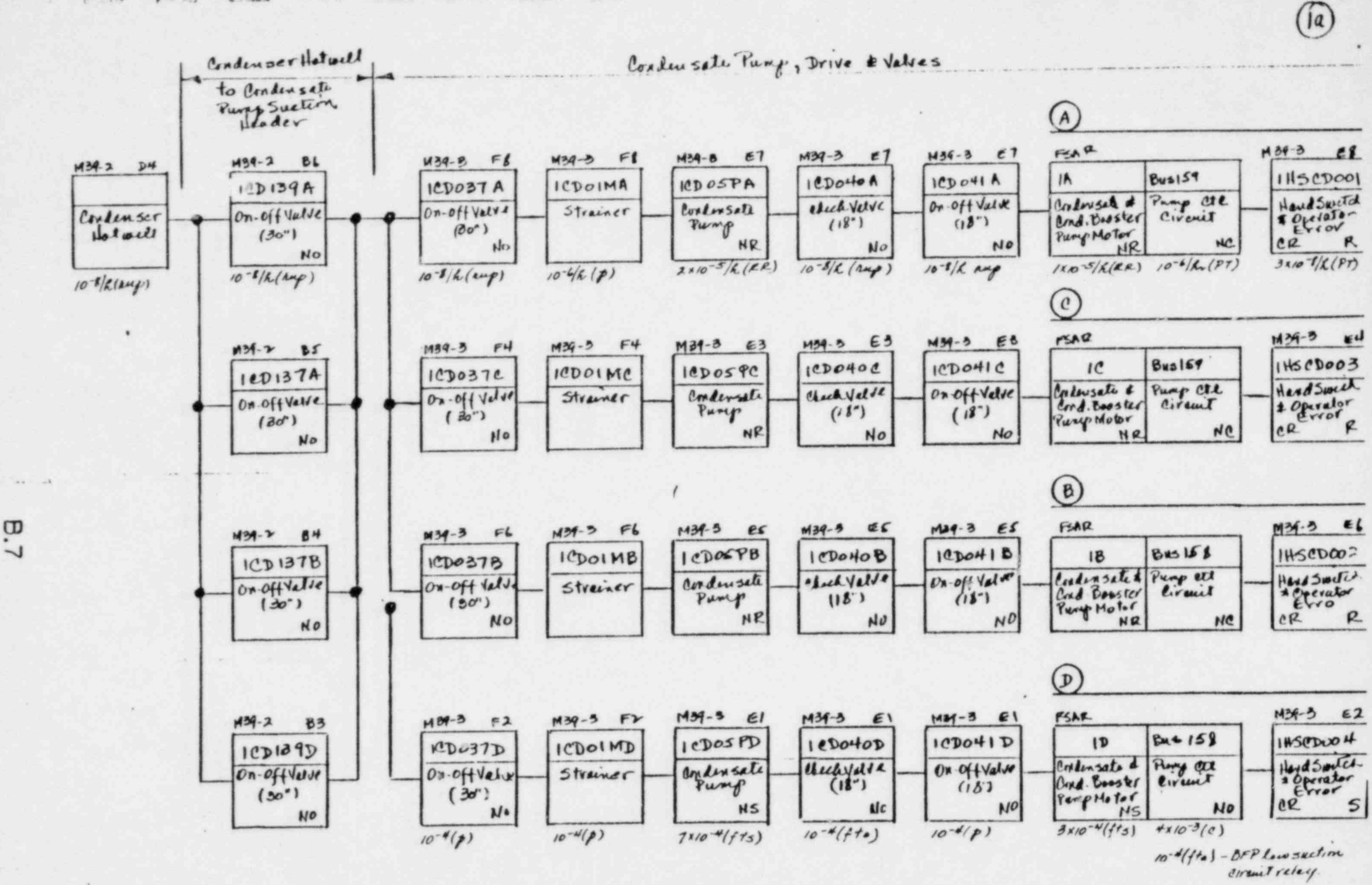


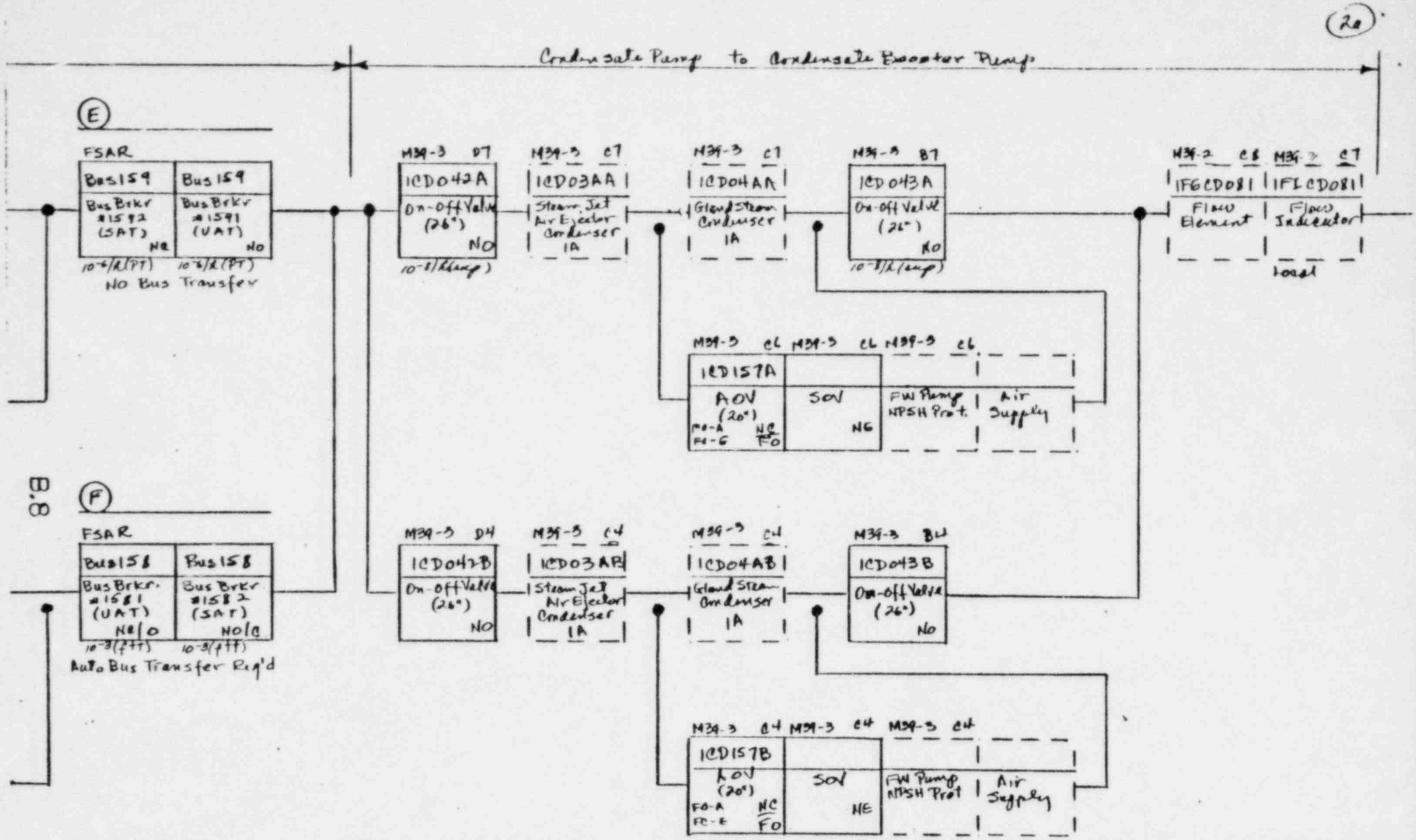
Dwg M-4037-1AF02
Open AF Pump Discharge Test Valves
Close AF Pump Discharge Test Valves
Open AF Pump 1A Test Valve, if closed, on ESF Signal
M37 D5
AF004A
AOV (6")
ND/NO
AF Pump 1A Disch. Test Valve
10-4(p)
LS/C
AF004A Valve closed
3x10-4(fta)
HSAF121
Hand Switch
Auto
10-5(fta)
ESF-A
ESF Logic 'A'
NE/NE D/O
7x10-8(AL)
HSAF121
Hand Switch
Auto close
10-6(fta)
HSAF121
Hand Switch
Auto or open
10-3(op)
HSAF122
Hand Switch
Auto or open
Open AF Pump 1B Test Valve, if closed, on ESF Signal.
M37 B5
AF004B
AOV (6")
ND/NO
AF Pump 1B
LS/C
AF004B Valve close
HSAF122
Hand Switch
Auto
ESF-B
ESF Logic B
NE/NE D/O
HSAF122
Hand Switch
Auto close
M37 E6
1FE-AF016
Flow Limiting Orifice
3x10-4(p)
M37 E6
1AF005G
AO Control Valve
( ) NO/FO
10-4(p)
M37 E8
1AF013G-2
AC MOV On-Off Valve (4")
NO
10-4(p)
M37 E6
1FE-AF015
Flow Limiting Orifice
M37 E6
1AF005C
AO Control Valve
( ) NO/FO
M37 E8
1AF013C-1
AC MOV On-Off Valve (4")
NO
M37 D6
1FE-AF012
Flow Limiting Orifice
M37 D6
1AF005E
AO Control Valve
( ) NO/FO
M37 D8
1AF013E-2
AC MOV On-Off Valve (4")
NO
M37 D6
1FE-AF011
Flow Limiting Orifice
M37 D6
1AF005A
AO Control Valve
( ) NO/FO
M37 D8
1AF013A-1
AC MOV On-Off Valve (4")
NO
M37 C6
1FE-AF018
Flow Limiting Orifice
M37 C6
1AF005H
AO Control Valve
( ) NO/FO
M37 C8
1AF013H-2
AC MOV On-Off Valve (4")
NO
M37 B6
1FE-AF017
Flow Limiting Orifice
M37 B6
1AF005D
AO Control Valve
( ) NO/FO
M37 B8
1AF013D-1
AC MOV On-Off Valve (4")
NO
M37 B6
1FE-AF014
Flow Limiting Orifice
M37 B6
1AF005F
AO Control Valve
( ) NO/FO
M37 B8
1AF013F-2
AC MOV On-Off Valve (4")
NO
M37 A6
1FE-AF013
Flow Limiting Orifice
M37 A6
1AF005B
AO Control Valve
( ) NO/FO
M37 A8
1AF013B-1
AC MOV On-Off Valve (4")
NO

4

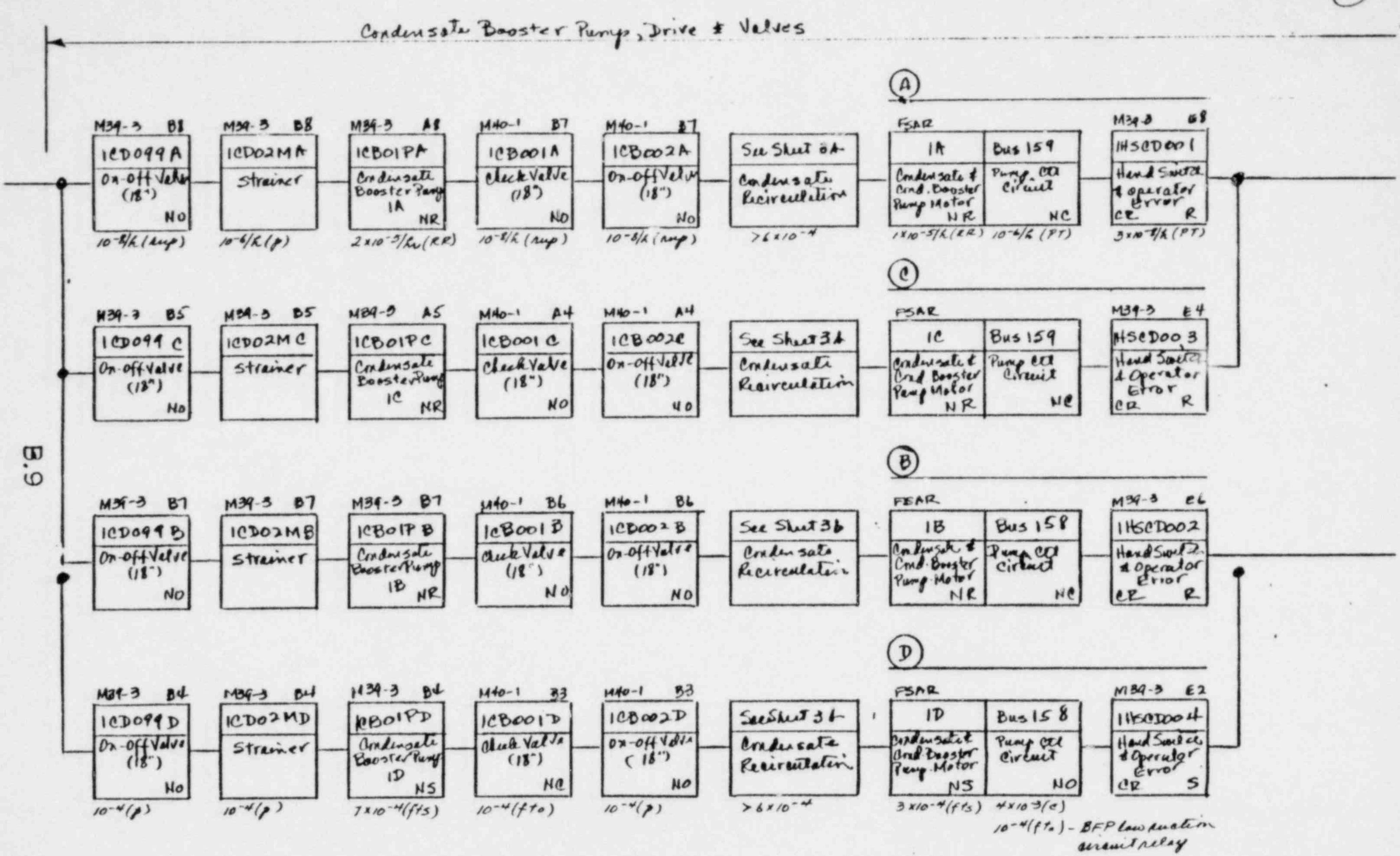


lock. pump train
At least 2 trains required
M37 E8
1AF014 G
Check Valve (4")
NC
10^-2(fto)
M37 E8
1AF014 C
Check Valve (4")
NC
Train 3 Downcomer Sheet 8a
M36 F6
FW037C
Check Valve (6")
NO
10^-2(fto)
Train 3 Main FW Sheet 8a
Blowdown AOV (2") NO/FC
3x10^-4(ftc)
Blowdown AOV (2") NO/FC
3x10^-4(ftc)
J
Blowdown AOV (6") NO/FC
3x10^-4(ftc)
K
Blowdown Valve Control
M36 B6
1RC01BC
1C SG Loop 3
M37 D8
1AF014 E
Check Valve (4")
NC
M37 D8
1AF014 A
Check Valve (4")
NC
M36 D6
FW037A
Check Valve (6")
NO
Blowdown AOV (2") NO/FC
Blowdown AOV (2") NO/FC
Blowdown AOV (6") NO/FC
Blowdown Valve Control
M36 D6
1RC01BA
1A SG Loop 1
M37 C8
1AF014 H
Check Valve (4")
NC
M37 B8
1AF014 D
Check Valve (4")
NC
M36 C6
FW037D
Check Valve (6")
NO
Blowdown AOV (2") NO/FC
Blowdown AOV NO/FC
Blowdown AOV (6") NO/FC
Blowdown Valve Control
M36 C6
1RC01BD
1D SG Loop 4
M37 B8
1AF014 F
Check Valve (4")
NC
M37 B8
1AF014 B
Check Valve (4")
NC
M36 A6
FW037B
Check Valve (6")
NO
Blowdown AOV (2") NO/FC
Blowdown AOV (2") NO/FC
Blowdown AOV (6") NO
Blowdown Valve Control
M36 A6
1RC01BB
1B SG Loop 2
Blowdown Valve Control
Common to All SG trains
ESF-A
ESF Logic A
7x10^-3(AL)
1HS
Hand Switch
CR
10^-2(op)
1HS
Hand Switch
SD
10^-2(op)
ESF-B
ESF Logic B
7x10^-3(AL)
1HS
Hand Switch
CR
10^-2(op)
1HS
Hand Switch
SD
10^-2(op)
5


(1a)
Condenser Hotwell to Condensate Pump Suction Header
Condensate Pump, Drive & Valves
M39-2 D4
Condenser Hotwell
10^-8/h (amp)
M39-2 B6
1CD139A
On-Off Valve (30")
NO
10^-8/h (amp)
M39-2 B5
1CD137A
On-Off Valve (30")
NO
M39-2 B4
1CD137B
On-Off Valve (30")
NO
M39-2 B3
1CD139D
On-Off Valve (30")
NO
A
M39-3 F6
1CD037A
On-Off Valve (30")
NO
10^-8/h (amp)
M39-3 F8
1CD01MA
Strainer
10^-6/h (p)
M39-3 E7
1CD05PA
Condensate Pump
NR
2x10^-5/h (RR)
M39-3 E7
1CD040A
Check Valve (18")
NO
10^-8/h (amp)
M39-3 E7
1CD041A
On-Off Valve (18")
NO
10^-8/h amp
FSAR
1A
Condensate & Cond. Booster Pump Motor
NR
1x10^-5/h (RR)
Bus 159
Pump Ckt Circuit
NC
10^-6/hr (PT)
M39-3 E8
1HSCD001
Hand Switch & Operator Error
CR R
3x10^-8/h (PT)
C
M39-3 F4
1CD037C
On-Off Valve (30")
NO
M39-3 F4
1CD01MC
Strainer
M39-3 E3
1CD05PC
Condensate Pump
NR
M39-3 E3
1CD040C
Check Valve (18")
NO
M39-3 E8
1CD041C
On-Off Valve (18")
NO
FSAR
1C
Condensate & Cond. Booster Pump Motor
NR
Bus 159
Pump Ckt Circuit
NC
M39-3 E4
1HSCD003
Hand Switch & Operator Error
CR R
B
M39-3 F6
1CD037B
On-Off Valve (30")
NO
M39-3 F6
1CD01MB
Strainer
M39-3 E5
1CD05PB
Condensate Pump
NR
M39-3 E5
1CD040B
Check Valve (18")
NO
M39-3 E5
1CD041B
On-Off Valve (18")
NO
FSAR
1B
Condensate & Cond. Booster Pump Motor
NR
Bus 158
Pump Ckt Circuit
NC
M39-3 E6
1HSCD002
Hand Switch & Operator Error
CR R
D
M39-3 F2
1CD037D
On-Off Valve (30")
NO
10^-4 (p)
M39-3 F2
1CD01MD
Strainer
10^-4 (p)
M39-3 E1
1CD05PD
Condensate Pump
NS
7x10^-4 (fts)
M39-3 E1
1CD040D
Check Valve (18")
NC
10^-4 (fto)
M39-3 E1
1CD041D
On-Off Valve (18")
NO
10^-4 (p)
FSAR
1D
Condensate & Cond. Booster Pump Motor
NS
3x10^-4 (fts)
Bus 158
Pump Ckt Circuit
NO
4x10^-3 (c)
M39-3 E2
1HSCD004
Hand Switch & Operator Error
CR S
10^-4 (fto) - BFP low suction circuit relay
(1a)

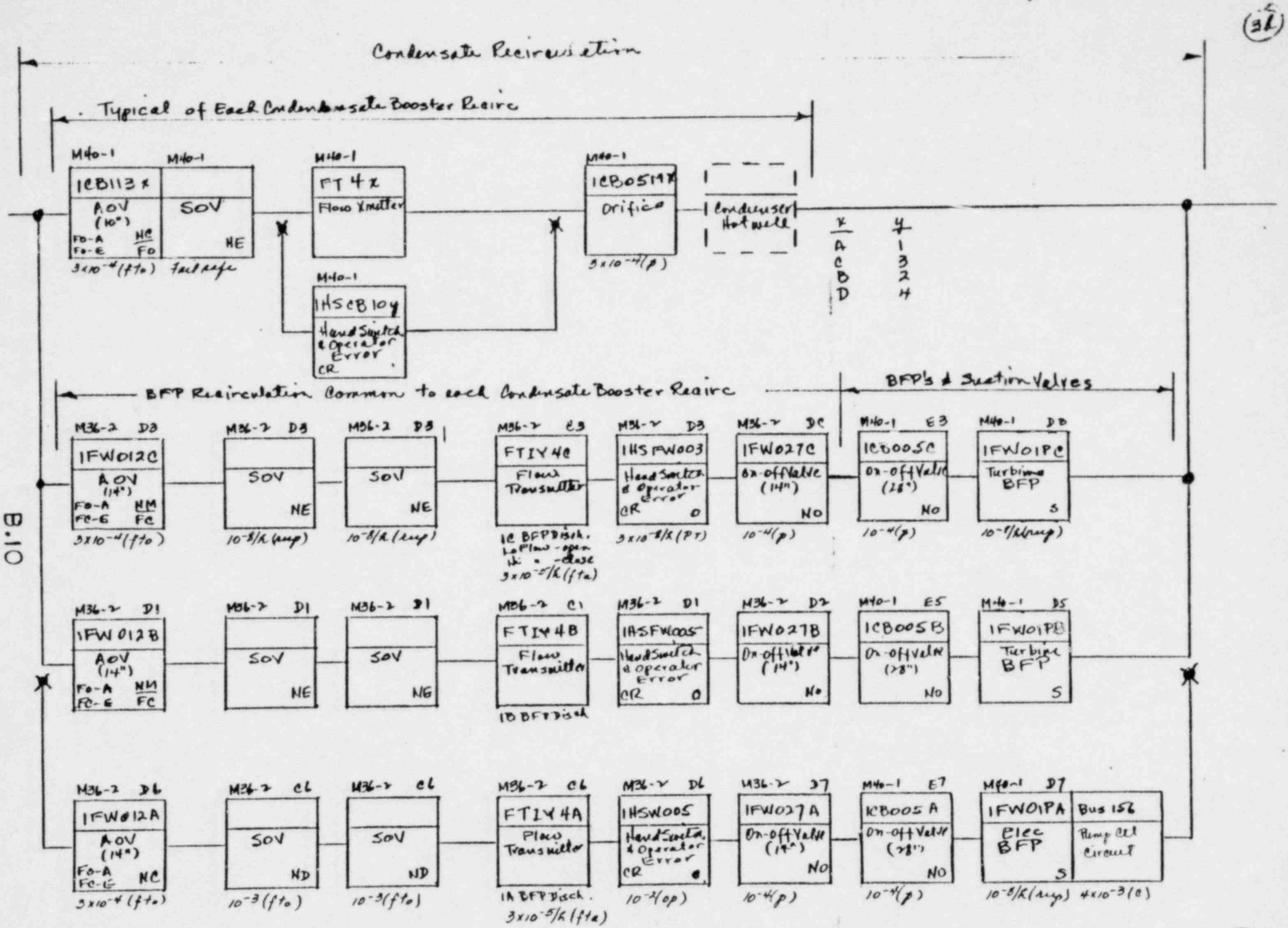

(2a)
Condensate Pump to Condensate Booster Pump
E
FSAR
Bus159
Bus Brkr
#1592
(SAT)
NC
10-6/R(PT)
Bus 159
Bus Brkr
#1591
(UAT)
NO
10-6/R(PT)
No Bus Transfer
F
FSAR
Bus158
Bus Brkr.
#1581
(UAT)
NC/O
10-3(ftt)
Bus158
Bus Brkr
#1582
(SAT)
NO/C
10-3(ftt)
Auto Bus Transfer Req'd
M39-3 D7
1CD042A
On-Off Valve
(26")
NO
M39-3 C7
1CD03AA
Steam Jet
Air Ejector
Condenser
1A
M39-3 C7
1CD04AA
Gland Steam
Condenser
1A
M39-3 B7
1CD043A
On-Off Valve
(26")
NO
M39-2 C8
1FECD081
Flow
Element
M39-2 C7
1FICD081
Flow
Indicator
Local
M39-3 C6
1CD157A
AOV
(20")
FO-A
FC-E
NC
FO
M39-3 C6
SOV
NC
M39-3 C6
FW Pump
NPSH Prot.
Air
Supply
M39-3 D4
1CD042B
On-Off Valve
(26")
NO
M39-3 C4
1CD03AB
Steam Jet
Air Ejector
Condenser
1A
M39-3 C4
1CD04AB
Gland Steam
Condenser
1A
M39-3 B4
1CD043B
On-Off Valve
(26")
NO
M39-3 C4
1CD157B
AOV
(20")
FO-A
FC-E
NC
FO
M39-3 C4
SOV
NE
M39-3 C4
FW Pump
NPSH Prot
Air
Supply
(2c)

B.8

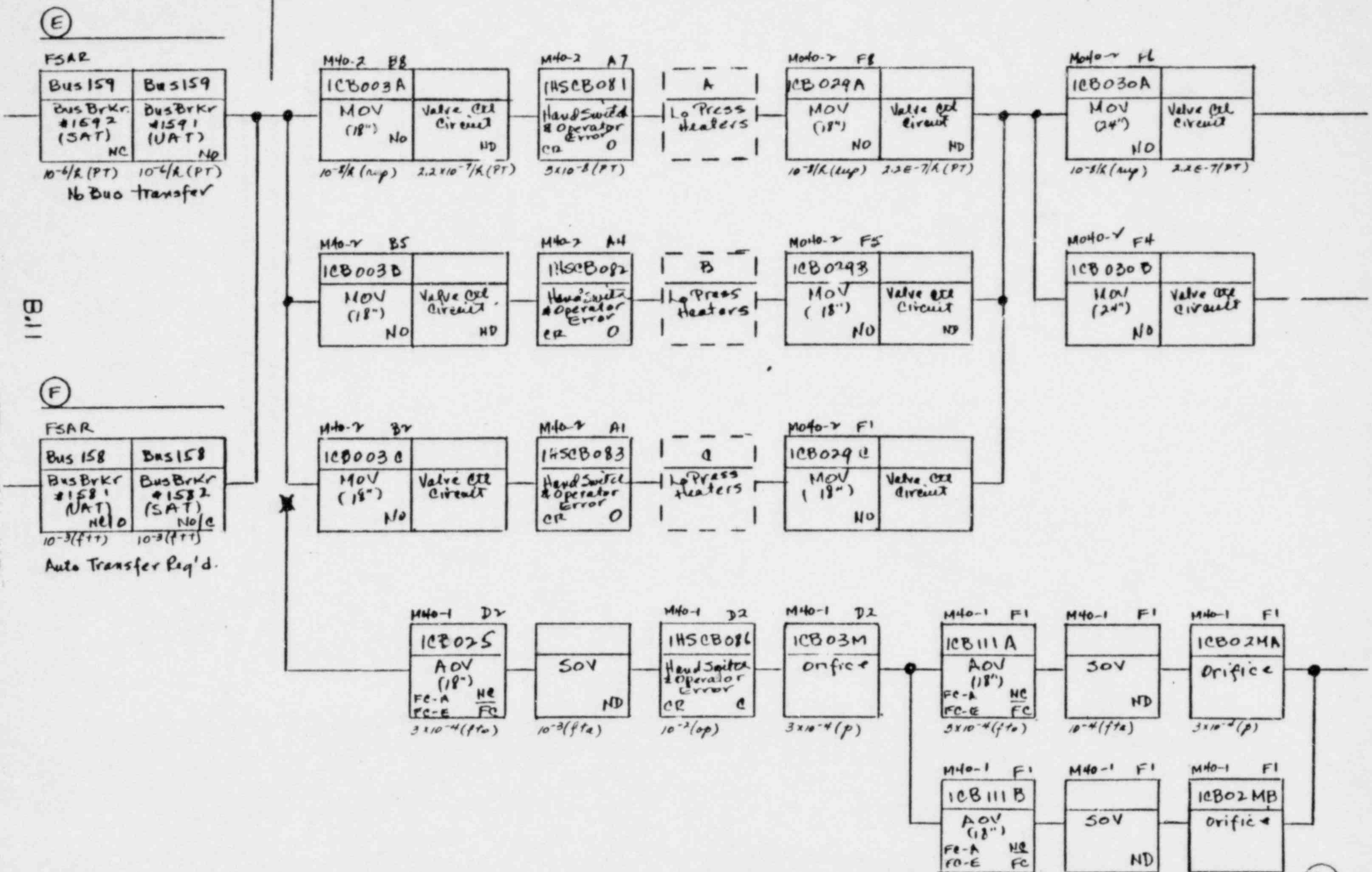


Condensate Booster Pump, Drive & Valves
A
C
B
D
M39-3 B8
ICD099A
On-Off Valve (18")
NO
10-8/h (mp)
M39-3 B8
ICD02MA
Strainer
10-6/h (p)
M39-3 A8
ICB01PA
Condensate Booster Pump 1A
NR
2x10-5/hr (RR)
M40-1 B7
ICB001A
Check Valve (18")
NO
10-8/h (mp)
M40-1 B7
ICB002A
On-Off Valve (18")
NO
10-8/h (mp)
See Sheet 3A
Condensate Recirculation
>6x10-4
FSAR
1A
Condensate & Cond. Booster Pump Motor
NR
1x10-5/h (RR)
Bus 159
Pump Ckt Circuit
NC
10-6/h (PT)
M39-3 E8
1HSCD001
Hand Switch & Operator Error
CR R
3x10-8/h (PT)
M39-3 B5
ICD099C
On-Off Valve (18")
NO
M39-3 B5
ICD02MC
Strainer
M39-3 A5
ICB01PC
Condensate Booster Pump 1C
NR
M40-1 A4
ICB001C
Check Valve (18")
NO
M40-1 A4
ICB002C
On-Off Valve (18")
NO
See Sheet 3A
Condensate Recirculation
FSAR
1C
Condensate & Cond Booster Pump Motor
NR
Bus 159
Pump Ckt Circuit
NC
M39-3 E4
1HSCD003
Hand Switch & Operator Error
CR R
M39-3 B7
ICD099B
On-Off Valve (18")
NO
M39-3 B7
ICD02MB
Strainer
M39-3 B7
ICB01PB
Condensate Booster Pump 1B
NR
M40-1 B6
ICB001B
Check Valve (18")
NO
M40-1 B6
ICB002B
On-Off Valve (18")
NO
See Sheet 3B
Condensate Recirculation
FSAR
1B
Condensate & Cond Booster Pump Motor
NR
Bus 158
Pump Ckt Circuit
NC
M39-3 E6
1HSCD002
Hand Switch & Operator Error
CR R
M39-3 B4
ICD099D
On-Off Valve (18")
NO
10-4(p)
M39-3 B4
ICD02MD
Strainer
10-4(p)
M39-3 B4
ICB01PD
Condensate Booster Pump 1D
NS
7x10-4(fts)
M40-1 B3
ICB001D
Check Valve (18")
NC
10-4(fto)
M40-1 B3
ICB002D
On-Off Valve (18")
NO
10-4(p)
See Sheet 3B
Condensate Recirculation
>6x10-4
FSAR
1D
Condensate & Cond Booster Pump Motor
NS
3x10-4(fts)
Bus 158
Pump Ckt Circuit
NO
4x10-3(c)
10-4(fto) - BFP low suction circuit relay
M39-3 E2
1HSCD004
Hand Switch & Operator Error
CR S
3a

(3a)


Condensate Recirculation
Typical of Each Condensate Booster Recirc
M40-1
1CB113X
AOV
(10")
FO-A
FO-E
NC
FO
3x10⁻⁴(fto)
M40-1
SOV
NE
Fail safe
M40-1
FT4X
Flow Xmitter
M40-1
1HSCB104
Hand Switch & Operator Error
CR
M40-1
1CB051MX
Orifice
3x10⁻⁴(p)
Condenser Hot well
X Y
A 1
C 3
B 2
D 4
BFP Recirculation Common to each Condensate Booster Recirc
BFP's & Suction Valves
M36-2 D3
1FW012C
AOV
(14")
FO-A
FC-E
NM
FC
3x10⁻⁴(fto)
M36-2 D3
SOV
NE
10⁻⁸/h(amp)
M36-2 D3
SOV
NE
10⁻⁸/h(amp)
M36-2 E3
FT1Y4C
Flow Transmitter
1C BFP Disch.
Lo Flow - open
Hi - close
3x10⁻⁵/h(fto)
M36-2 D3
1HSFW003
Hand Switch & Operator Error
CR
O
3x10⁻⁸/h(PT)
M36-2 DC
1FW027C
On-off Valve
(14")
NO
10⁻⁴(p)
M40-1 E3
1CB005C
On-off Valve
(28")
NO
10⁻⁴(p)
M40-1 DD
1FW01PC
Turbine BFP
S
M36-2 D1
1FW012B
AOV
(14")
FO-A
FC-E
NM
FC
M36-2 D1
SOV
NE
M36-2 D1
SOV
NE
M36-2 C1
FT1Y4B
Flow Transmitter
1B BFP Disch
M36-2 D1
1HSFW005
Hand Switch & Operator Error
CR
O
M36-2 D2
1FW027B
On-off Valve
(14")
NO
M40-1 E5
1CB005B
On-off Valve
(28")
NO
M40-1 D5
1FW01PB
Turbine BFP
S
M36-2 D6
1FW012A
AOV
(14")
FO-A
FC-E
NC
3x10⁻⁴(fto)
M36-2 C6
SOV
ND
10⁻³(fto)
M36-2 C6
SOV
ND
10⁻³(fto)
M36-2 C6
FT1Y4A
Flow Transmitter
1A BFP Disch.
3x10⁻⁵/h(fto)
M36-2 D6
1HSW005
Hand Switch & Operator Error
CR
10⁻²(op)
M36-2 D7
1FW027A
On-off Valve
(14")
NO
10⁻⁴(p)
M40-1 E7
1CB005A
On-off Valve
(28")
NO
10⁻⁴(p)
M40-1 D7
1FW01PA
Elec BFP
S
10⁻⁸/h(amp)
Bus 156
Pump Ckt Circuit
4x10⁻³(0)
3b

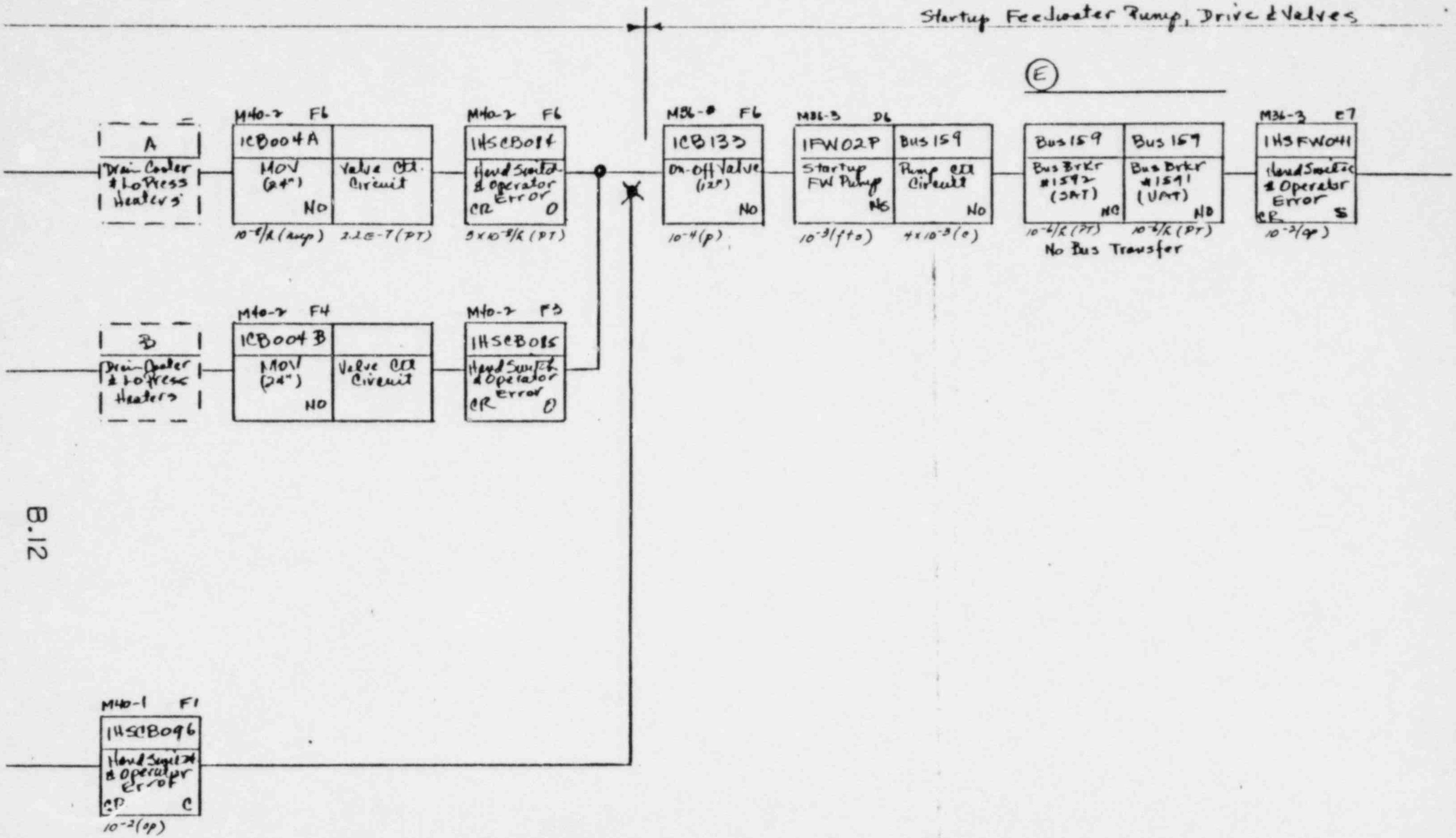
Condensate Booster Pump to Startup Feedwater Pump



B.11

4a

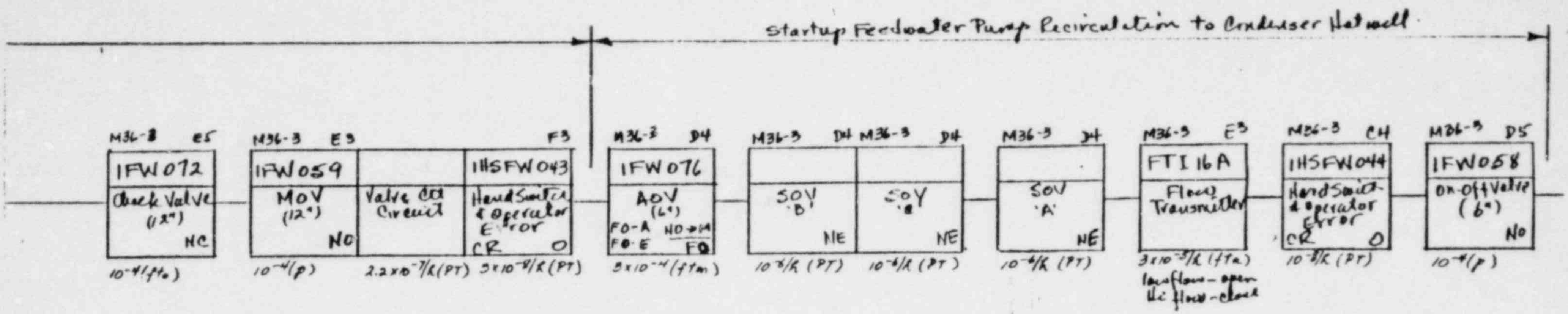
Startup Feedwater Pump, Drive & Valves



B.12

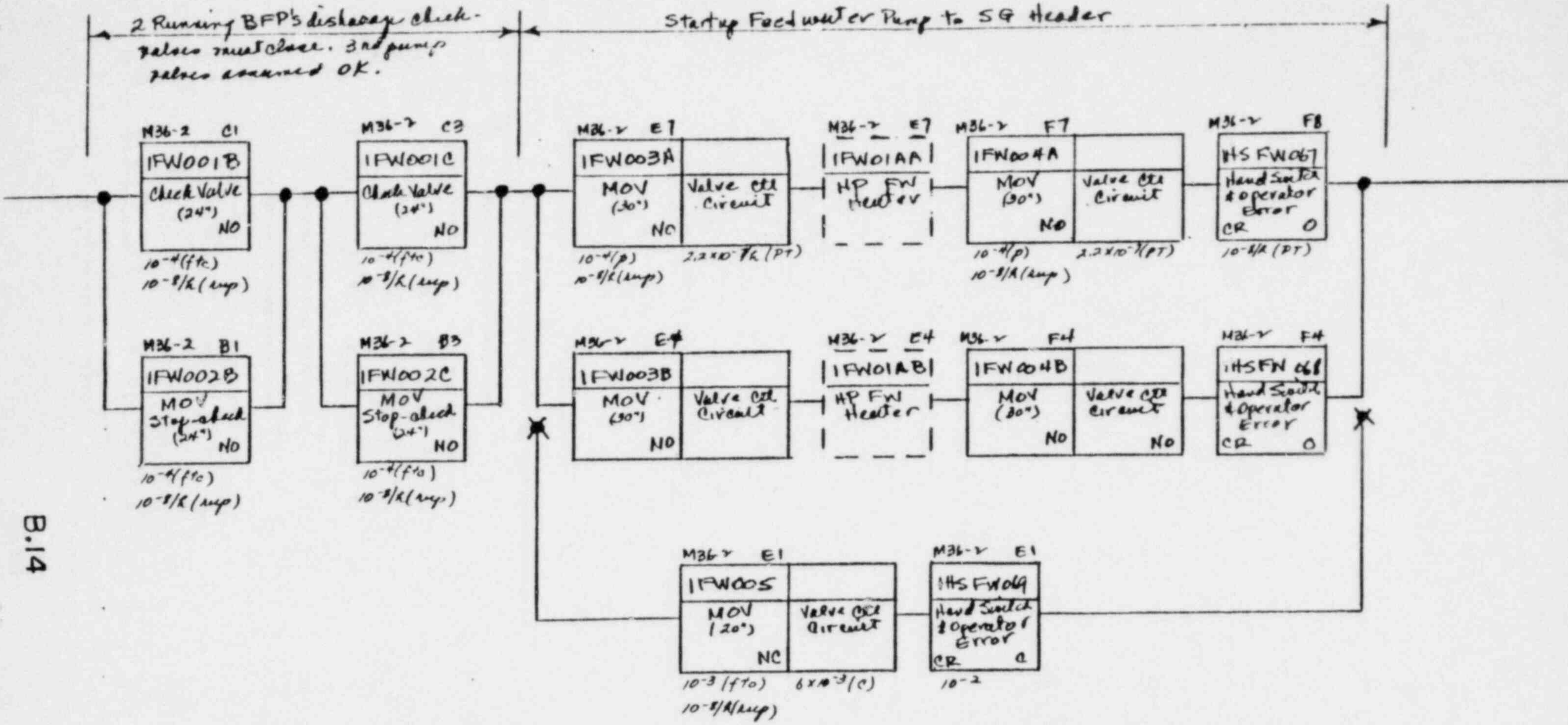
5a

(6a)


Startup Feedwater Pump Recirculation to Condenser Hotwell
M36-3 E5
1FW072
Check Valve (12")
NC
10^-4/(fto)
M36-3 E3
1FW059
MOV (12")
NO
10^-4(p)
Valve Ctl Circuit
2.2x10^-7/R(PT)
F3
1HSFW043
Hand Switch & Operator Error
CR
O
3x10^-8/R(PT)
M36-3 D4
1FW076
AOV (6")
FO-A NO→M
FO-E FO
3x10^-4(ftm)
M36-3 D4
SOV 'B'
NE
10^-6/R(PT)
M36-3 D4
SOV 'B'
NE
10^-6/R(PT)
M36-3 D4
SOV 'A'
NE
10^-6/R(PT)
M36-3 E3
FTI16A
Flow Transmitter
3x10^-5/R(fta)
low flow - open
hi flow - close
M36-3 C4
1HSFW044
Hand Switch & Operator Error
CR
O
10^-8/R(PT)
M36-3 D5
1FW058
On-Off Valve (6")
NO
10^-4(p)

(6a)

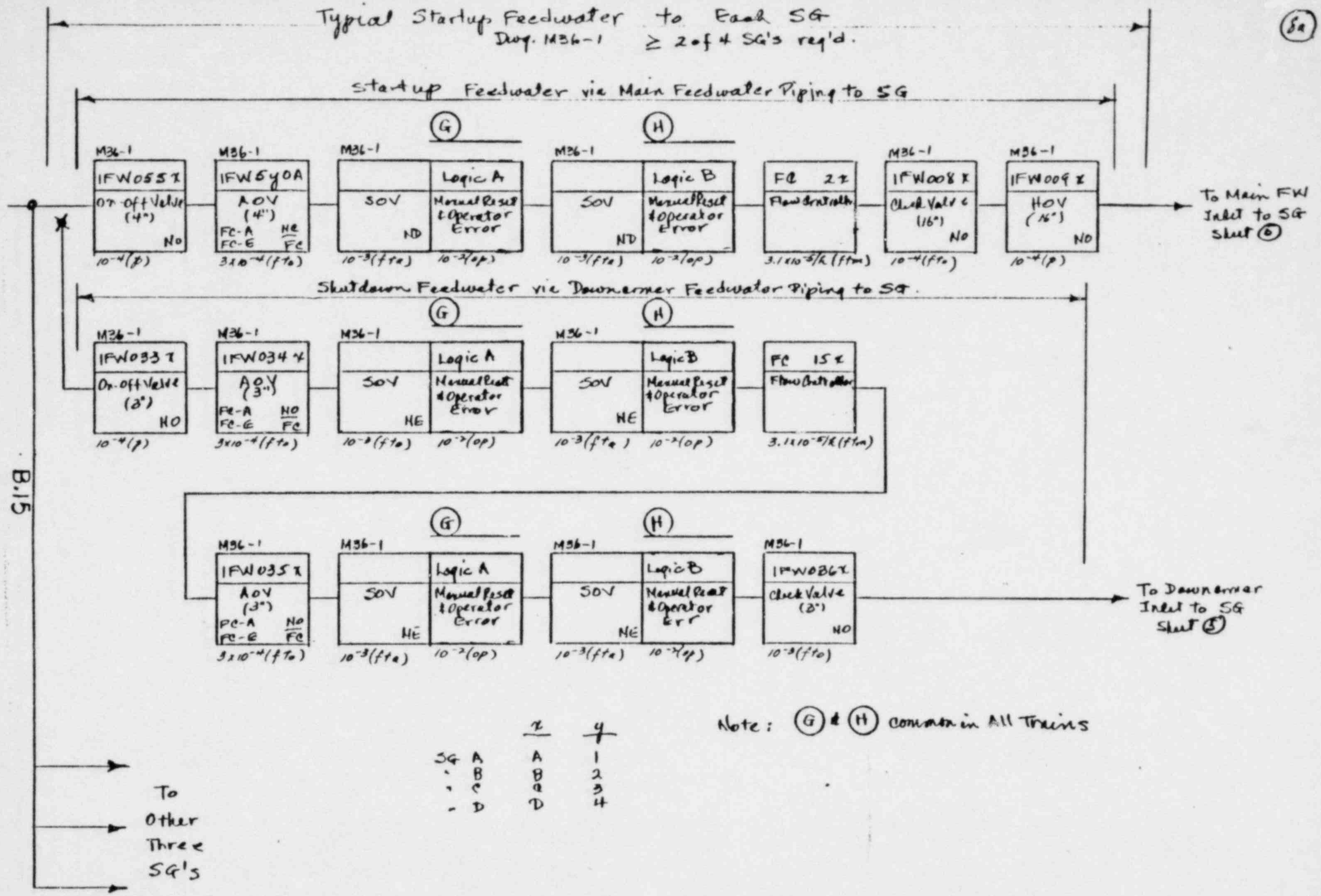
(7a)



2 Running BFP's discharge check-valves must close. 3rd pump valves assumed OK.
Startup Feedwater Pump to SG Header
M36-2 C1
1FW001B
Check Valve
(24")
NO
10^-4(ftc)
10^-8/h(rup)
M36-2 C3
1FW001C
Check Valve
(24")
NO
10^-4(ftc)
10^-8/h(rup)
M36-2 B1
1FW002B
MOV
Stop-check
(24")
NO
10^-4(ftc)
10^-8/h(rup)
M36-2 B3
1FW002C
MOV
Stop-check
(24")
NO
10^-4(ftc)
10^-8/h(rup)
M36-2 E7
1FW003A
MOV
(30")
NO
Valve Ctl Circuit
10^-4(p)
10^-8/h(rup)
2.2x10^-7/h (PT)
M36-2 E7
1FW01AA
HP FW Heater
M36-2 F7
1FW004A
MOV
(30")
NO
Valve Ctl Circuit
10^-4(p)
10^-8/h(rup)
2.2x10^-7/h(PT)
M36-2 F8
1HSFW067
Hand Switch & Operator Error
CR O
10^-8/h (PT)
M36-2 E4
1FW003B
MOV
(30")
NO
Valve Ctl Circuit
M36-2 E4
1FW01AB
HP FW Heater
M36-2 F4
1FW004B
MOV
(30")
NO
Valve Ctl Circuit
NO
M36-2 F4
1HSFW068
Hand Switch & Operator Error
CR O
M36-2 E1
1FW005
MOV
(20")
NC
Valve Ctl Circuit
10^-3 (fto)
10^-8/h(rup)
6x10^-3(c)
M36-2 E1
1HSFW069
Hand Switch & Operator Error
CR C
10^-2

B.14

(7a)

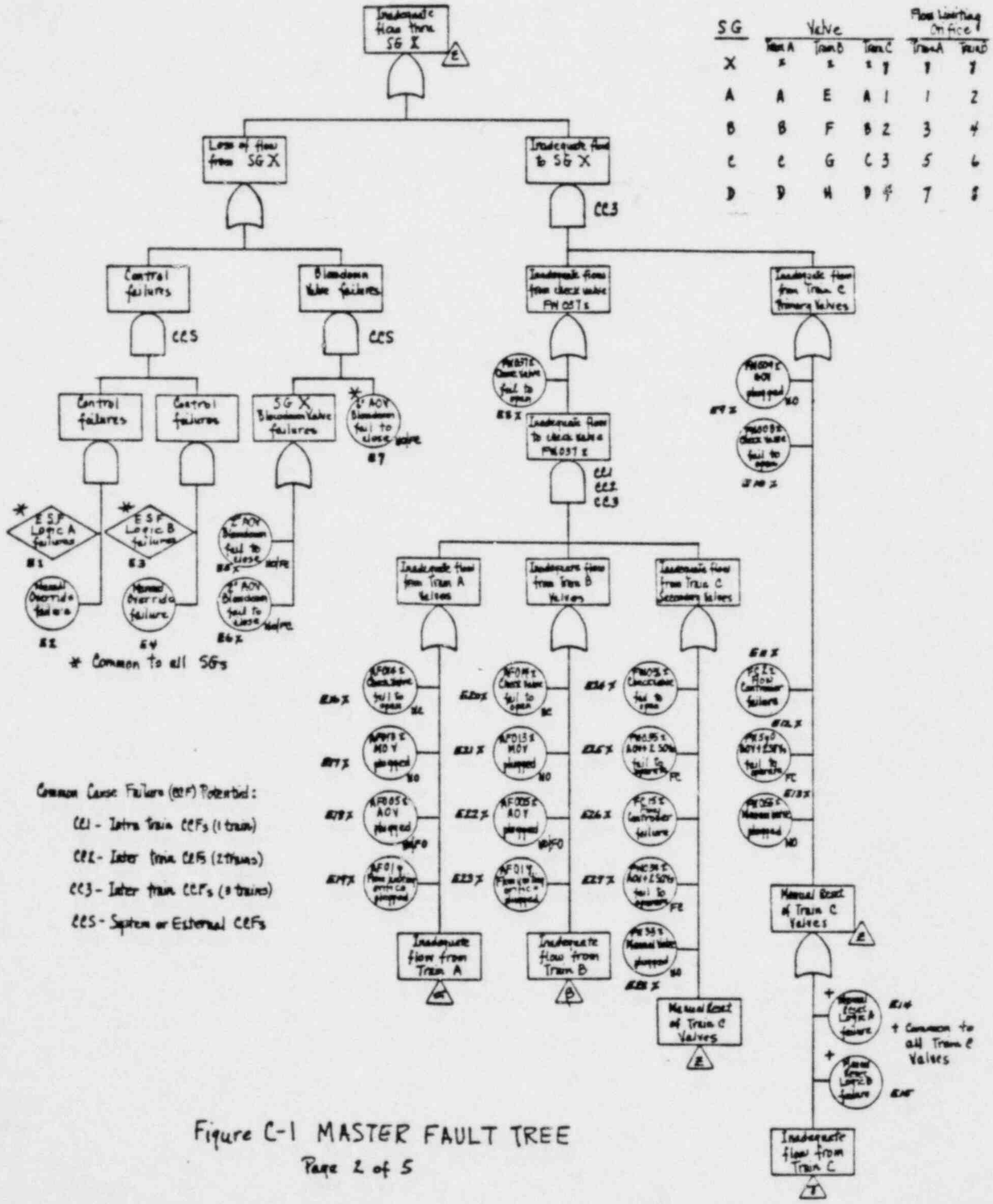


	x	y
SG A	A	1
" B	B	2
" C	C	3
" D	D	4

8a

APPENDIX C

MASTER FAULT TREE



SG	Valve Train A	Valve Train B	Valve Train C		Flow Limiting Orifice Train A	Flow Limiting Orifice Train B	FW037x Check Valve
X	x	x	x	y	y	y	x
A	A	E	A	1	1	2	A
B	B	F	B	2	3	4	B
C	C	G	C	3	5	6	C
D	D	H	D	4	7	8	D

Common Cause Failure (CCF) Potential:

CC1 - Intra train CCFs (1 train)

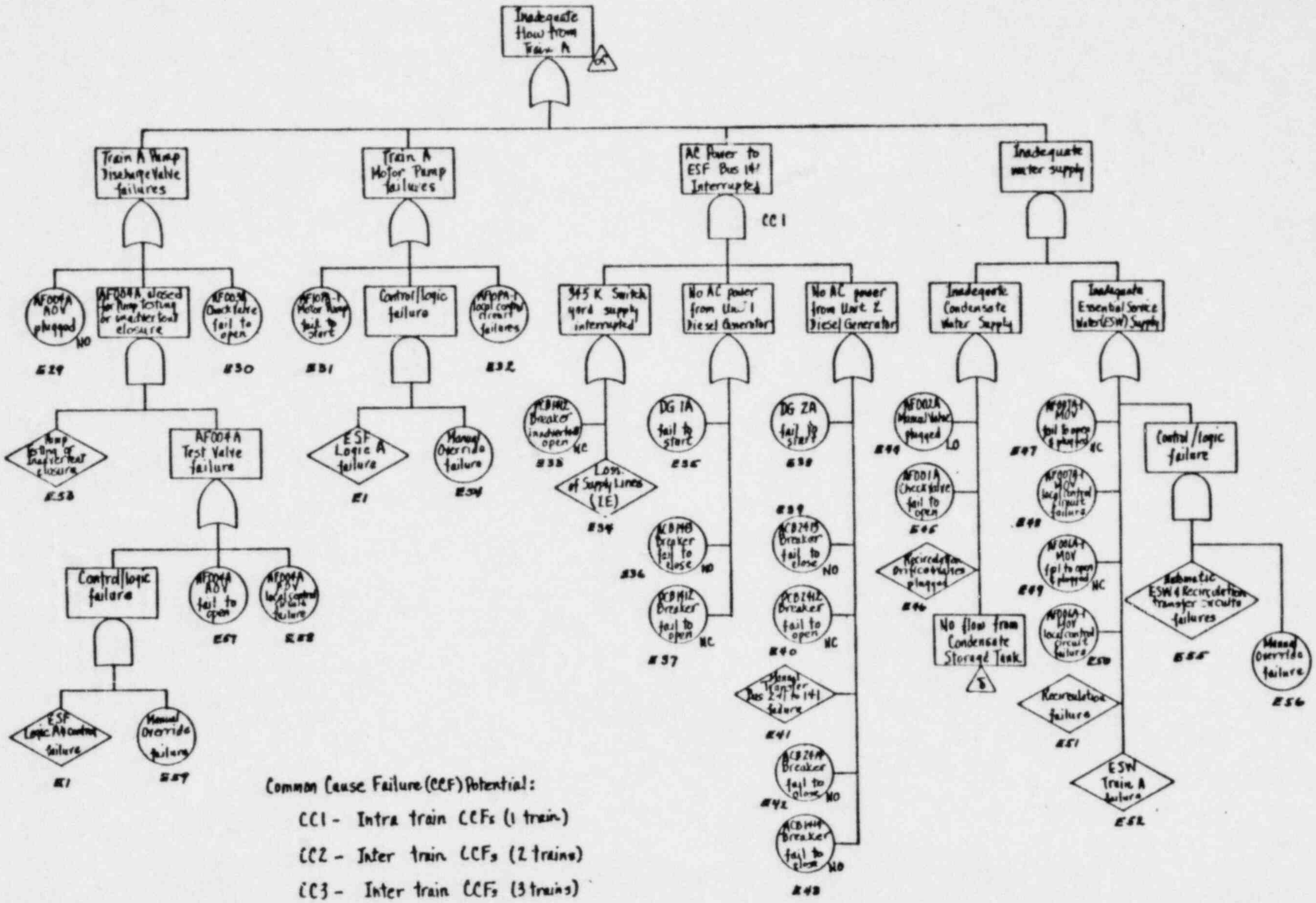
CC2 - Inter train CCFs (2 trains)

CC3 - Inter train CCFs (3 trains)

CCS - System or External CCFs

Figure C-1 MASTER FAULT TREE

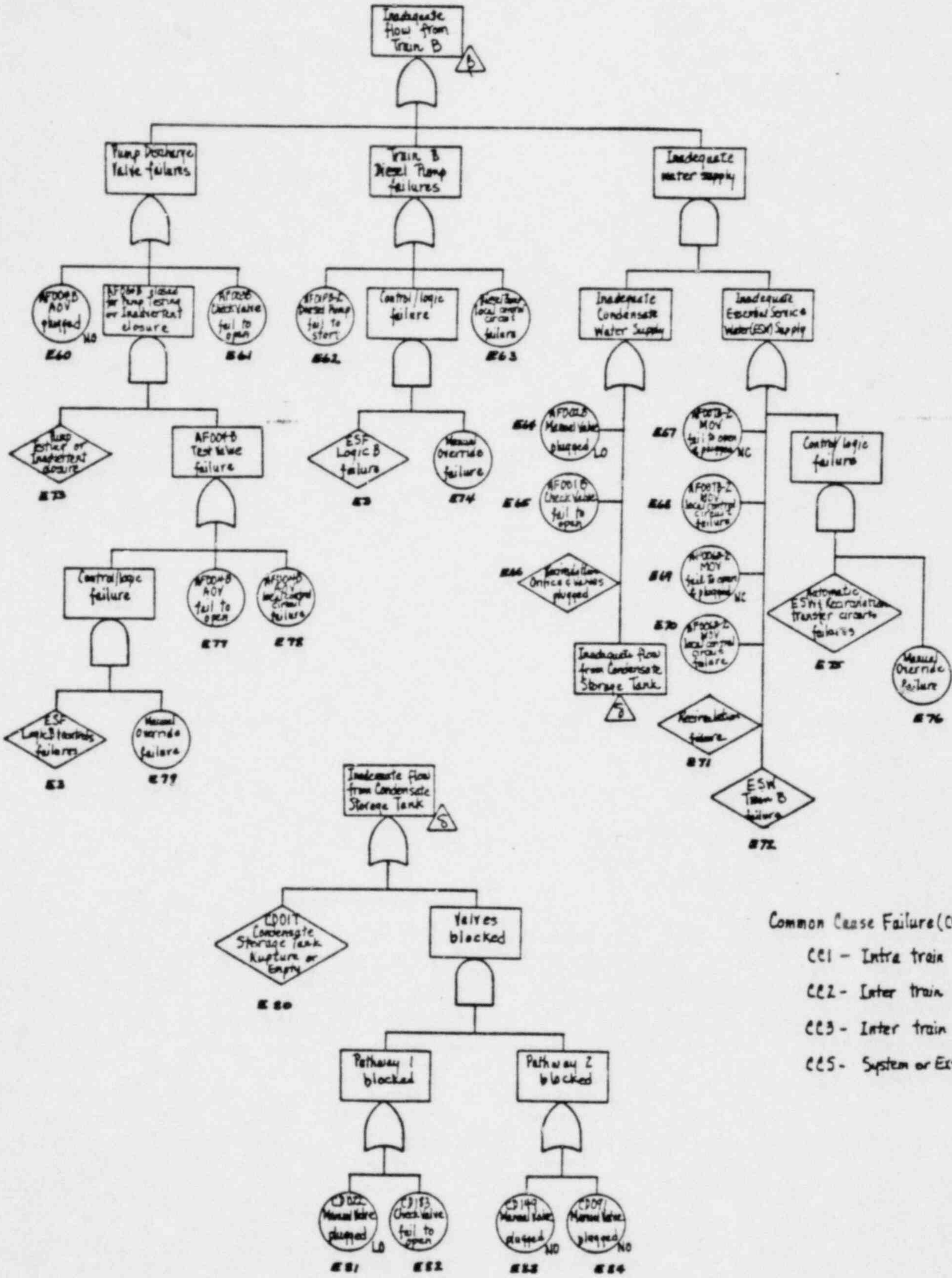
Page 2 of 5



Common Cause Failure (CCF) Potential:

- CC1 - Intra train CCFs (1 train)
- CC2 - Inter train CCFs (2 trains)
- CC3 - Inter train CCFs (3 trains)
- CCS - System or External CCFs

Figure C-1 MASTER FAULT TREE Page 3 of 5



Common Cause Failure (CCF) Potential:

- CC1 – Intra train CCFs (1 train)
- CC2 – Inter train CCFs (2 trains)
- CC3 – Inter train CCFs (3 trains)
- CC5 – System or External CCFs

Figure C-1 MASTER FAULT TREE Page 4 of 5

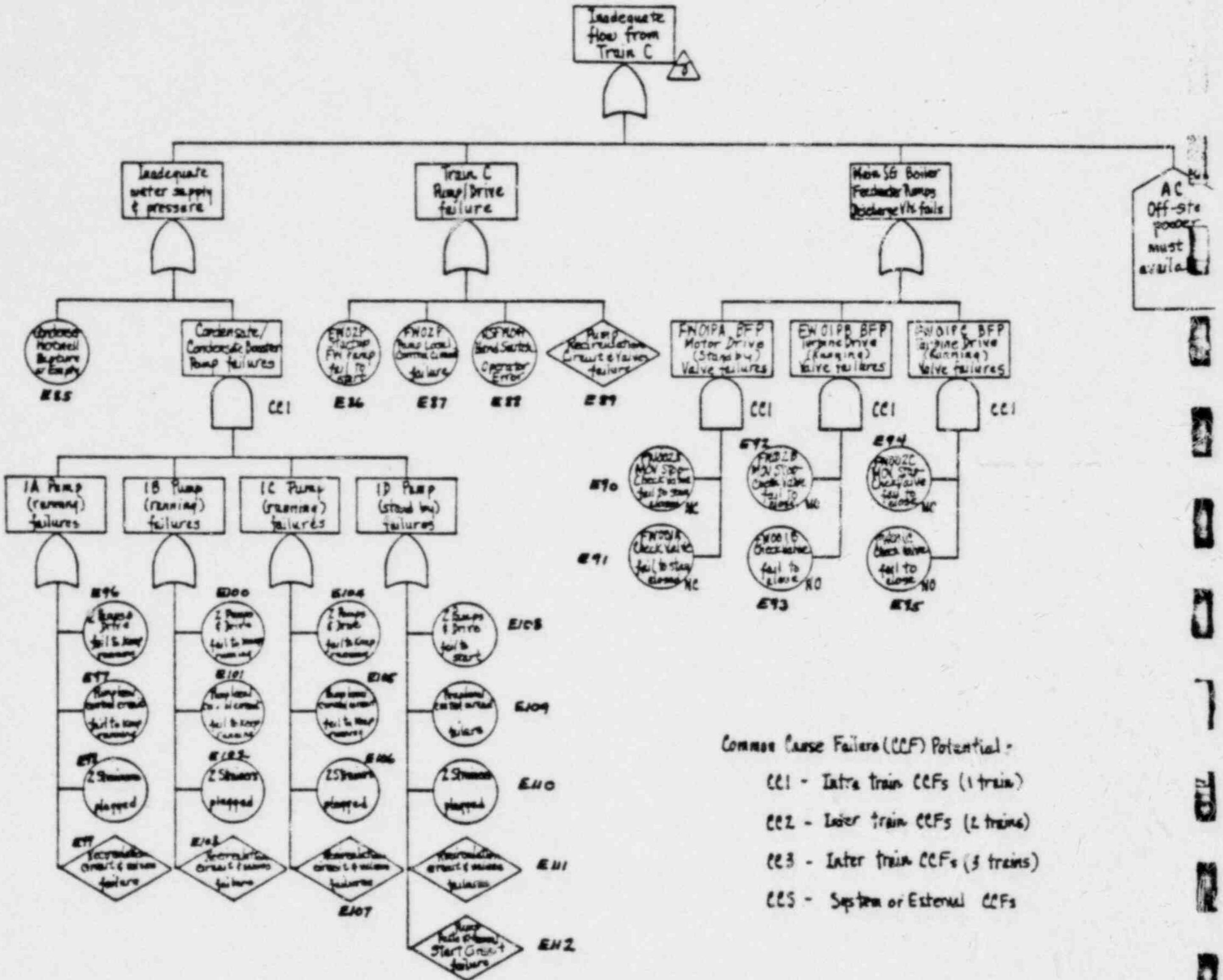
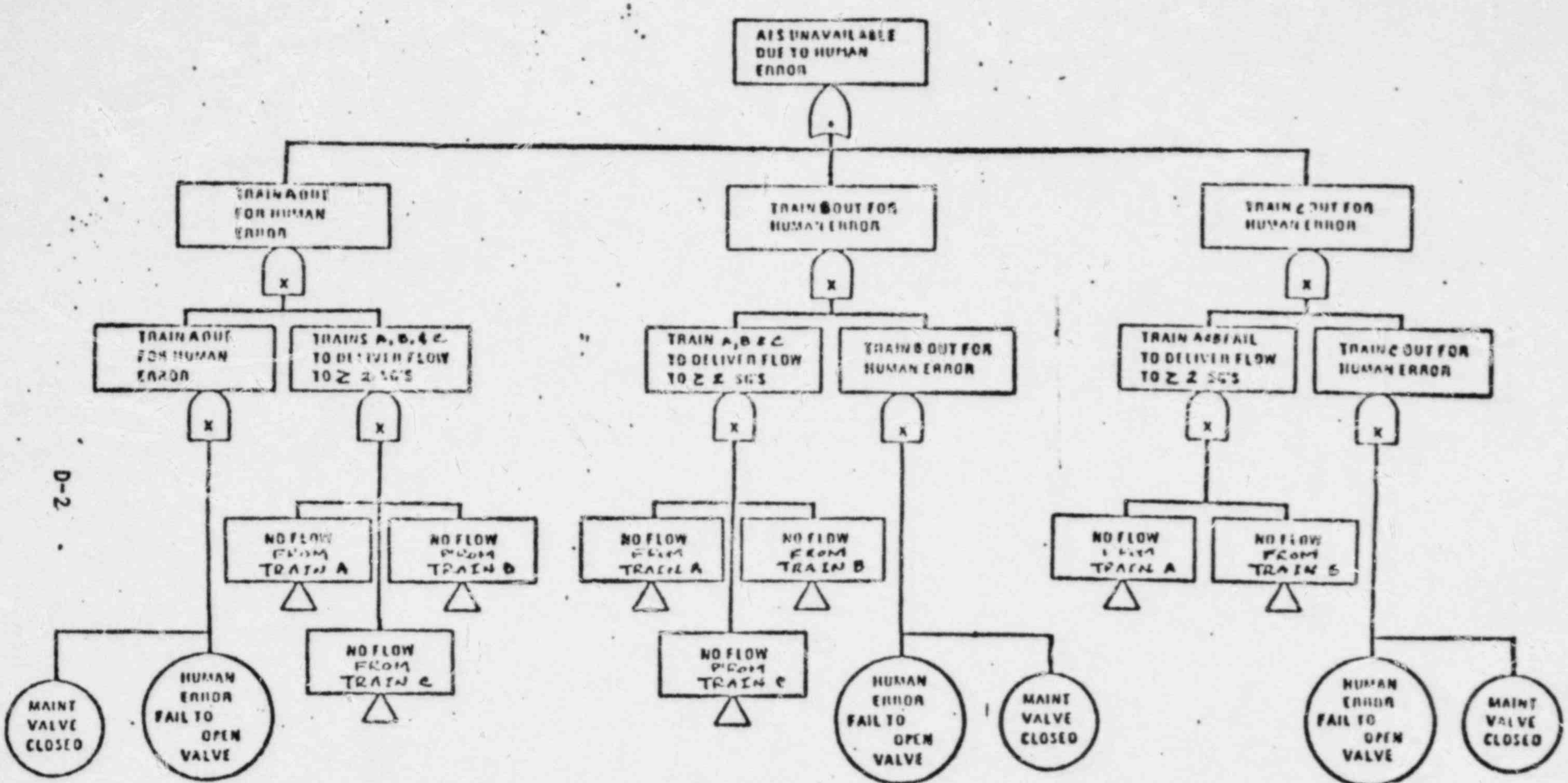


Figure C-1 MASTER FAULT TREE Page 5 of 5

APPENDIX D

HUMAN ERROR FAULT TREE



* Pump (mechanical) fail to start

Fig. D-1 HUMAN ERROR FAULT TREE

APPENDIX E

TESTING AND MAINTENANCE FAULT TREES

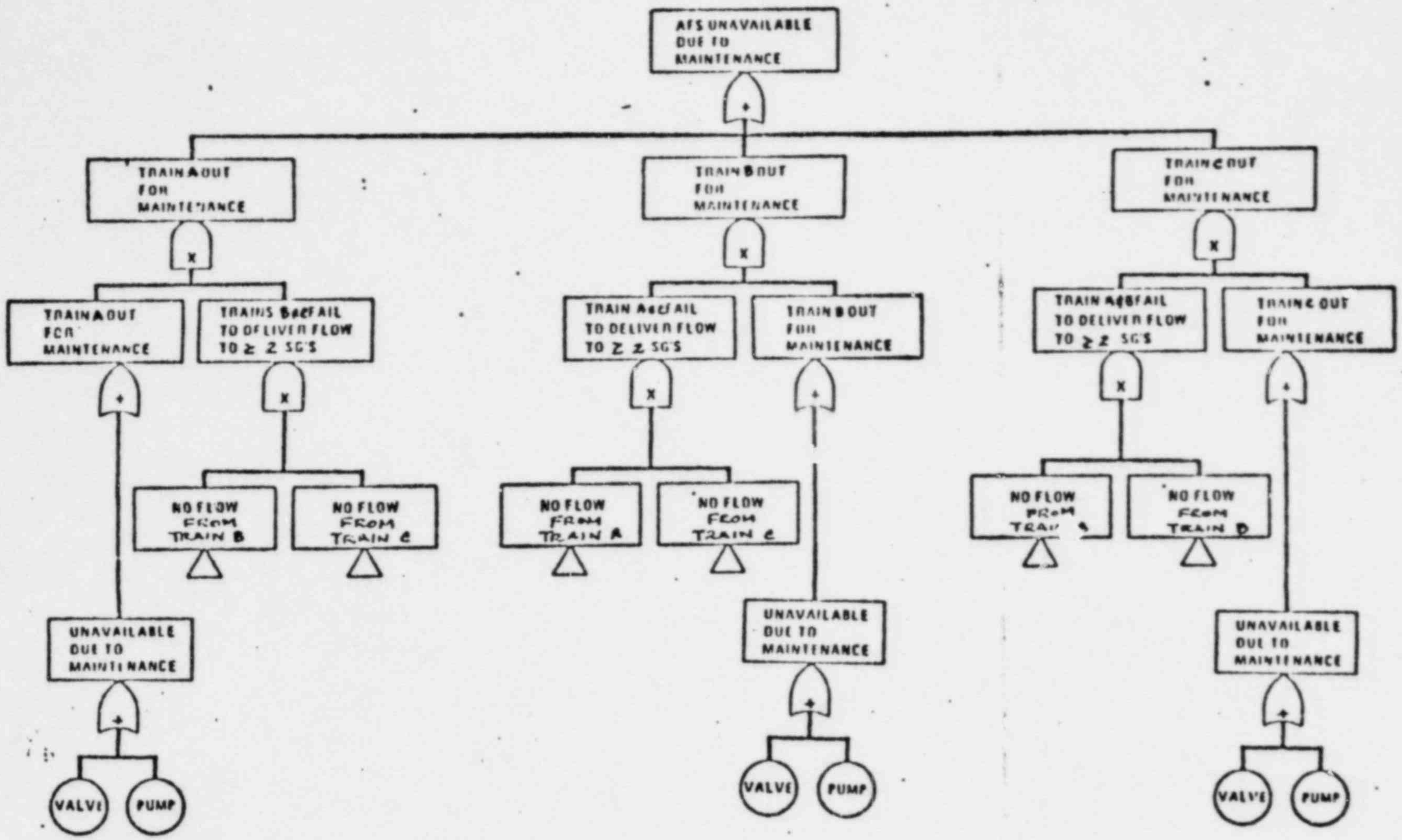
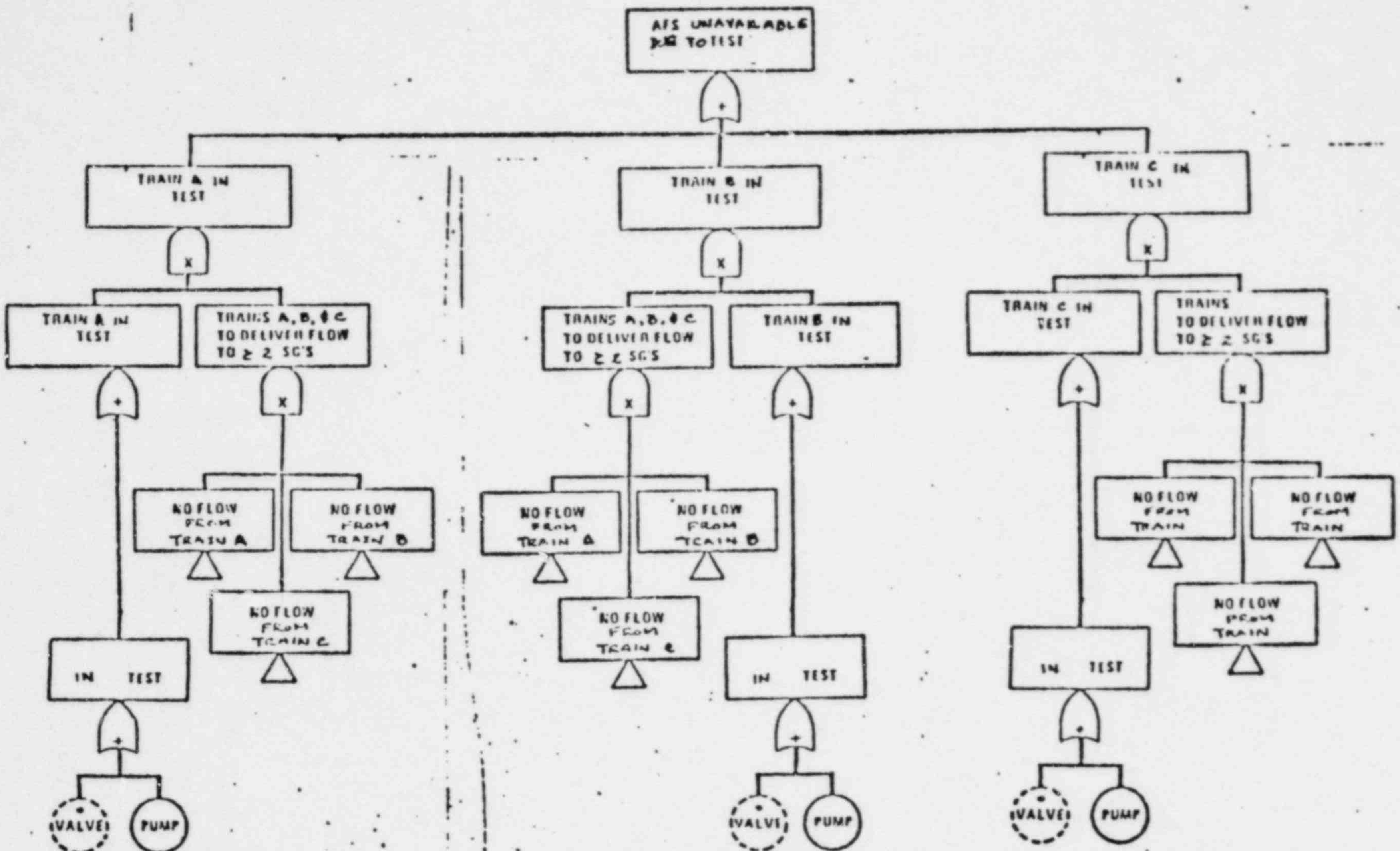


Fig. E-1 Maintenance Fault Tree



*VALVES WERE CONSIDERED BUT HAD NO IMPACT DUE TO TESTING DURING SHUTDOWN.

Fig. E-2 Test Fault Tree

APPENDIX F

COMMON CAUSE FAILURES
Hardware, Test and Maintenance, Human Errors

APPENDIX F

COMMON CAUSE FAILURES,
Hardware, Test and Maintenance, Human Errors

F. <u>Common Cause Hardware, Test and Maintenance and Human Error Analysis</u>

Common cause analysis was performed both qualitatively and quantitatively, qualitatively to identify potential sources of common cause failures and quantitatively to indicate the limited effect that increased redundancy can have on the reliability of a system.

Qualitative Analysis - The identification of common or similar hardware, test, maintenance, human actions or physical links between redundant trains was the first step in this analysis. Based on the logic modeling (RBDs and FTs) the experience with other similar systems which use redundancy, the testing and maintenance plans, the operator interactions, the power supplies and service systems, the AFS Trains A and B can be classified as partly diverse as shown in Figure F.1, Train C is almost fully diverse from A and B. The major dependencies from the hardware viewpoint have been accounted for by considering the different initiating events which impact the power supplies for each train. The hardware dependencies are mostly outside the AFS components. These include check valves and blowdown valves on the steam generators.

As a final qualitative check, the potential for common cause failures as discussed in reference 6 were reviewed and are addressed below. Reference 6, listed seven "common cause" failures that occurred in 1975 AFS experience. These failures are discussed below as to the effect if they were to occur in Byron/Braidwood AFS:

A. Operator failed to open the valve from the condensate storage tank to the Train A and B pumps. The two AFS pump loops failed to be available on demand as required by technical specifications. Docket 50317-516.

   This failure indicates that a "single" valve provided condensate to the Train A and B AFS pumps. This appears to be a "single" failure point. The Byron /Braidwood AFS has separate supply lines and valves to each of the AFS pumps. Thus, a single valve closure will not cause AFS failure. Only a common cause failure, that of a multiple redundant inadvertant valve closure, will simulate this condition in the Byron/Braidwood AFS Train A and B design. In the Byron/Braidwood design Train C comes from an independent source of condensate. Also, the Essential Service Water (ESW) System can "automatically" supply water to Trains A and B should be condensate supply be unavailable.

B. Filters (in parallel) on suction side of three pumps plugged up with foreign material which restricted flow. Docket 50305-354.

   Byron/Braidwood AFS pumps have startup suction filters. Train A and B pumps have full flow test procedures that will detect any restricted flow including valve plugging.

C. Condensate storage tank water level was intentionally drawn down below technical specification limits to maintain maximum steam generator blowdown. Failure to maintain water supply to multiple AFS pumps within specifications. Docket 50315-340.

Byron/Braidwood condensate storage tank for Trains A and B maintain a maximum of 500,000 gallons and, when the volume decreases to 200,000 gallons, the refill system can provide makeup water. The AFS requirement is 200,000 gallons. In addition, the other unit condensate storage tank with a maximum capacity of 500,000 gallons can be manually transferred to the AFS. A backup water supply is also automatically available from the essential service water system.

D. Condensate storage tank water level was intentionally drawn down below technical specification limits because makeup water supply was dirty (high oxygen content). Failure to maintain water supply to multiple AFWS pumps with specifications. Docket 50247-449.

In the B/B design the multiple supplies of water reduce dependence on any one supply.

E. Two AFS pumps failed to start because of defective contol switches which failed to close contacts. Docket 50305-350.

This could happen in any AFS. Since the Train B pump is an automatically initiated diesel drive, the Train A pump is an automatically started electric drive, and Train C is a manually started electric drive; the control switching has elements of diversity. Thus, all AFS failure requires independent failures in diverse systems. Common switches and breakers in the 2 out of 4 Auxiliary Feedwater Actuation logic for Trains A and B appear to have the greatest potential for a common cause failure. Manual override of the logic can minimize this potential common cause failure in the Byron/Braidwood designs.

F. A breaker accidentally opened and interrupted power to the turbine overspeed protection (which tripped the reactor), and also interrupted power to an AFS lube oil pump preventing start of the related AFS pump. Docket 50305-361.

The Byron/Braidwood AFS lube oil pump is a direct mechanical drive from the diesel driven feed pump. Thus, this failure mode should have no effect on the Byron/Braidwood AFS reliability.

G. Two AFS valves were upgraded during the licensing process and were not seismically qualified because of oversight. Docket 50289-491.

All safety related valves on the Byron/Braidwood AFS are seismically qualified.

Quantitative Analysis - The method known as the Beta Factor Method of Reference 9 was used to quantitatively estimate the effect of common cause failures. Simply stated, the Beta factor method assumes that a fraction of the operationally independent failure probabilities of one loop of a redundant

system will result in the loss of all the redundant loops in that system. The hand calculations based on the point estimate uses a generic Beta Factor of = 3×10^{-2} for inter train redundancies. This Beta Factor is a median value based on an assumed range of 10^{-1} to 10^{-3}. An intra train Beta Factor of 0.1 was also used. The common cause failure probability, Q_{cc}, for a redundant system can be approximated by the failure probability of one loop of a redundant system, Q_{loop}, times . The total failure rate is the sum of the common cause failure contributions added to the independent failures in redundant Trains. Contributions to the Beta factor include human error, manufacturing, design, maintenance, testing, quality assurance, and external events.

The equations used to calculate the failure probability on demand were developed for each "AND" gate in the fault tree. The system failure probability Q_f is determined from the following formulation:

$$Q_f = Q_{independent\ failures} + Q_{common\ cause\ failures} = Q_{if} + Q_{ccf}$$

$$Q_f \quad (Q_1(1-\beta) \times Q_2(1-\beta) \times \ldots Q_n(1-\beta)) + \beta \left(\frac{Q_1 + Q_2 + \ldots Q_n}{n}\right),$$

where n is the number of redundant Trains

$$Q_{independent\ failure} = (Q_1(1-\beta) \times (Q_2(1-\beta) \times \ldots Q_n(1-\beta)) + \text{other component failures}$$

$$Q_{ccf} = \beta_a \left(\frac{Q_{a1} + Q_{a2} + \ldots Q_{an}}{n}\right) + \beta_b \left(\frac{Q_{b1} + Q_{b2} + \ldots Q_{bn}}{n}\right) + \ldots .$$

$$\beta_j \left(\frac{Q_{j1} + Q_{j2} + \ldots Q_{jn}}{n}\right)$$

where a, b ... j are the common mode contributions from each redundant system within the system fault tree.

Since $\beta = 0.1$ and 0.03 the contribution of $(1-\beta)$ in the $Q_{independent}$ failure probability has only a small impact on the numerical estimate and therefore only slightly decreases the independent estimate.

For this analysis, the following assumptions were made:

1. The valves, ESF signal with manual override, electric pump and human error were redundant and were considered with the common cause Beta factor.

2. The diesel drive and electric drive pump were diverse and thus subject to very low common cause Beta factor.

3. The major ultra-train and inter-train common cause failures were considered separately for the three initiating events.

The common cause failure probability contributions to the AFS were calculated with the FT analysis code per inputs of Table A.IV and added to the independent failure probabilities. The results are shown in Sections 2 and 4.

System Design	Impact on Reliability	
The simplest form of system is a single channel arrangement which will have a lower limit of probability of failure of approximately 10^{-2}. By introducing redundancy into	the system to improve the reliability performance due to random independent failures the CMF problem becomes apparent, and limits the improvement	SINGLE CHANNEL SYSTEM
A system which has redundancy of its input channels only, might have a failure probability in a range from $5\ 10^{-3}$ to 10^{-3}. The inference of this arrangement is that the most significant contributors to failure	probability are the components of the input measuring system, although the redundancy might also be extended to the other sub-systems to make some further reduction of failure probability possible	REDUNDANT SYSTEM
The logical development in the quest for greater system reliability is to reduce the CMF failure probability by introducing diversity into those parts of the system where identical redundancy has been previously considered as above. A typical system arrangement has functionally diverse measurements of two plant parameters, each of which is capable of initiating the	required action and each of which has identical redundancy applied. A variation is to provide inter-connections between channels, but the intended improvement of system reliability due to random independent failures could be nullified by CMF possibilities that are introduced. Such a system would be capable of a failure probability in a range from 10^{-3} down to approximately 10^{-4}	PARTLY DIVERSE SYSTEM
For further reduction of system failure probability the independence of functionally diverse input measurements must be enhanced by applying equipment diversity and eliminating channel interconnections. Systems have therefore been evolved to give failure	probabilities in a range from 10^{-3} to less than 10^{-4}. A common further development of this basic form is to include identical redundancy within each of the diverse sub-systems	FULLY DIVERSE SYSTEM
The final stage in the evolution of redundancy system arrangement is to provide two separate and diverse output sub-systems such that they can each be operated by diverse input and intermediate sub-systems. These are therefore completely diverse and separate systems	throughout, and might be expected to have failure probabilities in a range from 10^{-4} down to 10^{-6}. It is unlikely that for practical reasons, more than twofold diversity can be applied to each sub-system, as indicated on the diagram.	TWO DIVERSE SYSTEMS

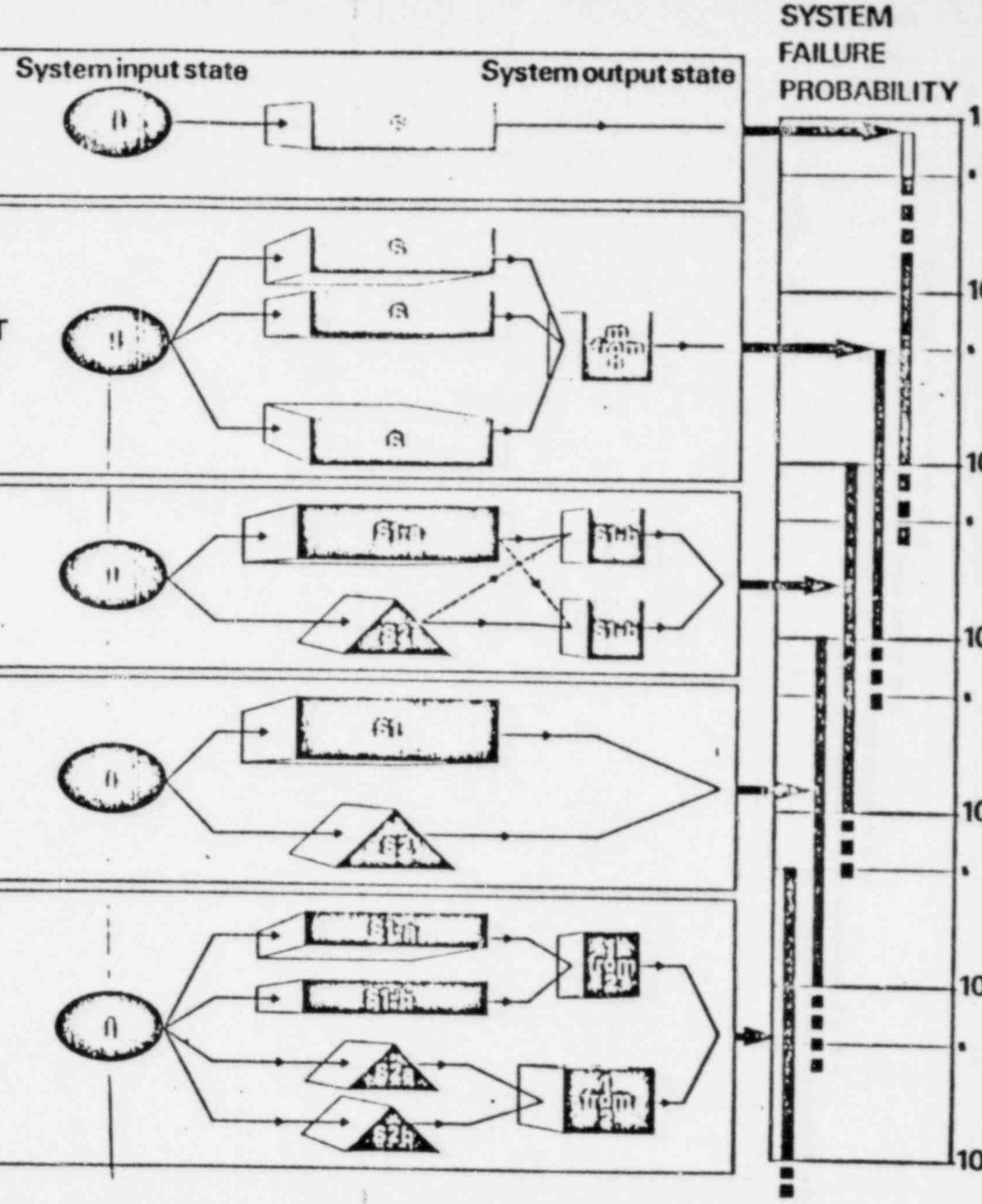


Table F.1 A Guide for Assessing the Impact of Common Mode Failures on System Reliability (Ref. 13)

APPENDIX G

FAULT TREE ANALYSIS USING MOCUS AND STADIC

APPENDIX G

G. Fault Tree Analysis Using MOCUS and STADIC

Fault tree analysis is particularly useful in providing a schematic view of how the failures of primary events could lead to the failure of the top event. In this particular study, the top event is the failure to supply sufficient auxiliary feedwater to two of four steam generators within 20 minutes of a LMFW, LMFW/LOOP, LMFW/LOAC events. To calculate the probabilities of these events, one can assign numerical probability values to the primary events in order to quantify the probability of faiure of the defined event.

The analysis consists of two basic steps. First, the minimal cut sets from the fault tree are determined. This is easily done with the MOCUS code (Ref. 10). An example of the cut sets determined using MOCUS is shown in Table G-1. To reduce computer time for obtaining the minimal cut sets, the master fault tree shown in Fig. C-1 was divided into independent subtrees. Separate MOCUS runs were performed to determine minimal cut sets for these subtrees. The results were then combined manually following the Boolean Algebra logic. Thus, any event starting with A, shown in the list of cut sets, represents a set of minimal cut sets having one or more basic events (i.e., all events starting with E). These cut sets represent those events which could lead to the failure of three out of four steam generators to receive water and consequently, lead to the top event. From these cut sets one can formulate mathematical expressions which define the probability of the top event. The available failure rate data for the primary events have some degree of uncertainty and this should be accounted for in the quantification process. The STADIC code (Ref. 11) provides a fast and efficient method of doing this.

STADIC uses a Monte Carlo simulation technique to generate a pseudo-random sample statistical distribution for a user-defined output function. For example, in this study, one output function is the probability of the top event given the loss of main feedwater. The independent variables for this output function are the failure frequency rates of each primary event found in the minimal cut sets. Each variable exhibits random statistical variations represented by a particular probability distribution. STADIC generates a statistical distribution for the output function by selecting at random, values for each of the independent variables according to their assigned probability distributions and combining these distributions in accordance with the mathematical operations specified by the output function. A second set of randomly selected values for the independent variables is then chosen and a second evaluation of the function is made. This process is repeated several thousand times on the computer. The resulting values for the output function are then sorted and arranged in increasing order of magnitude. Confidence limits of the output distribution may then be determined directly from the ordered array. As an illustration of the method, we have in Tables G-2 and G-3 a list of equations defining the relationship of basic events which lead to the top event.

In the fault tree quantification using STADIC, only those dominant events (in terms of high failure probability values) were considered. Thus, if one looks at the equations developed for the LMFW initiating event (Table G-2, not all the events found in the list of minimal cut sets (Table G-1) are represented.

Table G-1 - Minimal Cut Sets for LMFW Initiating Event

MOCUS - - VERSION 3/78

MINIMAL CUT SETS FOR GATE G2 = HARDWARE / OPERATOR ERROR FAILURES

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

NONE EXIST.

CUT SETS WITH 3 COMPONENTS

1)	A12A	A12B	A12C
2)	A12A	A12B	A12D
3)	A12A	A12C	A12D
4)	A12B	A12C	A12D

CUT SETS WITH 4 COMPONENTS

1)	E5A	E5B	E5C	E7
2)	E5A	E5B	E5D	E7
3)	E5A	E5C	E5D	E7
4)	E5B	E5C	E5D	E7
5)	E1	E3	E2	E4
6)	A12A	E5B	E5C	E7
7)	E6A	E5B	E5C	E7
8)	A12A	E5B	E5D	E7
9)	E6A	E5B	E5D	E7
10)	A12A	E5C	E5D	E7
11)	E6A	E5C	E5D	E7
12)	A12B	E5C	E5D	E7
13)	E6B	E5C	E5D	E7
14)	E5A	A12B	E5C	E7
15)	E5A	E6B	E5C	E7
16)	E5A	A12B	E5D	E7
17)	E5A	E6B	E5D	E7
18)	E5A	A12C	E5D	E7
19)	E5A	E6C	E5D	E7
20)	E5B	A12C	E5D	E7
21)	E5B	E6C	E5D	E7
22)	A12A	A12B	E5C	E7
23)	A12A	E6B	E5C	E7

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 4 COMPONENTS

24)	E6A	A12B	E5C	E7
25)	E6A	E6B	E5C	E7
26)	A12A	A12B	E5D	E7
27)	A12A	E6B	E5D	E7
28)	E6A	A12B	E5D	E7
29)	E6A	E6B	E5D	E7
30)	A12A	A12C	E5D	E7
31)	A12A	E6C	E5D	E7
32)	E6A	A12C	E5D	E7
33)	E6A	E6C	E5D	E7
34)	A12B	A12C	E5D	E7
35)	A12B	E6C	E5D	E7
36)	E6B	A12C	E5D	E7
37)	E6B	E6C	E5D	E7
38)	E5A	E5B	A12C	E7
39)	E5A	E5B	E6C	E7
40)	E5A	E5B	A12D	E7
41)	E5A	E5B	E6D	E7
42)	E5A	E5C	A12D	E7
43)	E5A	E5C	E6D	E7
44)	E5B	E5C	A12D	E7
45)	E5B	E5C	E6D	E7
46)	A12A	E5B	A12C	E7
47)	A12A	E5B	E6C	E7
48)	E6A	E5B	A12C	E7
49)	E6A	E5B	E6C	E7
50)	A12A	E5B	A12D	E7
51)	A12A	E5B	E6D	E7
52)	E6A	E5B	A12D	E7
53)	E6A	E5B	E6D	E7
54)	A12A	E5C	A12D	E7
55)	A12A	E5C	E6D	E7
56)	E6A	E5C	A12D	E7
57)	E6A	E5C	E6D	E7
58)	A12B	E5C	A12D	E7
59)	A12B	E5C	E6D	E7
60)	E6B	E5C	A12D	E7
61)	E6B	E5C	E6D	E7
62)	E5A	A12B	A12C	E7
63)	E5A	A12B	E6C	E7
64)	E5A	E6B	A12C	E7
65)	E5A	E6B	E6C	E7
66)	E5A	A12B	A12D	E7
67)	E5A	A12B	E6D	E7
68)	E5A	E6B	A12D	E7
69)	E5A	E6B	E6D	E7
70)	E5A	A12C	A12D	E7
71)	E5A	A12C	E6D	E7
72)	E5A	E6C	A12D	E7
73)	E5A	E6C	E6D	E7
74)	E5B	A12C	A12D	E7
75)	E5B	A12C	E6D	E7
76)	E5B	E6C	A12D	E7
77)	E5B	E6C	E6D	E7

Table G-1 (cont.)

7B1	A12A	A12B	E6C	E7

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 4 COMPONENTS

79)	A12A	E6B	A12C	E7
80)	A12A	E6B	E6C	E7
81)	E6A	A12B	A12C	E7
82)	E6A	A12B	E6C	E7
83)	E6A	E6B	A12C	E7
84)	E6A	E6B	E6C	E7
85)	A12A	A12B	E6D	E7
86)	A12A	E6B	A12D	E7
87)	A12A	E6B	E6D	E7
88)	E6A	A12B	A12D	E7
89)	E6A	A12B	E6D	E7
90)	E6A	E6B	A12D	E7
91)	E6A	E6B	E6D	E7
92)	A12A	A12C	E6D	E7
93)	A12A	E6C	A12D	E7
94)	A12A	E6C	E6D	E7
95)	E6A	A12C	A12D	E7
96)	E6A	A12C	E6D	E7
97)	E6A	E6C	A12D	E7
98)	E6A	E6C	E6D	E7
99)	A12B	A12C	E6D	E7
100)	A12B	E6C	A12D	E7
101)	A12B	E6C	E6D	E7
102)	E6B	A12C	A12D	E7
103)	E6B	A12C	E6D	E7
104)	E6B	E6C	A12D	E7
105)	E6B	E6C	E6D	E7

TOTAL NUMBER OF CUT SETS FOUND WAS 109
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G12A = A12A

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

1)	E8A	E9A
2)	E8A	E10A
3)	E8A	E11A
4)	E8A	E12A
5)	E8A	E13A
6)	E8A	A26

CUT SETS WITH 3 COMPONENTS

1)	A26	A21A	A22A

CUT SETS WITH 4 COMPONENTS

1)	E24A	E9A	A21A	A22A
2)	E25A	E9A	A21A	A22A
3)	E26A	E9A	A21A	A22A
4)	E27A	E9A	A21A	A22A
5)	E28A	E9A	A21A	A22A
6)	E24A	E10A	A21A	A22A
7)	E24A	E11A	A21A	A22A
8)	E24A	E12A	A21A	A22A
9)	E24A	E13A	A21A	A22A
10)	E25A	E10A	A21A	A22A
11)	E25A	E11A	A21A	A22A
12)	E25A	E12A	A21A	A22A
13)	E25A	E13A	A21A	A22A
14)	E26A	E10A	A21A	A22A
15)	E26A	E11A	A21A	A22A
16)	E26A	E12A	A21A	A22A
17)	E26A	E13A	A21A	A22A
18)	E27A	E10A	A21A	A22A
19)	E27A	E11A	A21A	A22A
20)	E27A	E12A	A21A	A22A
21)	E27A	E13A	A21A	A22A
22)	E28A	E10A	A21A	A22A
23)	E28A	E11A	A21A	A22A

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 4 COMPONENTS

24)	E28A	E12A	A21A	A22A
25)	E29A	E13A	A21A	A22A

TOTAL NUMBER OF CUT SETS FOUND WAS 32
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MINIMAL CUT SETS FOR GATE G12B = A/2/3

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

1)	E8B	E9B
2)	E8B	E10B
3)	E8B	E11B
4)	E8B	E12B
5)	E8B	E13B
6)	E8B	A26

CUT SETS WITH 3 COMPONENTS

1)	A26	A21B	A22B

CUT SETS WITH 4 COMPONENTS

1)	E24B	E9B	A21B	A22B
2)	E25B	E9B	A21B	A22B
3)	E26B	E9B	A21B	A22B
4)	E27B	E9B	A21B	A22B
5)	E28B	E9B	A21B	A22B
6)	E24B	E10B	A21B	A22B
7)	E24B	E11B	A21B	A22B
8)	E24B	E12B	A21B	A22B
9)	E24B	E13B	A21B	A22B
10)	E25B	E10B	A21B	A22B
11)	E25B	E11B	A21B	A22B
12)	E25B	E12B	A21B	A22B
13)	E25B	E13B	A21B	A22B
14)	E26B	E10B	A21B	A22B
15)	E26B	E11B	A21B	A22B
16)	E26B	E12B	A21B	A22B
17)	E26B	E13B	A21B	A22B
18)	E27B	E10B	A21B	A22B
19)	E27B	E11B	A21B	A22B
20)	E27B	E12B	A21B	A22B
21)	E27B	E13B	A21B	A22B
22)	E28B	E10B	A21B	A22B
23)	E28B	E11B	A21B	A22B
24)	E28B	E12B	A21B	A22B
25)	E28B	E13B	A21B	A22B

TOTAL NUMBER OF CUT SETS FOUND WAS 32
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

MOCUS - - VERSION 3/74

****

MINIMAL CUT SETS FOR GATE G12C = A12C

****

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

1)	E8C	E9C
2)	E8C	E10C
3)	E8C	E11C
4)	E8C	E12C
5)	E8C	E13C
6)	E8C	A26

CUT SETS WITH 3 COMPONENTS

1)	A26	A21C	A22C

CUT SETS WITH 4 COMPONENTS

1)	E24C	E9C	A21C	A22C
2)	E25C	E9C	A21C	A22C
3)	E26C	E9C	A21C	A22C
4)	E27C	E9C	A21C	A22C
5)	E28C	E9C	A21C	A22C
6)	E24C	E10C	A21C	A22C
7)	E24C	E11C	A21C	A22C
8)	E24C	E12C	A21C	A22C
9)	E24C	E13C	A21C	A22C
10)	E25C	E10C	A21C	A22C
11)	E25C	E11C	A21C	A22C
12)	E25C	E12C	A21C	A22C
13)	E25C	E13C	A21C	A22C
14)	E26C	E10C	A21C	A22C
15)	E26C	E11C	A21C	A22C
16)	E26C	E12C	A21C	A22C
17)	E26C	E13C	A21C	A22C
18)	E27C	E10C	A21C	A22C
19)	E27C	E11C	A21C	A22C
20)	E27C	E12C	A21C	A22C
21)	E27C	E13C	A21C	A22C
22)	E28C	E10C	A21C	A22C
23)	E28C	E11C	A21C	A22C
24)	E28C	E12C	A21C	A22C
25)	E28C	E13C	A21C	A22C

TOTAL NUMBER OF CUT SETS FOUND WAS 32
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - VERSION 3/74

MINIMAL CUT SETS FOR GATE G12D = A/2-D

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

1)	E8D	E9D
2)	E8D	E10D
3)	E8D	E11D
4)	E8D	E12D
5)	E8D	E13D
6)	E8D	A26

CUT SETS WITH 3 COMPONENTS

1)	A26	A21D	A22D

CUT SETS WITH 4 COMPONENTS

1)	E24D	E9D	A21D	A22D
2)	E25D	E9D	A21D	A22D
3)	E26D	E9D	A21D	A22D
4)	E27D	E9D	A21D	A22D
5)	E28D	E9D	A21D	A22D
6)	E24D	E10D	A21D	A22D
7)	E24D	E11D	A21D	A22D
8)	E24D	E12D	A21D	A22D
9)	E24D	E13D	A21D	A22D
10)	E25D	E10D	A21D	A22D
11)	E25D	E11D	A21D	A22D
12)	E25D	E12D	A21D	A22D
13)	E25D	E13D	A21D	A22D
14)	E26D	E10D	A21D	A22D
15)	E26D	E11D	A21D	A22D
16)	E26D	E12D	A21D	A22D
17)	E26D	E13D	A21D	A22D
18)	E27D	E10D	A21D	A22D
19)	E27D	E11D	A21D	A22D
20)	E27D	E12D	A21D	A22D
21)	E27D	E13D	A21D	A22D
22)	E29D	E10D	A21D	A22D
23)	E28D	E11D	A21D	A22D
24)	E29D	E12D	A21D	A22D
25)	E28D	E13D	A21D	A22D

TOTAL NUMBER OF CUT SETS FOUND WAS 32
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G26 = A26

Table G-1 (cont.)

MOCUS - - VERSION 3/74

```
CUT SETS WITH   1 COMPONENTS

         1)    A58
         2)    E14
         3)    E15
         4)    E86
         5)    E85
         6)    E87
         7)    E88
         8)    E89
CUT SETS WITH   2 COMPONENTS

         1)    E90      E91
         2)    E92      E93
         3)    E94      E95
CUT SETS WITH   3 COMPONENTS

     NONE EXIST.
CUT SETS WITH   4 COMPONENTS

     NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS    11
ONLY  CUT SETS WITH   4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G21A = A21A

CUT SETS WITH 1 COMPONENTS

1)	E16A
2)	E17A
3)	E19A
4)	E19A
5)	E29
6)	E30
7)	E31
8)	E32

CUT SETS WITH 2 COMPONENTS

1)	E1	E54
2)	E57	E53
3)	E59	E53
4)	E44	E47
5)	E44	E48
6)	E44	E49
7)	E44	E50
8)	E44	E51
9)	E44	E52
10)	E45	E47

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 2 COMPONENTS

11)	E45	E48
12)	E45	E49
13)	E45	E50
14)	E45	E51
15)	E45	E52
16)	E46	E47
17)	E46	E48
18)	E46	E49
19)	E46	E50
20)	E46	E51
21)	E46	E52
22)	A41	E47
23)	A41	E48
24)	A41	E49
25)	A41	E50
26)	A41	E51
27)	A41	E52

CUT SETS WITH 3 COMPONENTS

1)	E1	E53	E59
2)	E33	E35	E38
3)	E44	E55	E56
4)	E34	E35	E38
5)	E45	E55	E56
6)	E46	E55	E56
7)	A41	E55	E56
8)	E33	E36	E38
9)	E33	E37	E38
10)	E34	E36	E38
11)	E34	E37	E38
12)	E33	E35	E39
13)	E33	E35	E40
14)	E33	E35	E41
15)	E33	E35	E42
16)	E33	E35	E43
17)	E34	E35	E39
18)	E34	E35	E40
19)	E34	E35	E41
20)	E34	E35	E42
21)	E34	E35	E43
22)	E33	E36	E39
23)	E33	E36	E40
24)	E33	E36	E41
25)	E33	E36	E42
26)	E33	E36	E43
27)	E33	E37	E39
28)	E33	E37	E40
29)	E33	E37	E41
30)	E33	E37	E42
31)	E33	E37	E43
32)	E34	E36	E39
33)	E34	E36	E40
34)	E34	E36	E41
35)	E34	E36	E42

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 3 COMPONENTS

36)	E34	E36	E47
37)	E34	E37	E39
38)	E34	E37	E40
39)	E34	E37	E41
40)	E34	E37	E42
41)	E34	E37	E43

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 76
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G21B = A21B

CUT SETS WITH 1 COMPONENTS

1)	E16B
2)	E17B
3)	E18B
4)	E19B
5)	E29
6)	E30
7)	E31
8)	E32

CUT SETS WITH 2 COMPONENTS

1)	E1	E54
2)	E57	E53
3)	E58	E53
4)	E44	E47
5)	E44	E48
6)	E44	E49
7)	E44	E50
8)	E44	E51
9)	E44	E52
10)	E45	E47
11)	E45	E48
12)	E45	E49
13)	E45	E50
14)	E45	E51
15)	E45	E52
16)	E46	E47
17)	E46	E48
18)	E46	E49
19)	E46	E50
20)	E46	E51
21)	E46	E52
22)	A41	E47
23)	A41	E48
24)	A41	E49
25)	A41	E50
26)	A41	E51
27)	A41	E52

Table G-1 (cont.)

MOCUS - - VERSION 3/78

CUT SETS WITH 3 COMPONENTS

1)	E1	E53	E57
2)	E33	E35	E38
3)	E44	E55	E56
4)	E34	E35	E38
5)	E45	E55	E56
6)	E46	E55	E56
7)	A41	E55	E56
8)	E33	E36	E38
9)	E33	E37	E38
10)	E34	E36	E38
11)	E34	E37	E38
12)	E33	E35	E39
13)	E33	E35	E40
14)	E33	E35	E41
15)	E33	E35	E42
16)	E33	E35	E43
17)	E34	E35	E39
18)	E34	E35	E40
19)	E34	E35	E41
20)	E34	E35	E42
21)	E34	E35	E43
22)	E33	E36	E39
23)	E33	E36	E40
24)	E33	E36	E41
25)	E33	E36	E42
26)	E33	E36	E43
27)	E33	E37	E39
28)	E33	E37	E40
29)	E33	E37	E41
30)	E33	E37	E42
31)	E33	E37	E43
32)	E34	E36	E39
33)	E34	E36	E40
34)	E34	E36	E41
35)	E34	E36	E42
36)	E34	E36	E43
37)	E34	E37	E39
38)	E34	E37	E40
39)	E34	E37	E41
40)	E34	E37	E42
41)	E34	E37	E43

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 76
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G21C = A21C

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 1 COMPONENTS

1)	E16C
2)	E17C
3)	E18C
4)	E19C
5)	E29
6)	E30
7)	E31
8)	E32

CUT SETS WITH 2 COMPONENTS

1)	E1	E54
2)	E57	E53
3)	E58	E53
4)	E44	E47
5)	E44	E48
6)	E44	E49
7)	E44	E50
8)	E44	E51
9)	E44	E52
10)	E45	E47
11)	E45	E48
12)	E45	E49
13)	E45	E50
14)	E45	E51
15)	E45	E52
16)	E46	E47
17)	E46	E48
18)	E46	E49
19)	E46	E50
20)	E46	E51
21)	E46	E52
22)	A41	E47
23)	A41	E48
24)	A41	E49
25)	A41	E50
26)	A41	E51
27)	A41	E52

CUT SETS WITH 3 COMPONENTS

1)	E1	E53	E59
2)	E33	E35	E38
3)	E44	E55	E56
4)	E34	E35	E38
5)	E45	E55	E56
6)	E46	E55	E56
7)	A41	E55	E56
8)	E33	E36	E38
9)	E33	E37	E38
10)	E34	E36	E38
11)	E34	E37	E38
12)	E33	E35	E39
13)	E33	E35	E40

Table G-1 (cont.)

CUT SETS WITH 3 COMPONENTS

14)	E33	E35	E41
15)	E33	E35	E42
16)	E33	E35	E43
17)	E34	E35	E39
18)	E34	E35	E40
19)	E34	E35	E41
20)	E34	E35	E42
21)	E34	E35	E43
22)	E33	E36	E39
23)	E33	E36	E40
24)	E33	E36	E41
25)	E33	E36	E42
26)	E33	E36	E43
27)	E33	E37	E39
28)	E33	E37	E40
29)	E33	E37	E41
30)	E33	E37	E42
31)	E33	E37	E43
32)	E34	E36	E39
33)	E34	E36	E40
34)	E34	E36	E41
35)	E34	E36	E42
36)	E34	E36	E43
37)	E34	E37	E39
38)	E34	E37	E40
39)	E34	E37	E41
40)	E34	E37	E42
41)	E34	E37	E43

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 76
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G21D = A21D

CUT SETS WITH 1 COMPONENTS

```
1)   E16D
2)   E17D
3)   E18D
4)   E19D
5)   E29
6)   E30
7)   E31
8)   E32
```

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 2 COMPONENTS

1)	E1	E54
2)	E57	E53
3)	E58	E53
4)	E44	E47
5)	E44	E48
6)	E44	E49
7)	E44	E50
8)	E44	E51
9)	E44	E52
10)	E45	E47
11)	E45	E48
12)	E45	E49
13)	E45	E50
14)	E45	E51
15)	E45	E52
16)	E46	E47
17)	E46	E48
18)	E46	E49
19)	E46	E50
20)	E46	E51
21)	E46	E52
22)	A41	E47
23)	A41	E48
24)	A41	E49
25)	A41	E50
26)	A41	E51
27)	A41	E52

CUT SETS WITH 3 COMPONENTS

1)	E1	E53	E57
2)	E33	E35	E38
3)	E44	E55	E56
4)	E34	E35	E38
5)	E45	E55	E56
6)	E46	E55	E56
7)	A41	E55	E56
8)	E33	E36	E38
9)	E33	E37	E38
10)	E34	E36	E38
11)	E34	E37	E38
12)	E33	E35	E39
13)	E33	E35	E40
14)	E33	E35	E41
15)	E33	E35	E42
16)	E33	E35	E43
17)	E34	E35	E39
18)	E34	E35	E40
19)	E34	E35	E41
20)	E34	E35	E42
21)	E34	E35	E43
22)	E33	E36	E39
23)	E33	E36	E40
24)	E33	E36	E41

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 3 COMPONENTS

25)	E33	E36	E42
26)	E33	E36	E43
27)	E33	E37	E39
28)	E33	E37	E40
29)	E33	E37	E41
30)	E33	E37	E42
31)	E33	E37	E43
32)	E34	E36	E39
33)	E34	E36	E40
34)	E34	E36	E41
35)	E34	E36	E42
36)	E34	E36	E43
37)	E34	E37	E39
38)	E34	E37	E40
39)	E34	E37	E41
40)	E34	E37	E42
41)	E34	E37	E43

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 76
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G22A = A22A

CUT SETS WITH 1 COMPONENTS

1) E20A
2) E21A
3) E22A
4) E23A
5) A44
6) E60
7) E61
8) E62
9) E63

CUT SETS WITH 2 COMPONENTS

1) E3 E74
2) E77 E73
3) E78 E73

CUT SETS WITH 3 COMPONENTS

1) E3 E73 E79

Table G-1 (cont.)

MOCUS - - VERSION 3/74

```
CUT SETS WITH    4 COMPONENTS

    NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS     13
ONLY  CUT SETS WITH    4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO    6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)


```
********************************************************************************************************************

                                   MINIMAL CUT  SETS FOR GATE G22B = A22B

********************************************************************************************************************
CUT SETS WITH   1 COMPONENTS

          1)    E20B
          2)    E21B
          3)    E22B
          4)    E23B
          5)    A44
          6)    E60
          7)    E61
          8)    E62
          9)    E63
CUT SETS WITH   2 COMPONENTS

          1)    E3         E74
          2)    E77        E73
          3)    E79        E73
CUT SETS WITH   3 COMPONENTS

          1)    E3         E73        E79
CUT SETS WITH   4 COMPONENTS

     NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS    13
ONLY  CUT SETS WITH   4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)

MOCUS - - VERSION 3/78

MINIMAL CUT SETS FOR GATE G22C = A22C

CUT SETS WITH 1 COMPONENTS

1)	F20C
2)	E21C
3)	F22C
4)	E23C
5)	A44
6)	E60
7)	E61
8)	F62
9)	E63

Table G-1 (cont.)


```
CUT SETS WITH   2 COMPONENTS

        1)    E3       E74
        2)    E77      E73
        3)    E78      E73
CUT SETS WITH   3 COMPONENTS

        1)    E3       E73      E79
CUT SETS WITH   4 COMPONENTS

    NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS     13
ONLY  CUT SETS WITH    4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G22D = A22D

CUT SETS WITH 1 COMPONENTS

1) E20D
2) E21D
3) E22D
4) E23D
5) A44
6) E60
7) E61
8) E62
9) E63

CUT SETS WITH 2 COMPONENTS

1) E3 E74
2) E77 E73
3) E78 E73

CUT SETS WITH 3 COMPONENTS

1) E3 E73 E79

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 13
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

****

MINIMAL CUT SETS FOR GATE G41 = A41

****

CUT SETS WITH 1 COMPONENTS

1) E80

Table G-1 (cont.)

```
                                                                                MOCUS - - VERSION  3/74
 CUT SETS WITH   2 COMPONENTS

           1)    EB1      EB3
           2)    EB2      EB3
           3)    EB1      EB4
           4)    EB2      EB4
 CUT SETS WITH   3 COMPONENTS

     NONE EXIST.
 CUT SETS WITH   4 COMPONENTS

     NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS      5
ONLY  CUT SETS WITH   4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G44 = A44

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

1)	E64	E67
2)	E64	E68
3)	E64	E69
4)	E64	E70
5)	E64	E71
6)	E64	E72
7)	E65	E67
8)	E65	E68
9)	E65	E69
10)	E65	E70
11)	E65	E71
12)	E65	E72
13)	E66	E67
14)	E66	E68
15)	E66	E69
16)	E66	E70
17)	E66	E71
18)	E66	E72
19)	A41	E67
20)	A41	E68
21)	A41	E69
22)	A41	E70
23)	A41	E71

Table G-1 (cont.)

MOCUS - - VERSION 3/74

CUT SETS WITH 2 COMPONENTS

24)	A41	E72

CUT SETS WITH 3 COMPONENTS

1)	E64	E75	E76
2)	E65	E75	E76
3)	E66	E75	E76
4)	A41	E75	E76

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 28
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

****

MINIMAL CUT SETS FOR GATE G58 = A58

****

CUT SETS WITH 1 COMPONENTS

NONE EXIST.

CUT SETS WITH 2 COMPONENTS

NONE EXIST.

CUT SETS WITH 3 COMPONENTS

NONE EXIST.

CUT SETS WITH 4 COMPONENTS

1) A62 A63 A64 A65

TOTAL NUMBER OF CUT SETS FOUND WAS 1

ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/79

****

MINIMAL CUT SETS FOR GATE G62 = A62

****

CUT SETS WITH 1 COMPONENTS

1) E96
2) E97
3) E98
4) E99

Table G-1 (cont.)


```
CUT SETS WITH   2 COMPONENTS

     NONE EXIST.
CUT SETS WITH   3 COMPONENTS

     NONE EXIST.
CUT SETS WITH   4 COMPONENTS

     NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS      4
ONLY  CUT SETS WITH   4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G63 = A63

CUT SETS WITH 1 COMPONENTS

1) E100
2) E101
3) E102
4) E103

CUT SETS WITH 2 COMPONENTS

NONE EXIST.

CUT SETS WITH 3 COMPONENTS

NONE EXIST.

CUT SETS WITH 4 COMPONENTS

NONE EXIST.

TOTAL NUMBER OF CUT SETS FOUND WAS 4
ONLY CUT SETS WITH 4 OR LESS COMPONENTS HAVE BEEN DETERMINED.
SETS WITH UP TO 6 COMPONENTS MAY EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

MINIMAL CUT SETS FOR GATE G64 = A64

Table G-1 (cont.)

MOCUS - - VERSION 3/74

```
CUT SETS WITH   1 COMPONENTS

          1)    E104
          2)    E105
          3)    E106
          4)    E107
CUT SETS WITH   2 COMPONENTS

     NONE EXIST.
CUT SETS WITH   3 COMPONENTS

     NONE EXIST.
CUT SETS WITH   4 COMPONENTS

     NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS     4
ONLY  CUT SETS WITH   4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-1 (cont.)

MOCUS - - VERSION 3/79

****

MINIMAL CUT SETS FOR GATE G65 = A65

****

CUT SETS WITH 1 COMPONENTS

1) E108
2) E109
3) E110
4) E111
5) E112

CUT SETS WITH 2 COMPONENTS

NONE EXIST.

CUT SETS WITH 3 COMPONENTS

NONE EXIST.

Table G-1 (cont.)

MOCUS - - VERSION 3/74

```
CUT SETS WITH   4 COMPONENTS

    NONE EXIST.

TOTAL NUMBER OF  CUT SETS FOUND WAS      5
ONLY  CUT SETS WITH   4 OR LESS COMPONENTS HAVE BEEN DETERMINED.

SETS WITH UP TO   6 COMPONENTS MAY EXIST.
```

Table G-2 - Unavailability Expressions (STADIC INPUT)
For LMFW Initiating Event

```
C
C        LMFW DOMINANT EQUIP  FAILURES FOR TRAIN A
C
        TRA-E29+E30+E31+E32+(E33+E34)*(E35+E36+E37)*
     C       (E38+E39+E40+E41+E42+E43)
C
C        DOMINANT EQUIP  FAILURES FOR TRAIN B
C
        TRB-E60+E61+E62+E63
C
C        DOMINANT EQUIP  FAILURES FOR TRAIN C
C
        TRC-E85+E86+E87+E88+E89
C
C        SYSTEM FAILURES (NOT TRAIN SPECIFIC )
        P1-E1*E2*E3*E4*(1 -B2)
        P2-4 *(((1 -B2)*E8)**3 )
        P3-4 *((E6+E5)**3 )*E7
        P4-(E9+E10*(1 -B2)+E11+E12+E13)**3
        P5-P2*P4
C
C        COMMON CAUSE TRAIN A
        CA1-B1*E36
C
C        COMMON CAUSE TRAIN C
        CC1-B1*(E96+E90+E14)
C
C        COMMON CAUSE TRAINS A/B
        C2-B2*(E18+E16+E19)
C
C        SYSTEM COMMON CAUSE
        C3-B2*(E8+E1*E2)
135 >
```

Table G-2 (continued)

```
      C
      C         OUTPUT FUNCTIONS
      C
      C         LMFW INDEPENDENT
               XY(1)-TRA*TRB*TRC+P1+P3+P5
      C         LMFW IND & COMMON CAUSE
               XY(2)-((TRA+CA1)*TRB+C2)*(TRC+CC1)+C3+P1+P3+P5
      C         LMFW TRAIN A IN MAINTENANCE (IND)
               XY(3)-(TRB*TRC+P1+P3+P5)*QM
      C         LMFW TRAIN A IN MAINTENANCE (W/CC)
               XY(4)-(TRB*(TRC+CC1)+C3+P1+P3+P5)*QM
      C         LMFW TRAIN B IN MAINTENANCE (IND)
               XY(5)-(TRA*TRC+P1+P3+P5)*QM
      C         LMFW TRAIN B IN MAINTENANCE (W/CC)
               XY(6)-((TRA+CA1)*(TRC+CC1)+C3+B2*E35+P1+P3+P5)*QM
      C         TRAIN C IN MAINTENANCE
               XY(7)-(TRA*TRB+P1+P2+P3)*QM
      C         TRAIN C IN MAINTENANCE (W/CC)
               XY(8)-((TRA+CA1)*TRB+C3+P1+P2+P3)*QM
      C         LMFW TOTAL MAINTENANCE (IND)
               XY(9)-XY(3)+XY(5)+XY(7)
      C         LMFW TOTAL MAINTENANCE (W/CC)
               XY(10)-XY(4)+XY(6)+XY(8)
      C         LMFW HARDWARE & MAINTENANCE (IND)
                XY(11)-XY(1)+XY(9)
      C         LMFW HARDWARE & MAINTENANCE (W/CC)
                XY(12)-XY(2)+XY(10)
>
```

Table G-3 - Unavailability Expressions (STADIC INPUT)
For LOOP and LOAC Initiating Events

```
C
C        LOOP DOM EQUIP  FAILURES FOR TRAIN A
        TRA-E29+E30+E31+E32+(E35+E36+E37)*
     C      (E38+E39+E40+E41+E42+E43)
C
C        LOOP DOM EQUIP  FAILURES FOR TRAIN B
        TRB-E60+E61+E62+E63
C       TRAIN C FAILED DUE TO LOOP
C
C
C        SYSTEM FAILURES GIVEN LOOP
C
        P1-E1*E2*E3*E4*(1 -B2)
        P2-4 *(((1 -B2)*E8)**3 )
        P3-4 *((E6+E5)**3 )*E7
        P4-(E9+E10*(1 -B2)+E11+E12+E13)**3
        P5-P2*P4
C
C        COMMON CAUSE FAILURES
C
        CA1-B1*E36+B2*E35
        CC1-B1*(E96+E90+E14)
        C2-B2*(E18+E16+E19)
        C3-B2*(E8+E1*E2)
C
C        FAILURES DUE TO MAINTENANCE
C
        P6-(TRB+P1+P2+P3)*QM
        P7-(TRB+C3+P1+P2+P3)*QM
        P8-(TRA+P1+P3+P2)*QM
        P9-(TRA+CA1+C3+P1+P2+P3)*QM
C
135 >
```

Table G-3 (continued)

```
C
C        LOOP DOM EQUIP  FAILURES FOR TRAIN A
       TRA-E29+E30+E31+E32+(E35+E36+E37)*
     C      (E38+E39+E40+E41+E42+E43)
C
C        LOOP DOM EQUIP  FAILURES FOR TRAIN B
       TRB-E60+E61+E62+E63
C
C      TRAIN C FAILED DUE TO LOOP
C
C
C        SYSTEM FAILURES GIVEN LOOP
C
      P1-E1*E2*E3*E4*(1 -B2)
      P2-4 *(((1 -B2)*E8)**3 )
      P3-4 *((E6+E5)**3 )*E7
      P4-(E9+E10*(1 -B2)+E11+E12+E13)**3
      P5-P2*P4
C
C       COMMON CAUSE FAILURES
C
      CA1-B1*E36+B2*E35
      CC1-B1*(E96+E90+E14)
      C2-B2*(E18+E16+E19)
      C3-B2*(E8+E1*E2)
C
C       FAILURES DUE TO MAINTENANCE
C
      P6-(TRB+P1+P2+P3)*QM
      P7-(TRB+C3+P1+P2+P3)*QM
      P8-(TRA+P1+P3+P2)*QM
      P9-(TRA+CA1+C3+P1+P2+P3)*QM
135 >
```

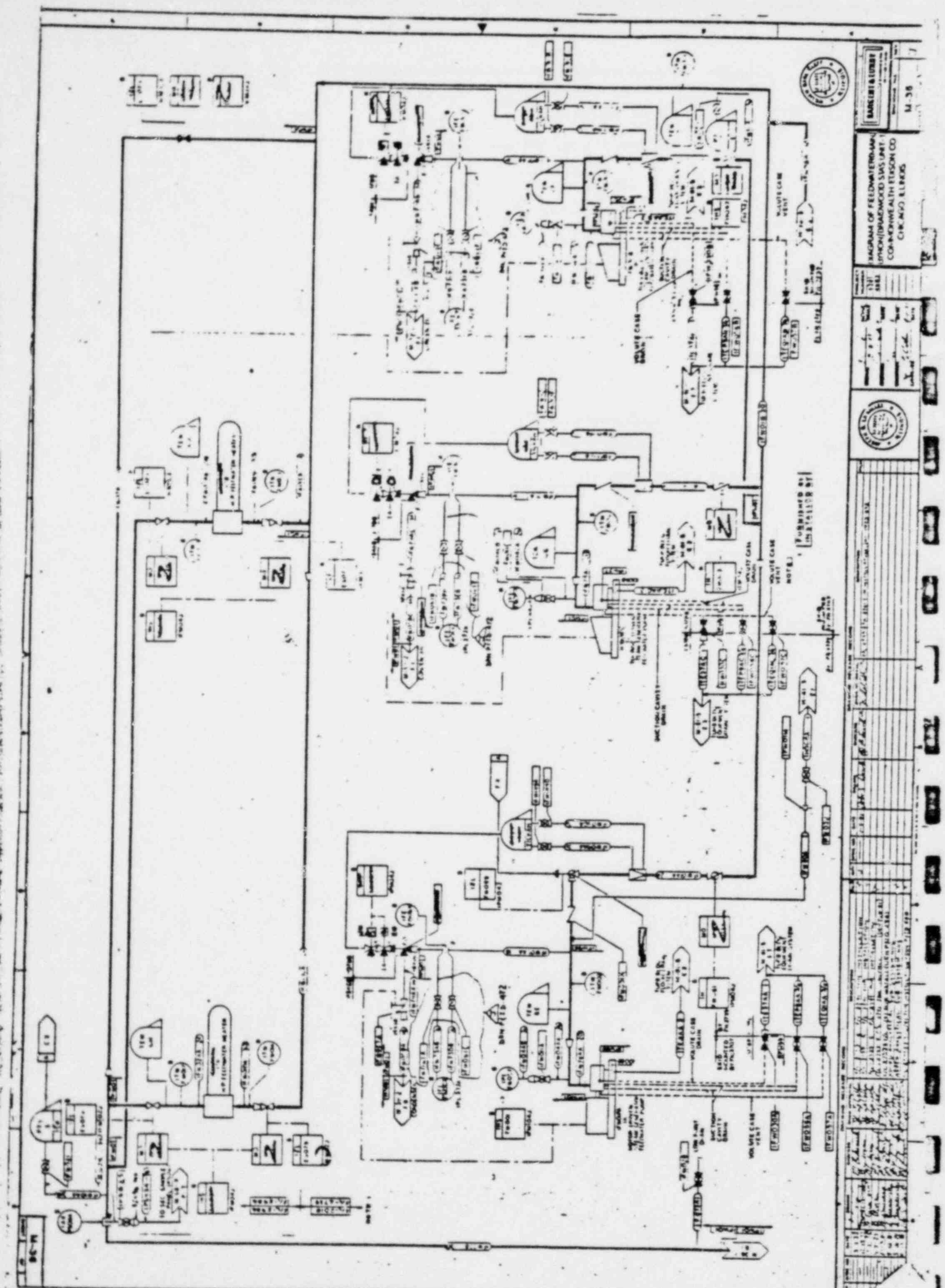
Table G-3 (continued)

```
C
C          OUTPUT FUNCTIONS
C
C          LOOP HARDWARE (IND)
         XY(1)-TRA*TRB+P1+P2+P3
C         LOOP HARDWARE (W/CC)
         XY(2)-((TRA+CA1)*TRB)+P1+P2+P3+C3+C2
C         LOOP MANTENANCE (IND)
         XY(3)-P6 + P8
C         LOOP MAINTENANCE (W/CC)
         XY(4)-P7+P9
C         LOOP TOTAL HARDWARE & MAINTENANCE (IND)
         XY(5)-XY(1)+XY(3)
C         LOOP TOTAL HARDWARE & MAINTENANCE (W/CC)
         XY(6)-XY(2)+XY(4)
C
C
C        LOAC TRAINS A AND  C FAILED
C
C         LOAC HARDWARE (IND)
         XY(7)-TRB+P1+P2+P3
C          LOAC IND AND COMMON CAUSE
         XY(8)-XY(7)+C3
C          LOAC MAINTENANCE (IND)
         XY(9)-QM*(1 Ø+P1+P2+P3)
C         LOAC MAINTENANCE (W/CC)
         XY(1Ø)-XY(9)+QM*C3
C          LOAC TOTAL HARDWARE & MAINTENANCE (IND)
         XY(11)-XY(7)+XY(9)
C         LOAC TOTAL HARDWARE & MAINTENANCE (W/CC)
         XY(12)-XY(8)+XY(1Ø)
166 >
```

APPENDIX H

BYRON/BRAIDWOOD

PIPING AND INSTRUMENT DRAWINGS FOR AUXILIARY FEEDWATER



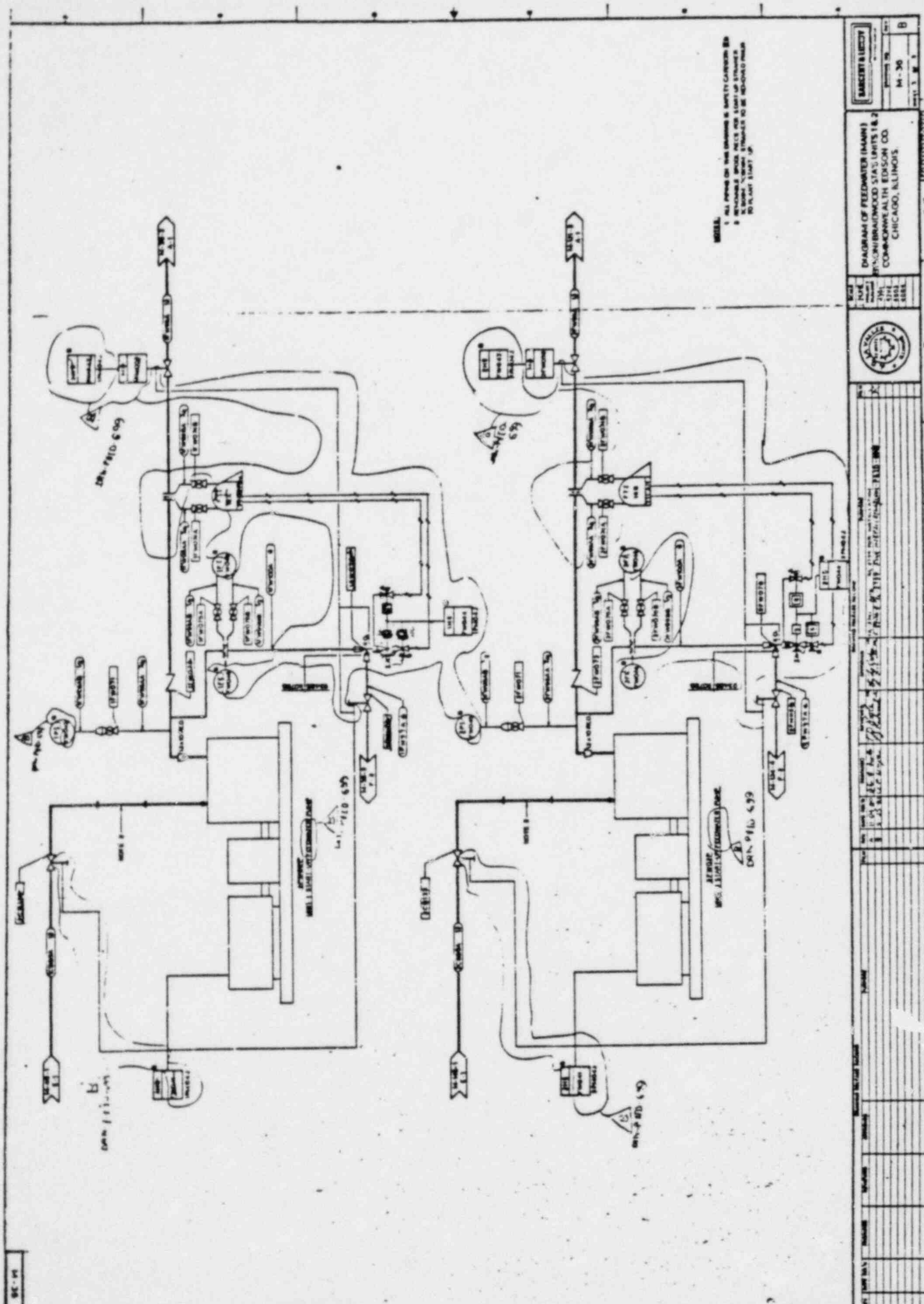


DIAGRAM OF FEEDWATER (MAIN)
BYRON/BRAIDWOOD STA'S UNITS 1 & 2
COMMONWEALTH EDISON CO.
CHICAGO, ILLINOIS
SARGENT & LUNDY
M-36
B

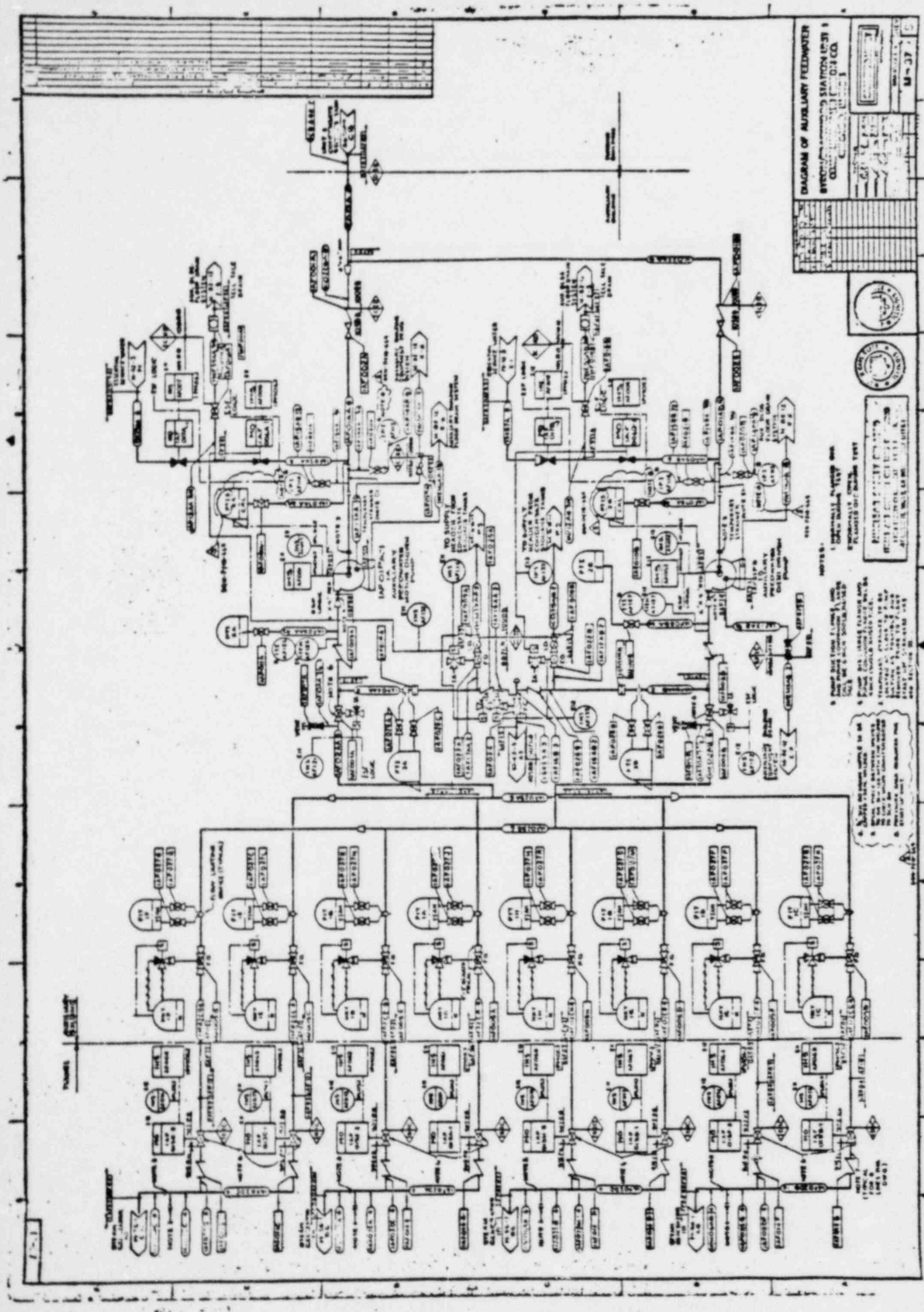
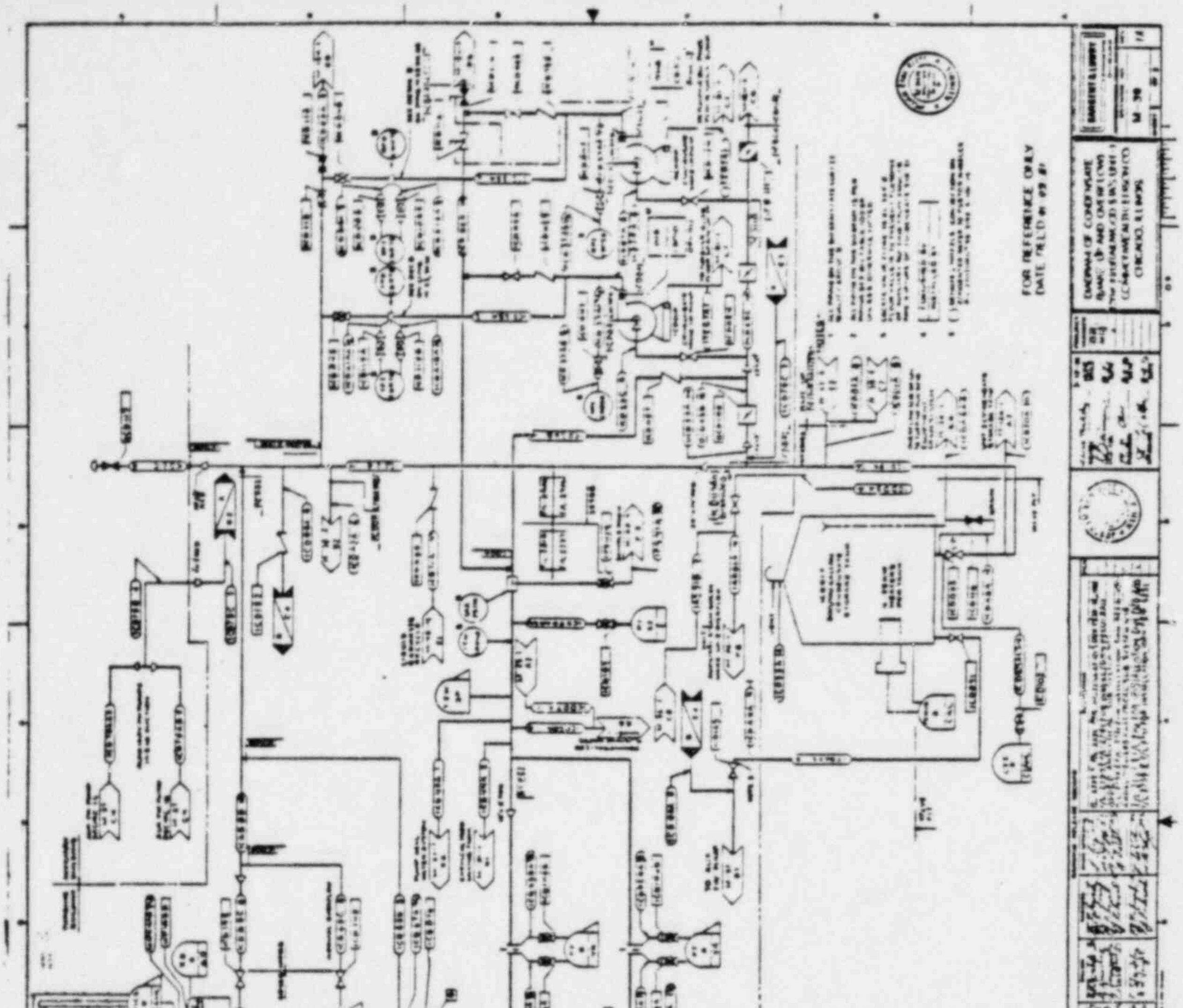


DIAGRAM OF AUXILIARY FEEDWATER
M-37


FOR REFERENCE ONLY

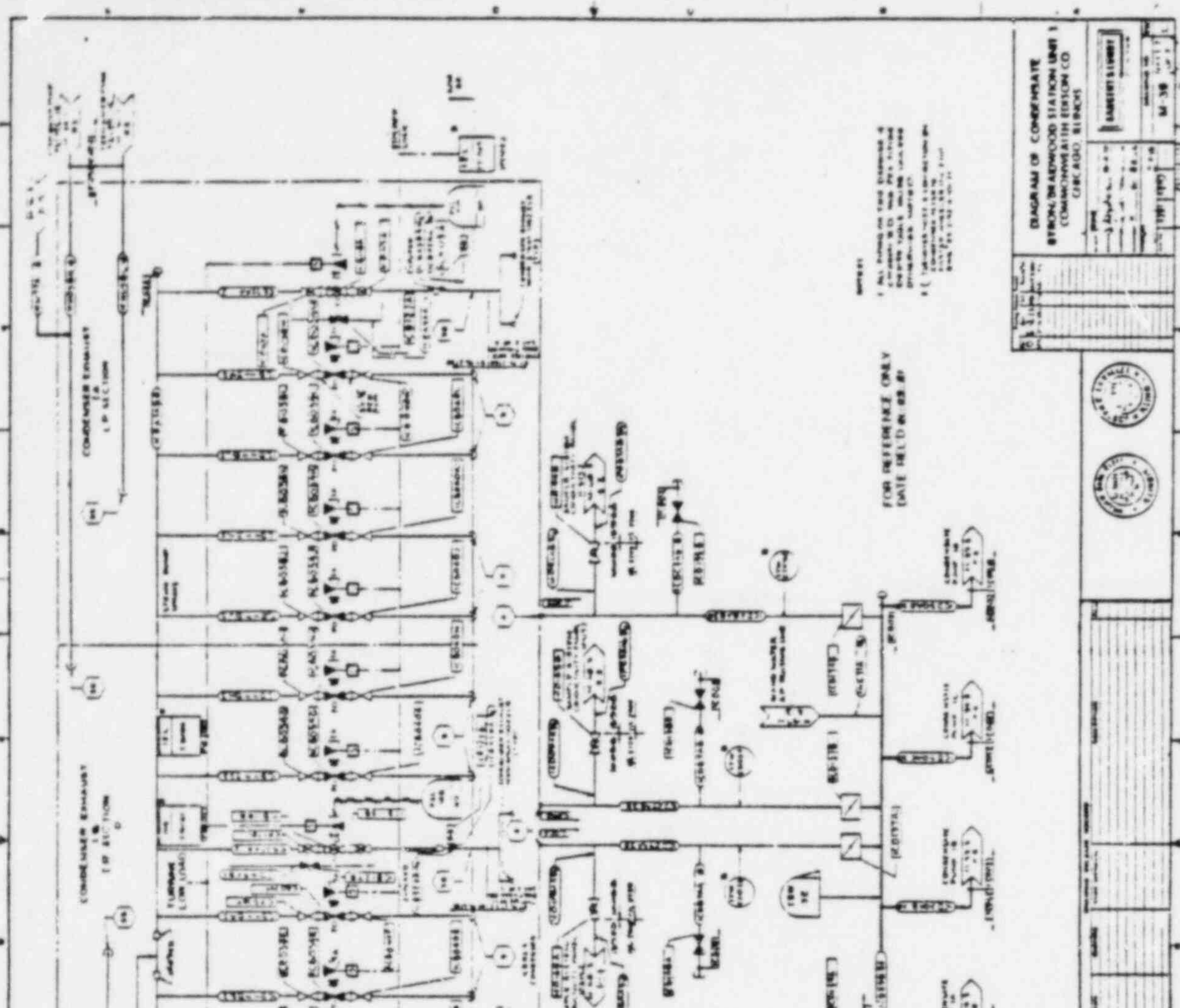


DIAGRAM OF CONDENSATE
BYRON/BRAIDWOOD STATION UNIT 1
COMMONWEALTH EDISON CO
CHICAGO, ILLINOIS
SARGENT & LUNDY
M-38
FOR REFERENCE ONLY

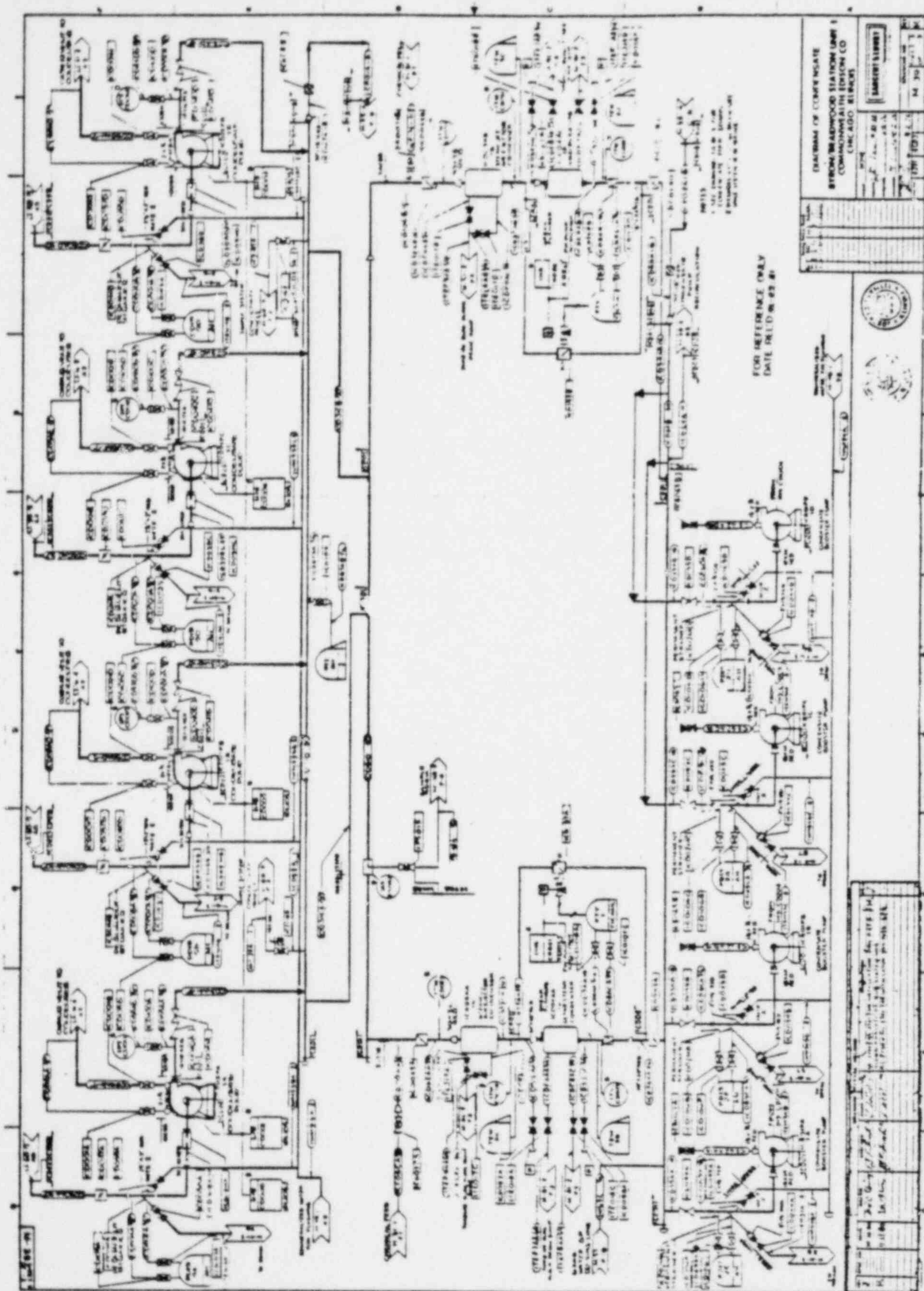
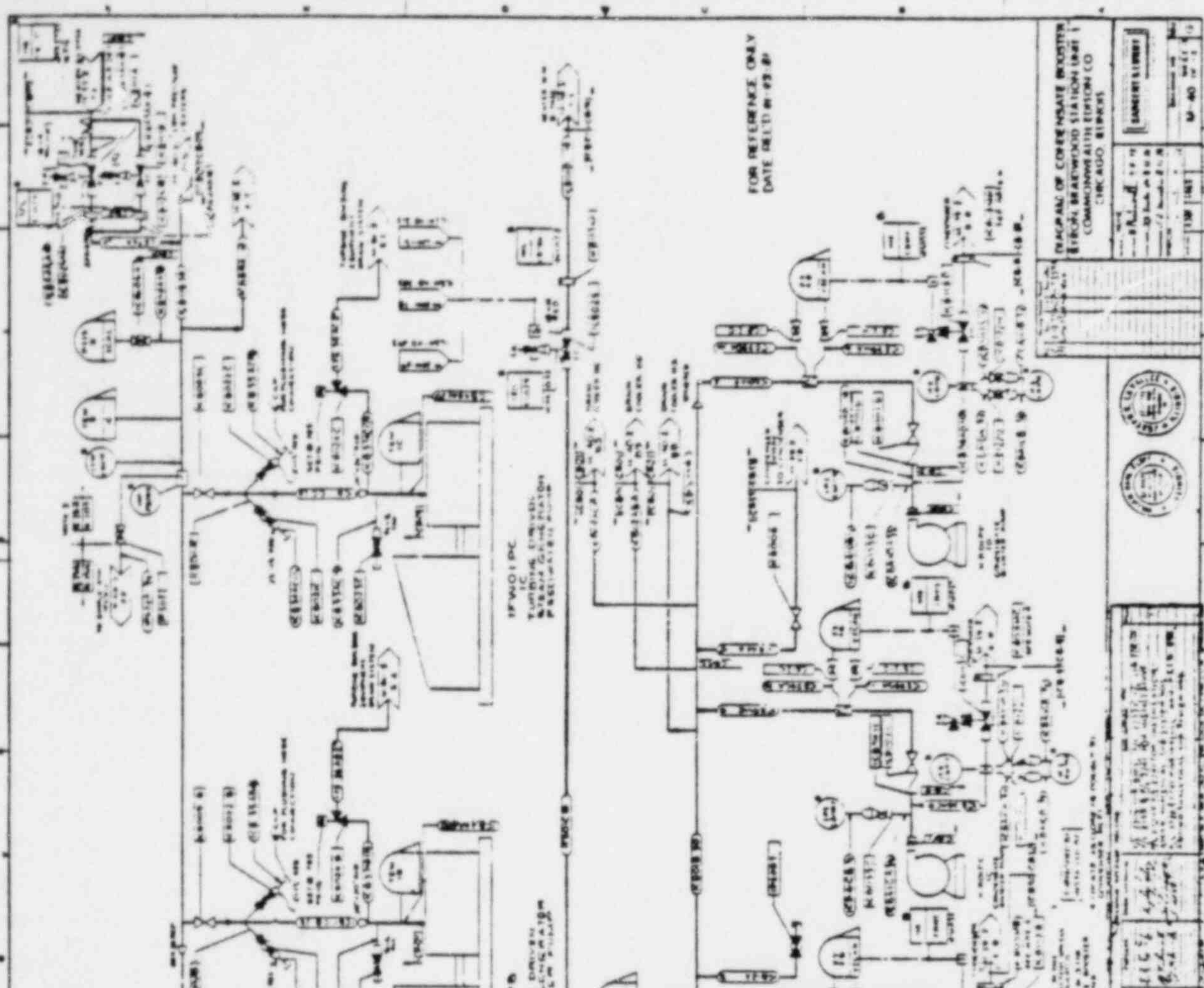
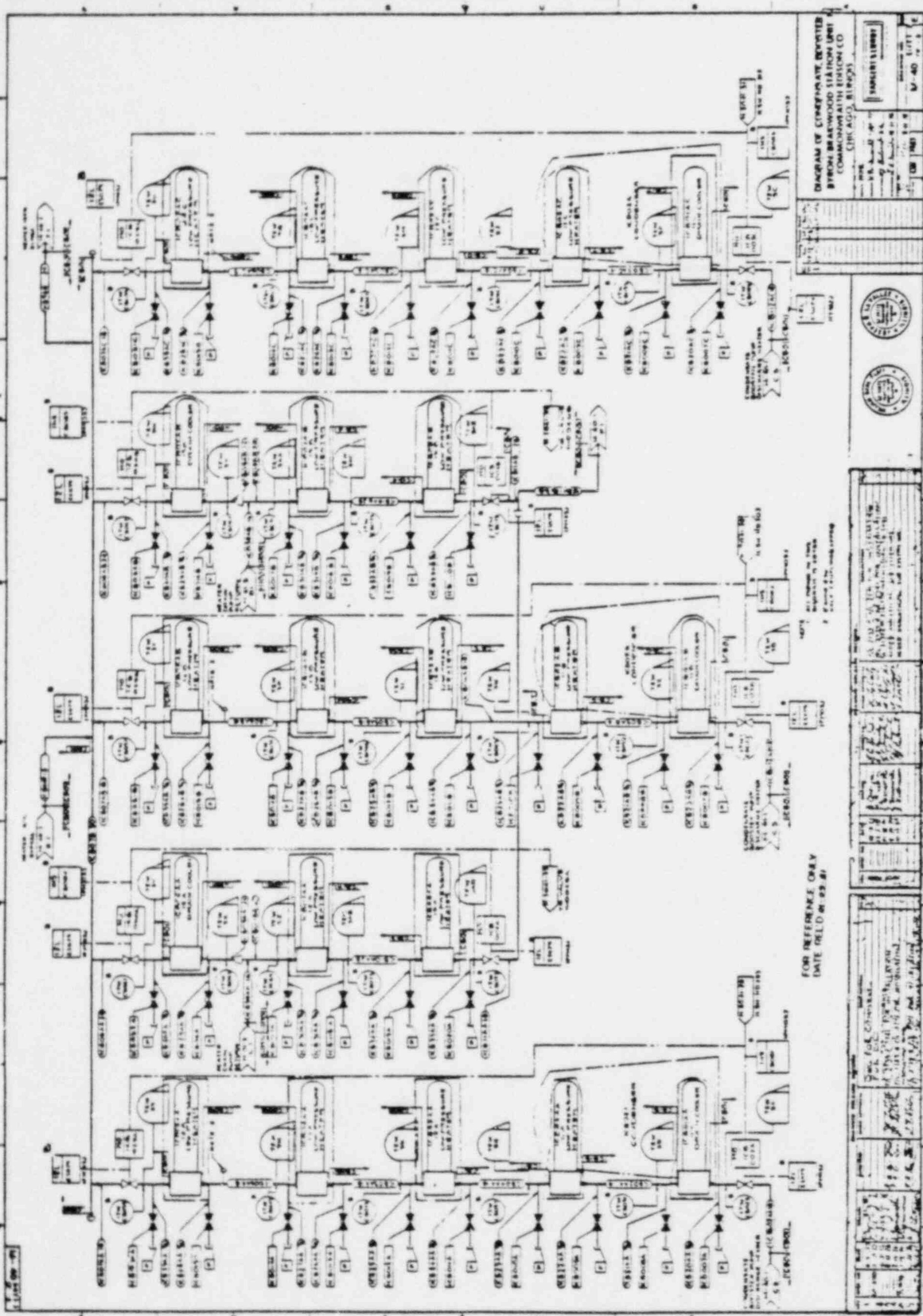
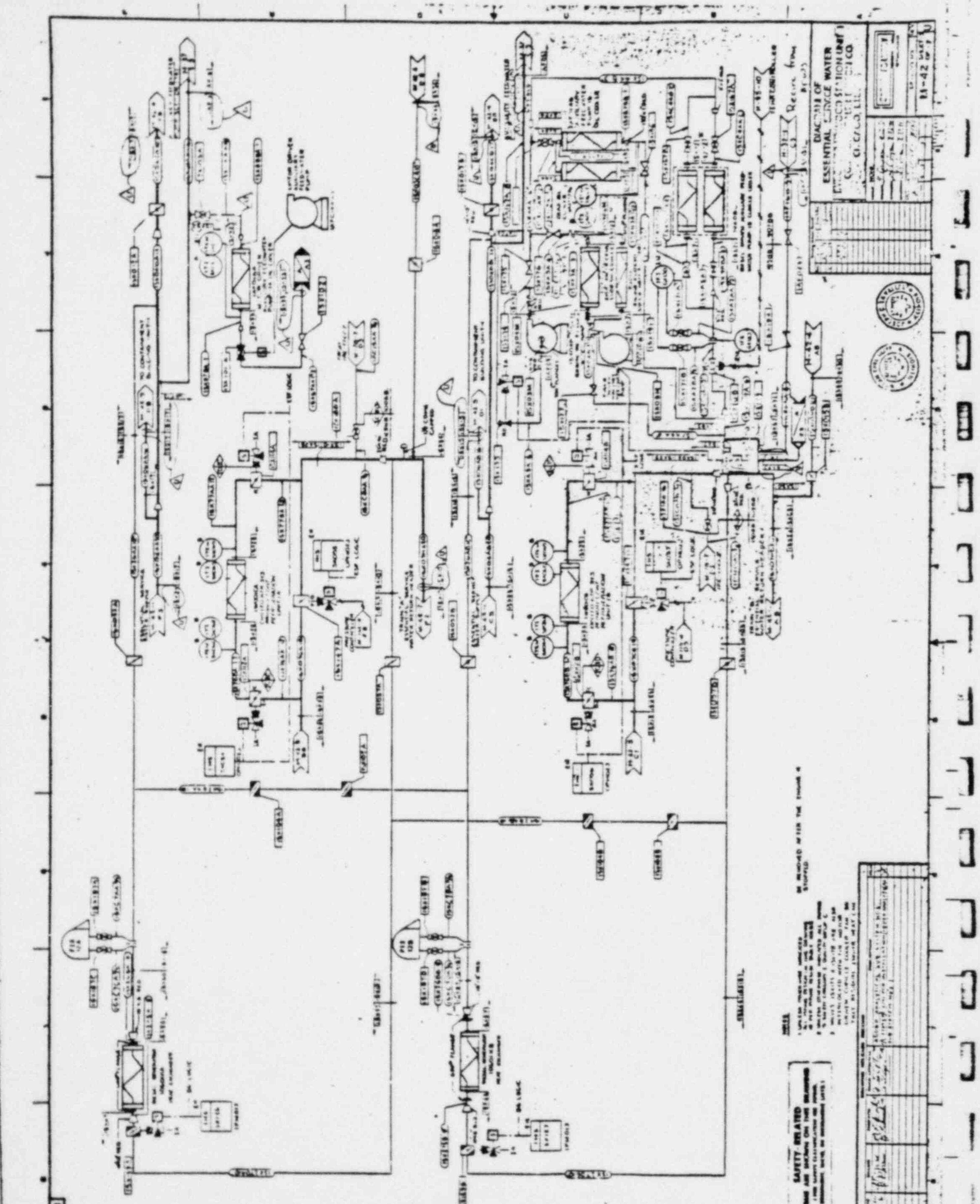
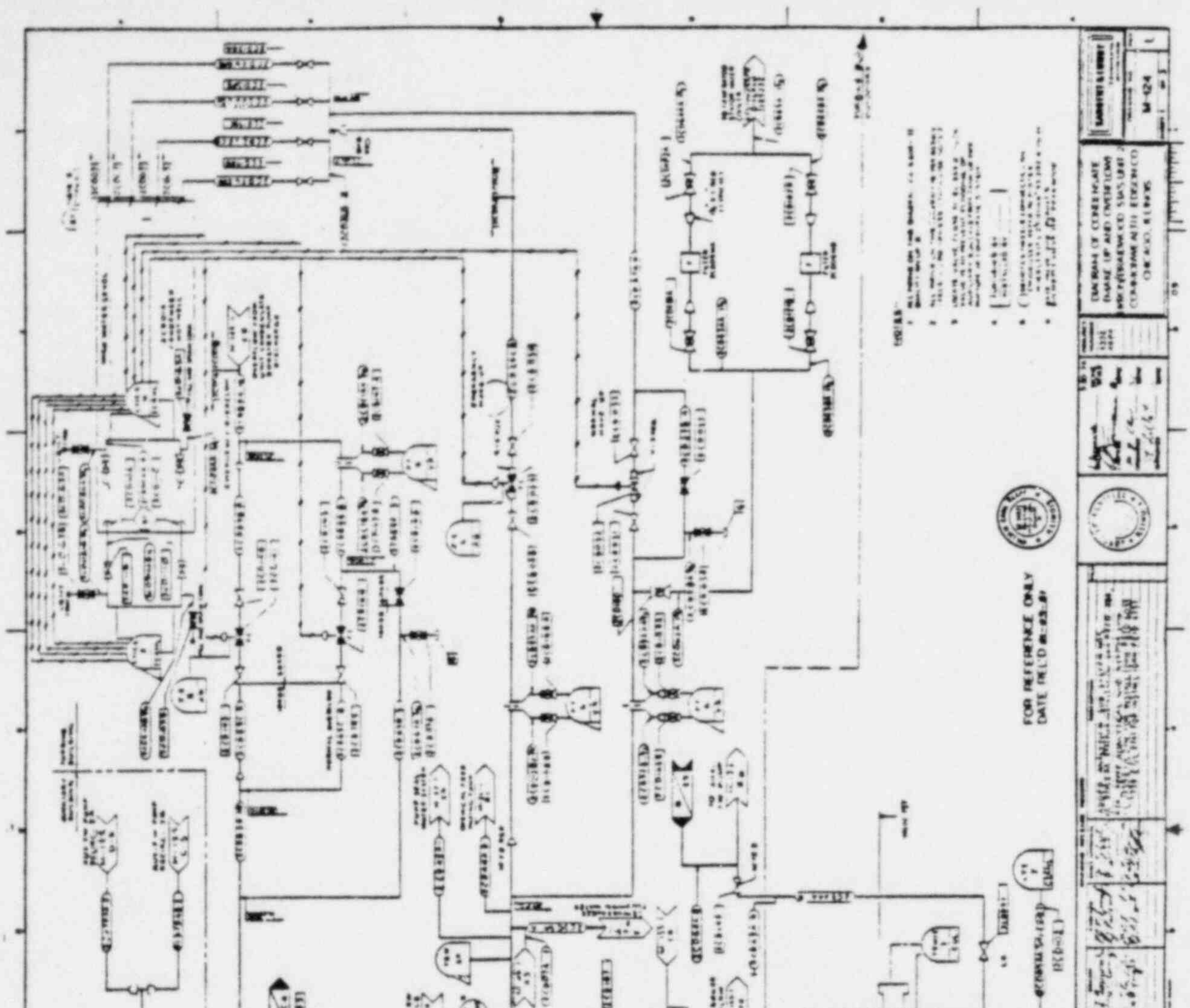


DIAGRAM OF CONDENSATE
BYRON/BRAIDWOOD STATIONS UNIT 1
COMMONWEALTH EDISON CO
CHICAGO ILLINOIS
FOR REFERENCE ONLY


FOR REFERENCE ONLY
DIAGRAM OF CONDENSATE BOOSTER
COMMONWEALTH EDISON CO
CHICAGO


FOR REFERENCE ONLY


ESSENTIAL SERVICE WATER
SAFETY - RELATED


FOR REFERENCE ONLY

APPENDIX I

BYRON/BRAIDWOOD ELECTRICAL DRAWINGS

Figure I.1 1A(2A) AUX FEEDWATER PUMP POWER SOURCES

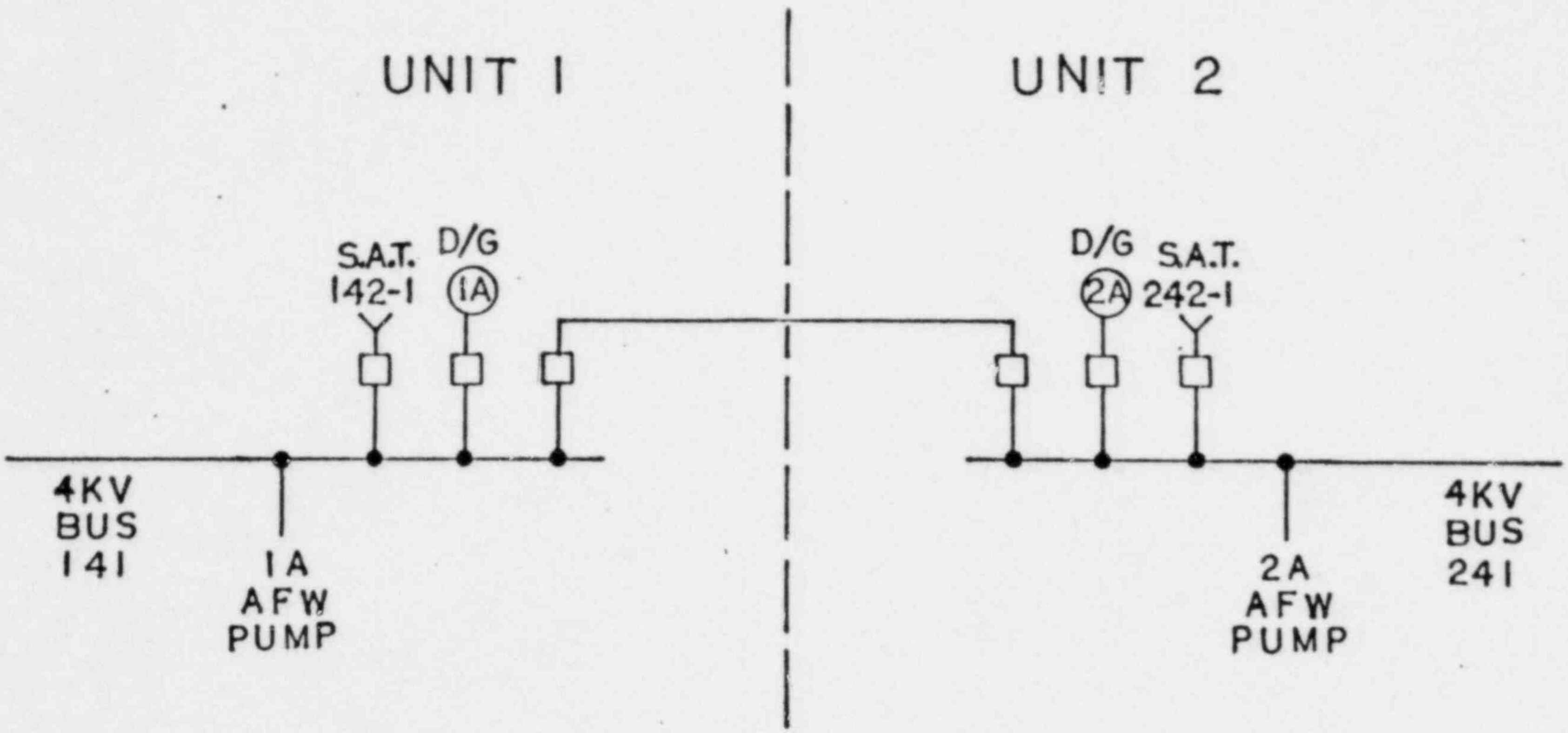


Figure I.2 6.9KV & 4KV DISTRIBUTION

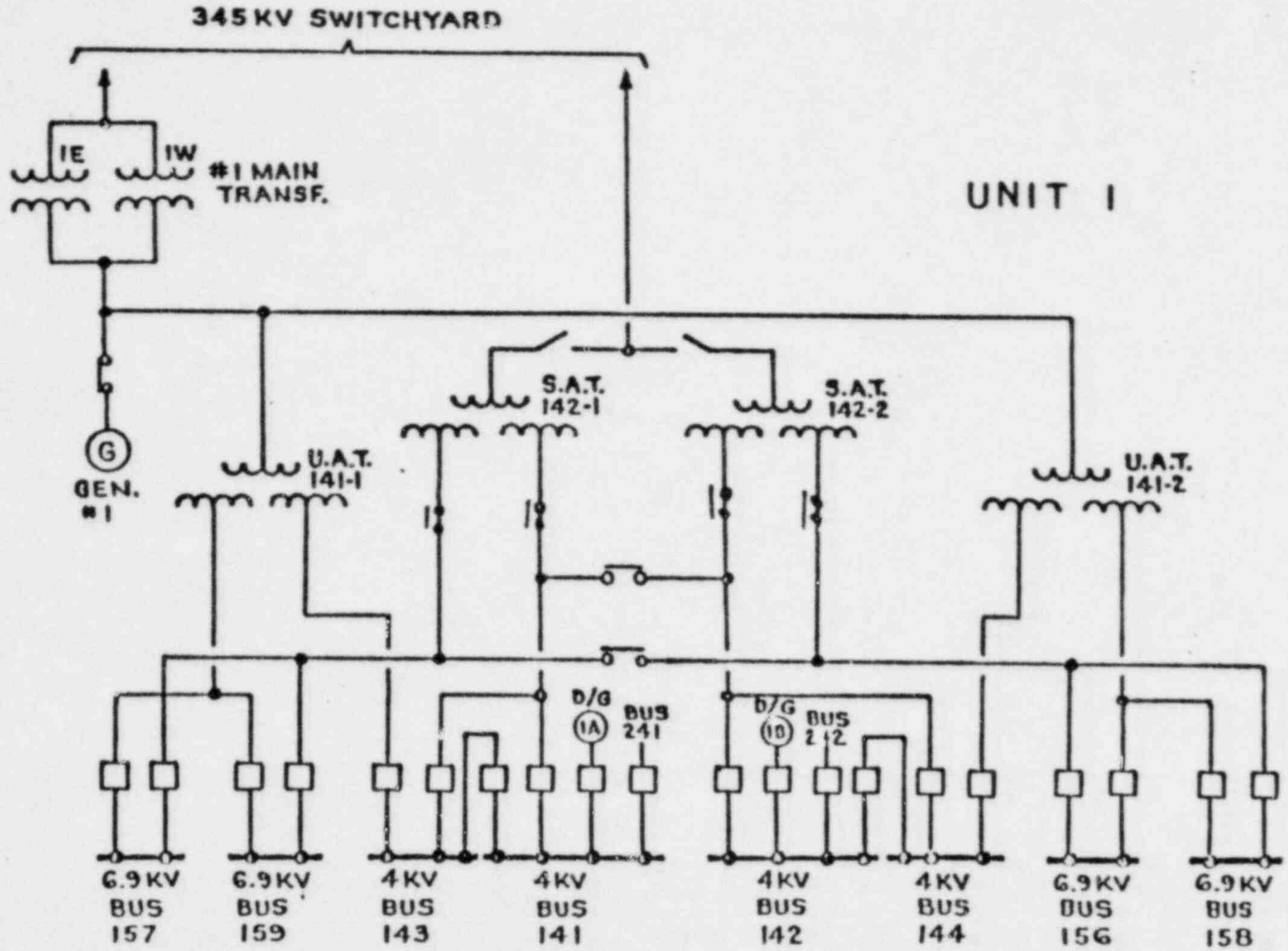


Figure I-3 6900VOLT DISTRIBUTION SYSTEM