NUREG/CR-0013

LMFBR FUEL ANALYSIS
TASK C: RELIABILITY ASPECTS OF LMFBRs

Final Report
October 1, 1976 - September 30, 1977

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Prepared for
U. S. Nuclear Regulatory Commission

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Manuscript Completed: October 1977
Date Published: February 1978

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Prepared for
Division of Project Management
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Under Contract No. NRC-03-77-001

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ABSTRACT

This report provides an analysis of the availability of the electrical power supplies upon reactor shutdown. Successful power supply is defined in terms of the ability of the associated pumps (pump motors) to provide forced circulation and to deliver sufficient feedwater for proper cooldown of the core. Previous investigations of the reliability of the CRBR shutdown heat removal system concentrated on the mechanical systems and/or did not yet consider the diverse power supply. The shutdown heat removal system (SHRS) is discussed in the light of the availability of the electrical power systems, depending upon various types of initiating events. The unavailabilities of the essential power distribution and power supply buses are estimated, so that they can easily be used in connection with analyses of the entire SHRS. Further estimates include mechanical failure of the pumps. This permits a study of the influences of electrical versus mechanical failures and a coarse estimate of the overall failure probability of the SHRS.

NOMENCLATURE

AFWP1 = Auxiliary feedwater pump driven by electrical motor

AFWP2 = Auxiliary feedwater pump driven by electrical motor

AFWPC = Auxiliary feedwater pump cooler

AFWS = Auxiliary feedwater system

BAT1 = Battery system 1 (125 volt battery, class 1E)

BAT3 = Battery system 3 (250 volt batter, diverse power supply)

CBDG1 = Circuit breaker for diesel generator 1

DB1 = Diesel bus 1 (main distribution bus)

DB11 = Diesel bus 11 (unit substation 12 N1E027A)

DCB1 = DC bus 1 (125 volt DC distribution bus 1)

DCB3 = DC bus 3 (250 volt DC distribution bus 3)

DG1 = Diesel generator 1

DPI = Diverse power supply inverter (250 volt vital AC inverter unit)

DPTR = Diverse power supply transformer

EOP = Emergency oil pump

F = Failure (short- or open-circuits)

FTO = Fails to operate

FTR = Fails to transfer

GLBS = Generator load break switch

IP1 = Intermediate sodium pump, 1 pony motor, loop 1

LOSP = Loss of off-site power supply

LPP = Loss of preferred power

MC = Main condenser

MFP = Main feedwater pump

MHTP = Main heat transfer path

MT = Main transformer

ND = New design (with diverse power supply)

NPDB1 = No power on DB1/no LOSP

NPDBL1 = No power on DB1/LOSP

OBN1 = Off-site power supplied bus, nuclear island 1 (4.16 kV N.I. SWGR bus 12 N1E-003C)

OHRS = Overflow heat removal service

PC = Premature closure

PD = Previous design (no diverse power supply)

PPS = Preferred power supply

PP1 = Primary sodium pump, pony motor, loop 1

RCP1 = Recirculation pump, steam/water loop 1

RPS = Reserve power supply

SHRS = Shutdown heat removal system

SGAHRS = Steam generator auxiliary heat removal system

SST1 = Secondary service transformer 1

TAFWP = Turbine-driven auxiliary feedwater pump

TR11 = Transformer 11 (unit substation 12 N1E-027A)

UST = Unit station service transformer

1.0 INTRODUCTION

According to the design of the Clinch River Breeder Reactor (CRBR), during the first phase after shutdown the heat removal is performed via the three main heat transfer paths, each one consisting of the primary sodium loop, the intermediate sodium loop, and the steam/water loop. In order to enable forced circulation upon loss of off-site power, the primary and intermediate sodium loop pumps will be equipped with pony motors which can be supplied from the stand-by electrical power sources. A more recent design of the on-site electrical power system provides a diverse power supply in addition to the two diesel generators, so that three independent and segregated stand-by power sources will be available for the pony motors of each of the three main heat transfer paths.

This report provides an analysis of the availability of the electrical power supplies upon reactor shutdown. Successful power supply is defined in terms of the ability of the associated pumps (pump motors) to provide forced circulation and to deliver sufficient feedwater for proper cooldown of the core. Previous investigations of the reliability of the CRBR shutdown heat removal system concentrated on the mechanical systems and/or did not yet consider the diverse power supply. The shutdown heat removal system (SHRS) is discussed in the light of the availability of the electrical power systems, depending upon various types of initiating events. The unavailabilities of the essential power distribution and power supply buses are estimated, so that they can easily be used in connection with analyses of the entire SHRS. Further estimates include mechanical failure of the pumps. This permits a study of the influences of electrical versus mechanical failures and a coarse estimate of the overall failure probability of the SHRS.

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2.0 THE ROLE OF A RELIABLE POWER SUPPLY FOR THE SHUTDOWN HEAT REMOVAL SYSTEM

The CRBR is of the three loop type, consisting of three primary sodium loops and three steam/water loops, with two evaporators and one superheater per loop supplying steam to the turbine.

The function of the main heat transfer paths (MHTP's) during normal power plant operation is as follows.

1. Primary sodium is circulated by the primary pump and the heat generated is transferred in the intermediate heat exchanger.
2. The intermediate pump circulates the secondary sodium and the heat is transferred to the steam/water loop in the superheater and evaporators.
3. Water is circulated through the evaporator by the recirculation pump and a percentage of the water is vaporized. The steam is then superheated and used to produce power in the balance of plant equipment.

The SHRS is a complex system, consisting for the most part of units which are used during normal plant operation. Other subsystems are on stand-by and are put in operation on demand, or require some re-configuration in order to meet the requirements of SHRS operation.

Immediately after shutdown of the reactor, the main heat transfer paths are normally used to remove decay heat and, as a result, plant operations verify the functionability of the normal shutdown heat removal path. Moreover, immediately after shutdown from full power operation, the MHTP's are the only system providing sufficient capability for shutdown heat removal. In order to cope with the loss of the main condenser (MC) or the main feedwater pumps (MFWP's), alternate heat sinks are provided by the steam generator auxiliary heat removal system (SGAHRS):

(a) The auxiliary feedwater system (AFWS) provides an alternate supply of feedwater. Sufffficient water is available in the protected water storate tank to remove the plant sensible heat. Steam generated during this mode of shutdown heat removal is vented to the atmosphere.

(b) After removing the majority of sensible heat by means of the AFWS, the protected air-cooled condensers can function as a closed system for the removal of heat.

The availability of the electrical power systems treated in this report are concerned with the problem of providing adequate power to the subsystems of the SHRS which are needed during shutdown of the reactor, and which were briefly described above. With respect to complete description of the SHRS and its various modes of operation to accomplish shutdown heat removal, reference should be made to the CRBR preliminary safety analysis report (PSAR).

2.1. Power Supply at Start of SHRS Operation

The SHRS is designed to provide cooling of the reactor core according to its needs during the various phases of the cooldown period. The general cooling capacity requirements become less as time proceeds, which leads to a rising redundancy in the SHRS. Based on the criterion that the SHRS needs to remove reactor decay heat to the extent that the bulk sodium temperature in the reactor vessel will not exceed 1,250° F, NEDM-14082 [5] defined three time periods, each one considering the system configurations which are necessary to provide sufficient cooling capacity. During the first period (1 hour), heat removal occurs only through the MHTP's and the MC, or through the MHTP's and the steam generator auxiliary heat removal system with safety and vent valve operation. This period ends when the overflow heat removal service (OHRS) has sufficient heat removal capability, i.e., sufficient shutdown heat removal is available independently of the MHTP's capability to remove heat.

The analyses of the electrical power systems performed in this report refer to that first time period, where the requirements are supposed to be the most stringent, and where only a little time is available to restore the initially lost power. Because of the short time period under consideration, the significant contribution will be from the probability of providing insufficient electrical power to the engineered safeguard features (ESF's) which have to operate during this period.

Reliability investigations of the SHRS performed by Batelle Northwest Laboratory (BNL), Nuclear Utility Services (NUS), and the University of California, Los Angeles (UCLA), have shown three areas of major concern:

(i) The integrity of the primary heat transfer loops.

(ii) The adequacy of coolant recirculation in the MHTP's.

(iii) The capability of providing feedwater to the steam/water loops.

With reference to the electrical power systems the two latter cases are of interest, because they are concerned with the power supply to the motors of the MHTP's and the SGAHRS's, respectively.

2.2. Success of Power Supply

The CRBR has three MHTP's each one consisting of the primary sodium loop, the secondary sodium loop, and the steam/water loop. Besides the layout of the loops for natural circulation, the pumps of the primary and intermediate loops are equipped with pony motors which, in contrast to

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the normal pump drives, can be operated from the on-site stand-by electrical power sources.

Different aspects of the problem as to what extent one can rely on natural circulation have been discussed in References [2] and [3]. In the former, for example, it was mentioned that events like partial failure of check valves or flow-measurement instrumentation, contaminant deposition in the loops, or sodium plugging should be considered in the context of interrupting or slowing down of natural circulation. Flow reductions of this type will, of course, affect the criterion as to how many MHTP's should be considered sufficient in providing adequate cooling of the core by natural circulation. In any case, more recently, a further step was taken for improvement of the forced recirculation by providing diverse electrical power sources in addition to the two diesel generators, so that now a separate standby power supply is available for the pony motors of each of the three MHTP's [1].

In order to cover all uncertainties in the context of natural circulation, we conservatively defined a baseline case, which only takes credit for the natural circulation capability of the steam/water circuits. Later it was assumed that at shutdown from full power operation, at least one MHTP with forced recirculation has to be available. That means fulfillment of the mission on shutdown from full power operation is achieved if at least two sodium heat transfer paths provide forced recirculation and their associated steam/water loops are on natural circulation <u>or</u> if at least one MHTP provides forced recirculation.

Up to now, only the shutdown heat transfer from the core to the steam/water loop and the associated problems of electrical power supply have been discussed. As already mentioned, final heat removal is performed either through the MC or the SGAHRS. If the main condenser or the main feedwater supply is lost, the SGAHRS provides water by means of the AFWS, while during the first time period steam is vented off to the atmosphere. Three pumps are provided to deliver water from the protected water storage tank to the steam drums of the steam/water loops. Two of them are driven by electrical motors (AFWP1 and AFWP2), which can be supplied from stand-by power sources. Each has the capacity of delivering 50% of the feedwater flow required. The third pump (TAFWP) is driven by a steam turbine which uses steam bled from the steam drum. The AFWS is common to the three steam/water loops and consequently has been of major concern in the various reliability analyses of the SHRS performed so far.

According to the configuration explained above, fulfillment of the mission of the AFWS during the first time period was defined as the ability of the two AFWP's <u>or</u> of the TAFWP to operate on demand, for those initiating events which disable the main feedwater system.

In summary, the success of power supply to the SHRS during the first time period was defined as the availability of electrical power at the pony motors of the main heat transfer paths, taking into account the failure-to-operate probability of the recirculation pumps (RCP's) of the steam/water loops, and the availability of electrical power supply at the auxiliary feed water pump motors (AFWP's), taking into account the failure-to-start probability of the turbine-driven auxiliary feedwater pump (TAFWP).

The estimation of power supply unavailability was performed by means of fault tree analyses for various initiating events. Based on the more general definition given above, in Section 4 the top events were redefined in terms of those motor power supplies which are involved in the cases considered.

2.3. Initiating Events

The initiating events calling for operation of the SHRS have been investigated in the light of their influence on electrical power supply. In addition, the initiating events applied in previous reliability analyses of the SHRS have been presented differently, so that the influence of the electrical system on the overall reliability of the SHRS becomes more apparent.

The number of the expected plant shutdowns requiring operation of the SHRS was estimated upon the bases of the information given in the Operating Units Status Reports issued by the NRC [6]. The nuclear power shutdowns listed there are split off into two main categories, Forced Outages during Month and Scheduled Outages during Month, where Forced Outage is defined as "An outage required to be initiated no later than the weekend folllwing discovery of an off-normal condition," and Scheduled Outage is defined as "Planned removal of a unit from service for refueling, inspection, training, or maintenance." As a consequence, it is not readily seen as to what extent post-shutdown heat removal was involved. However, a certain indication may be gained from another figure given, i. e. the number of shutdowns lasting longer than 72 hours each. When we look at the years 1974 through 1976, we get the following rounded figures:

Forced Outages:	13/plant-year
Scheduled Outages:	7/plant-year
Total Outages:	20/plant-year
Shutdowns greater than 72 hours:	9/plant-year

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On the basis of these figures we assumed for the baseline case a total number of 10 shutdowns per year requiring operation of the SHRS. That number was subdivided according to five initiator groups, whose relative contribution was estimated from the duty cycle given in the PSAR and from failure rate data:

1. Shutdown with 3 MHTP's available.
2. Shutdown with 2 MHTP's available.
3. Shutdown with 1 MHTP available.
4. Shutdown due to loss of AFWP's or MC.
5. Shutdown due to loss of off-site power.

Table 1 shows how the initiator groups were derived from the duty cycle events. The abbreviations in the third column are those used in the PSAR. In the following, some comments with respect to the grouping procedure are given.

<u>N-3a, N-3b (normal shutdown).</u> It is conservatively assumed that from the beginning of the cooldown process the plant generator is not available, so that power supply is either from the grid or from the on-site power systems.

<u>U-3a, U-4a (control malfunction/operator error causes the slowing down of one primary or one intermediate pump).</u> It is assumed that further operation of the affected pump can be accomplished by means of the pony motor.

<u>U-3b, U-4b (loss of power to one primary or one intermediate pump).</u> Further operation of the pump is achieved by means of the pony motor, which can be supplied also from on-site standy electrical power sources.

<u>U-5a (loss of power on one main feedwater pump motor).</u> The assumption of a reactor shutdown as a consequence of this event is conservative,

	Initiator Group	Duty Cycle Events	Number of Events
1a	Shutdown due to other than power supply failure of primary or intermediate pump motors	N-3a, N-3b, U-1, U-2a, U-2b, U-5a, U-13, U-15a, U-16 U-21a*, U-21b*, U-22*	571
1b	Shutdown due to power supply failure of primary or intermediate pump motors	U-3a, U-3b, U-4a, U-4b U-7a, U-7b	52
1c	Shutdown due to failure of recirculation pump	U-14	24
1	Shutdown with 3 MHTPs available		647
2a	Shutdown due to failure of primary sodium loop	derived from failure rates	(16)
2b	Shutdown due to failure of intermediate sodium loop	derived from failure rates	(19)
2c	Shutdown due to failure of steam/water loop	U-10, U-11a, U-11b, U-11c, U-19a, U-19b, U-19c, U-21a*, U-21b*, U-22* U-23, E-X	124
2	Shutdown with 2 MHTPs available		124+(35)
3	Shutdown with 1 MHTP available	U-6	10
4	Shutdown due to loss of MFWS or MC		32
5	Shutdown due to LOSP		16

Remarks: The duty cycle events and their numbers are taken from the PSAR /1/.
*It is assumed, that in one case each a shutdown with 2 MHTPs available would result

Table 1. Grouping of duty cycle events

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because there is automatic switching to the spare feedwater pump. Hence, the upset event 5a was counted as a contributor to the MHTP shutdown. Furthermore, loss of the main feedwater system is covered by initiator group 4.

U-7a, U-7b (primary pumps or intermediate pumps speed increases due to control system malfunction). Further operation of the affected pumps is achieved by means of the pony motors, which can be supplied also from on-site standby electrical power sources.

U-15a (turbine trip without reactor trip). Turbine trip is followed by the opening of the bypass valves to the main condenser, so that normal reactor shutdown can be performed. The electrical power requirements for the SHRS are assumed to be the same as for an instantaneous reactor trip.

U-21a, U21b (inadvertent opening of evaporator or superheater outlet safety/power relief valves). It is assumed that in one case a 2 MHTP shutdown would result.

U-22 (inadvertant opening of drum valve). It is assumed that in one case a 2 MHTP shutdown would result.

E-X (emergency events). As in Reference [2], it was assumed that the following emergency events contribute once each to failure of one steam/water loop:

E-3a (feedwater line rupture with steam drum blowdown).

E-4a (saturated steam line rupture with steam drum blowdown).

E-6 (steam generator sodium-water interaction).

E-13 (recirculation line break with steam drum blowdown).

E-14 (inadvertent dump of intermediate loop sodium).

As indicated in Table 1, the initiator groups 2a and 2b were

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derived from failure rates. On the basis of the data given in NEDM-14082 [5], we calculated the following initiator frequencies:

<u>Failure rates of one primary sodium loop:</u>

Piping leakage	$0.63 \times 10^{-6}\ hr^{-1}$
Check valve leakage	$0.11 \times 10^{-6}\ hr^{-1}$
Pump leakage	$0.21 \times 10^{-6}\ hr^{-1}$
Intermediate heat exchanger leakage	$0.38 \times 10^{-6}\ hr^{-1}$
Drain valve leakage	$0.21 \times 10^{-6}\ hr^{-1}$
Pump bearing seizure	$7.0 \times 10^{-6}\ hr^{-1}$
TOTAL	$8.54 \times 10^{-6}\ hr^{-}$

Hence, the shutdown frequency due to the failure of the primary sodium loop (2a) is:

$$3 \times 8.54 \times 10^{-6} \times 8{,}760 \times 0.85 = 0.19\ year^{-1},$$

when considering a plant-load factor of 0.85.

<u>Failure rates of one intermediate sodium loop:</u>

Piping leakage	$1.3 \times 10^{-6}\ hr^{-1}$
Pump leakage	$0.21 \times 10^{-6}\ hr^{-1}$
Venturi leakage	$0.01 \times 10^{-6}\ hr^{-1}$
Intermediate heat exchanger leakage	$0.5 \times 10^{-6}\ hr^{-1}$
Leakage of drain valves	$0.63 \times 10^{-6}\ hr^{-1}$
Pump bearing seizure	$7.0 \times 10^{-6}\ hr^{-1}$
TOTAL	$9.65 \times 10^{-6}\ hr^{-1}$

Hence, the shutdown frequency due to failure of the intermediate sodium loop (2b) is:

$$3 \times 9.65 \times 10^{-6} \times 8{,}760 \times 0.85 = 0.22\ year^{-1}.$$

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when considering a plant-load factor of 0.85.

Table 2 shows the occurrence frequencies of the five initiator groups, where the contributions of the primary and intermediate sodium loop failures were included in group 2 according the results given above. As already indicated, all the other frequencies are deduced from the duty cycle events.

	initiator group	percentage of contribution	number of shut-downs, yr^{-1}
1	shutdown with 3 MHTPs available	74.85	7.485
2	shutdown with 2 MHTPs available	18.44	1.844
3	shutdown with 1 MHTP available	1.16	0.116
4	shutdown due to loss of MFWS or MC	3.7	0.370
5	shutdown due to LOSP	1.85	0.185
	TOTAL	100.	10.

Table 2. Initiator groups and frequencies

3.0 DESCRIPTION OF THE SAFETY-RELATED ON-SITE POWER SYSTEMS

In this section the safety-related on-site power systems are described to the extent necessary to an understanding of the reliability analyses which were performed. A more extensive description is given in the CRBR PSAR [1].

The systems consist of the:

Safety-Related AC Power System,

125 Volt DC Power System,

Diverse Power System, and

120 Volt Vital AC Power System.

3.1. The Safety-Related AC Power System

The system is split into two branches, each one distributing power to a redundant load group via the two 4.16 kV diesel buses (DB1 and DB2). Each diesel bus receives AC power from the preferred power supply (PPS), from the reserve power supply (RPS), or the associated diesel generator.

The PPS consists of the two 161 kV transmission circuits in the generating switchyard connected to the main transformer (MT), and the unit station service transformer (UST). The RPS consists of the two 161 kV transmission circuits in the reserve switchyard connected to the two reserve transformers (RT's). Finally, either preferred power or reserve power is fed via secondary service transormers 1 and 2 (SST1 and SST2) to the two buses DB1 and DB2, respectively (Figures 1 and 2). These transformers also feed the non-class IE buses OBN1 and OBN2, to which the recirculation pumps (RCP) of the steam/water loops are connected (Figure 4). Note that the single line diagram Figure 1 does not show SST1 or SST2, which have evidently been added at a later design stage. The PPS

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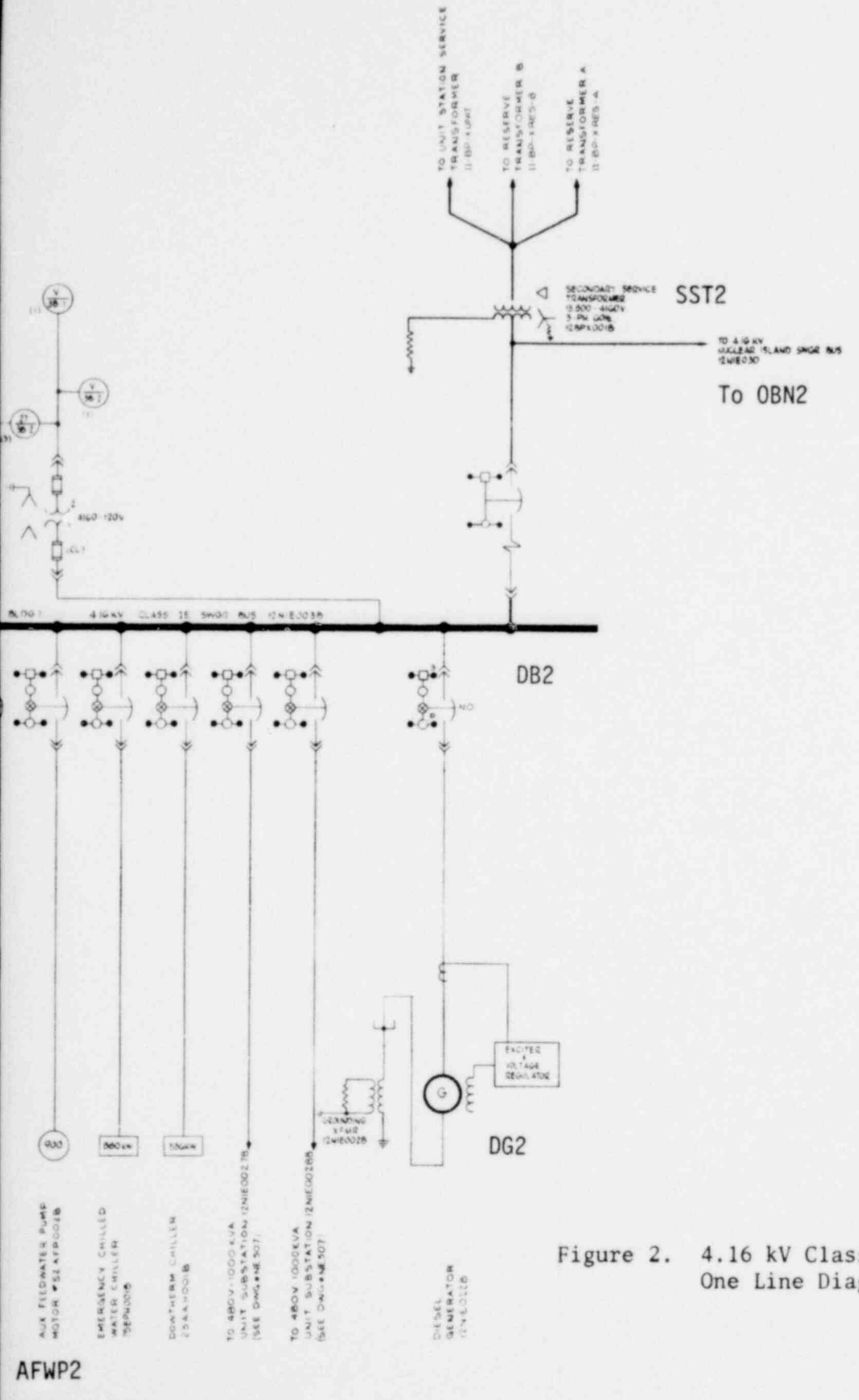

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Figure 2. 4.16 kV Class IE Switchgear One Line Diagram (DB2).

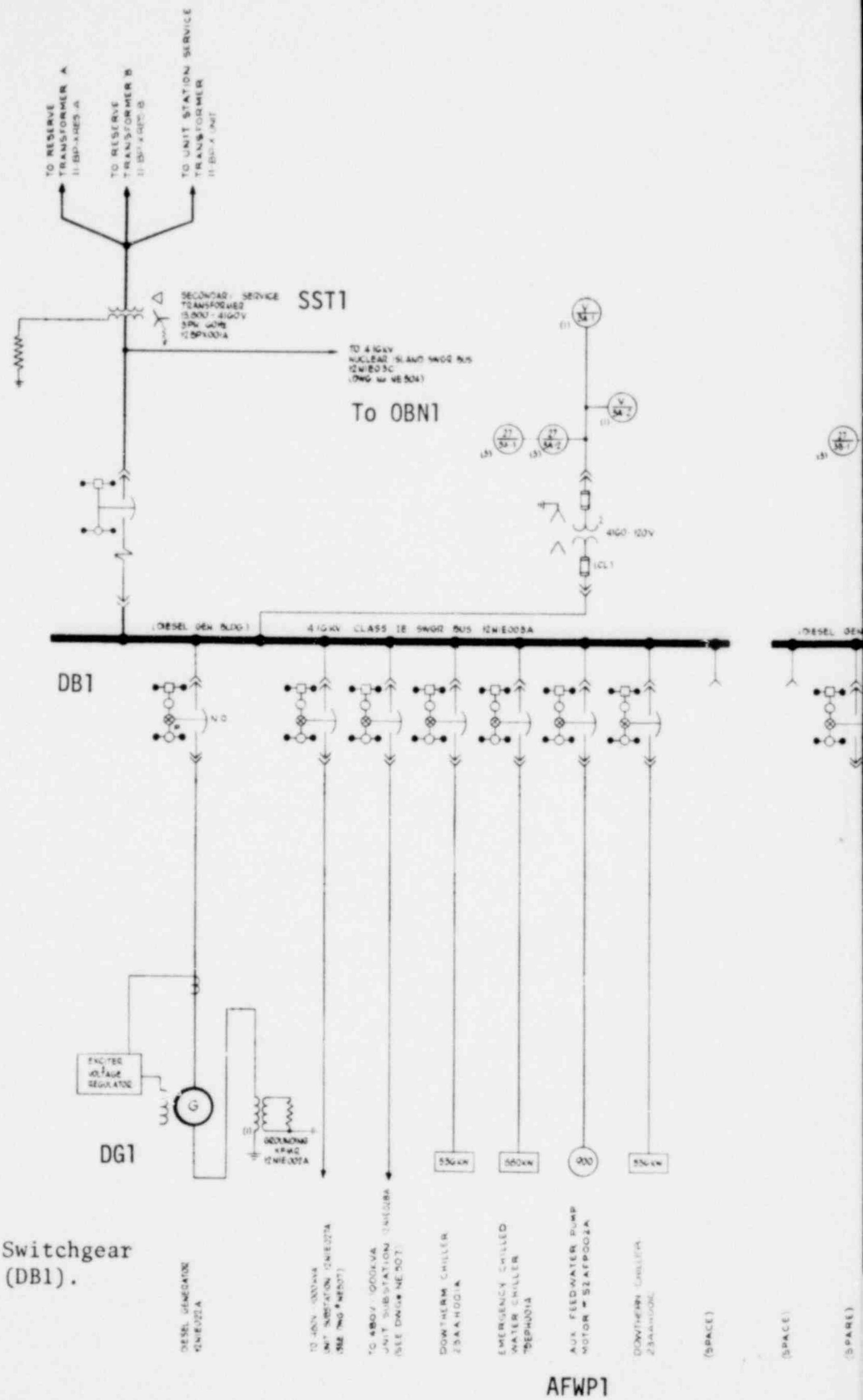

Figure 1. 4.16 kV Class IE Switchgear One Line Diagram (DB1).

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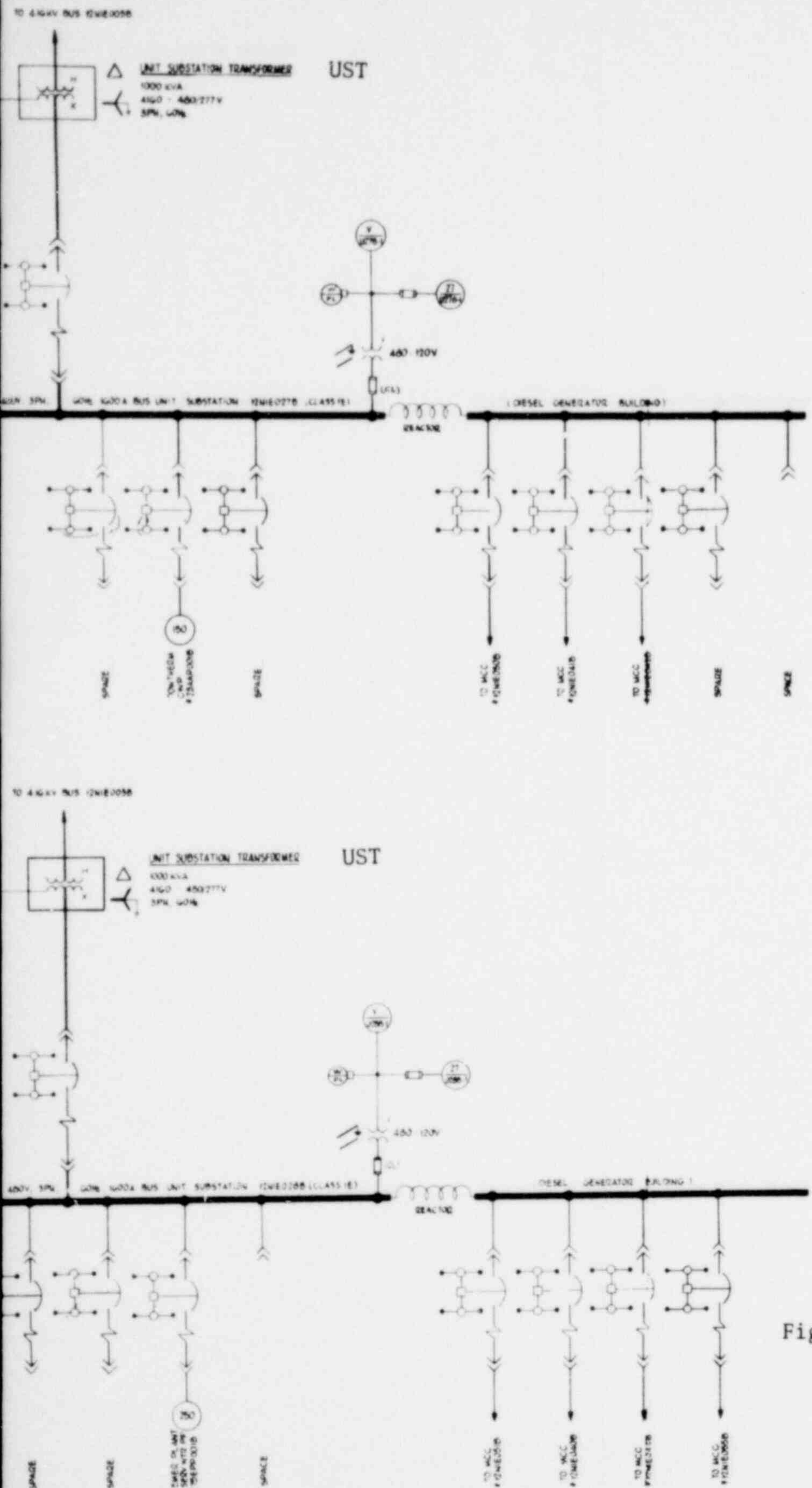

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Figure 3. 480 V Unit Substation One Line Diagram.

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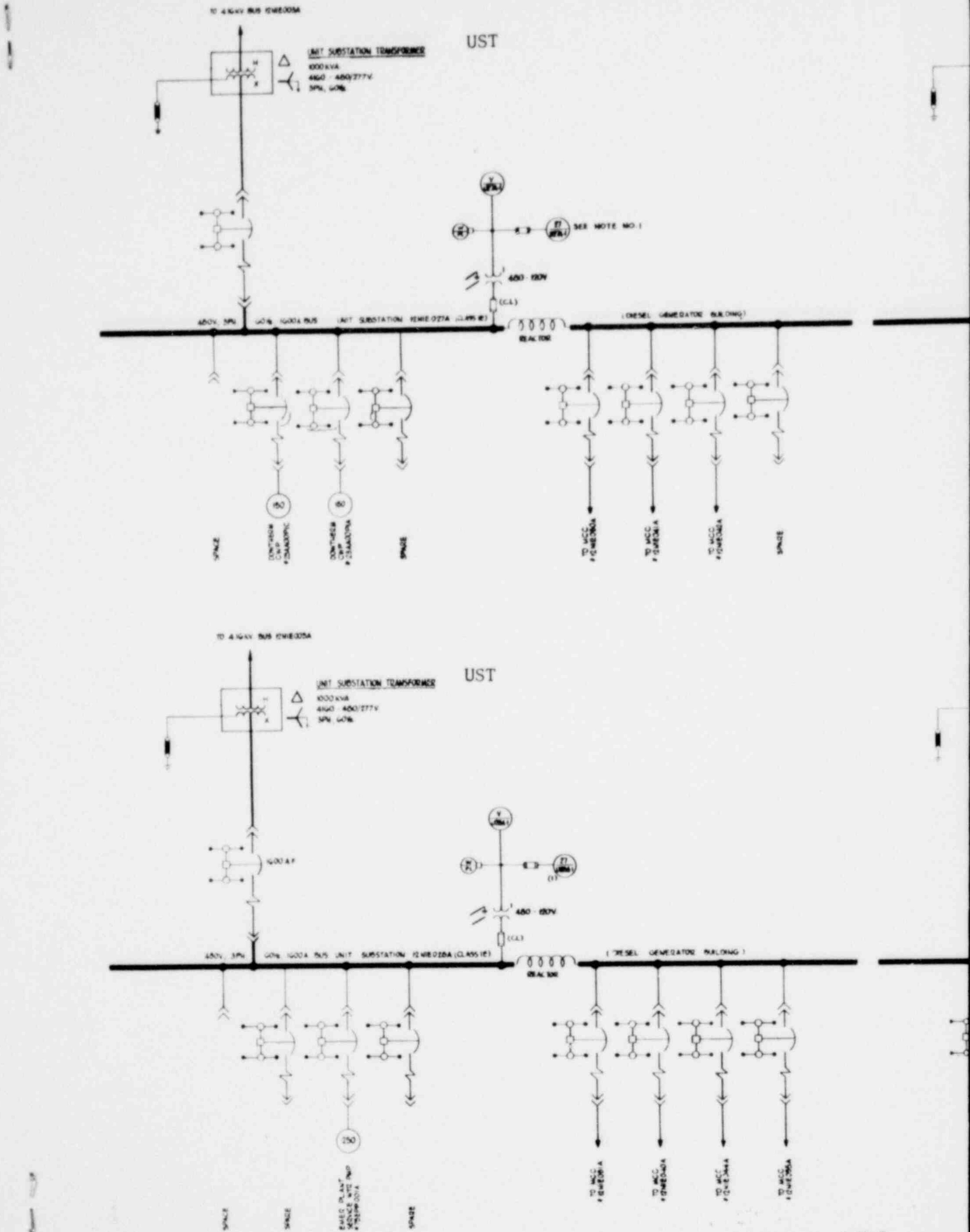
UST
UNIT SUBSTATION TRANSFORMER
1000 KVA
UST
UNIT SUBSTATION TRANSFORMER
1000 KVA
REACTOR
REACTOR
250

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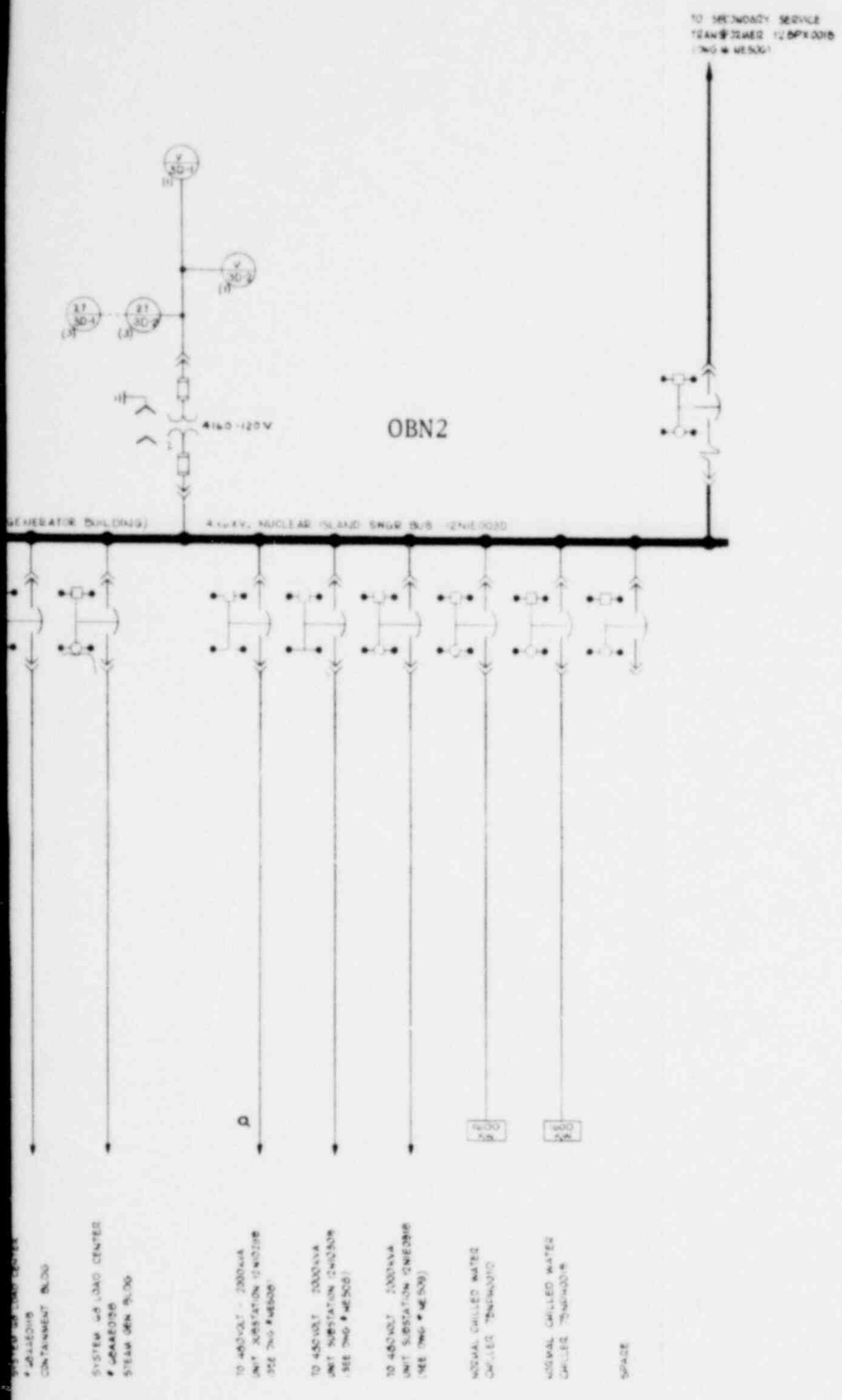

Figure 4. 4.16 kV Switchgear
. One Line Diagram.

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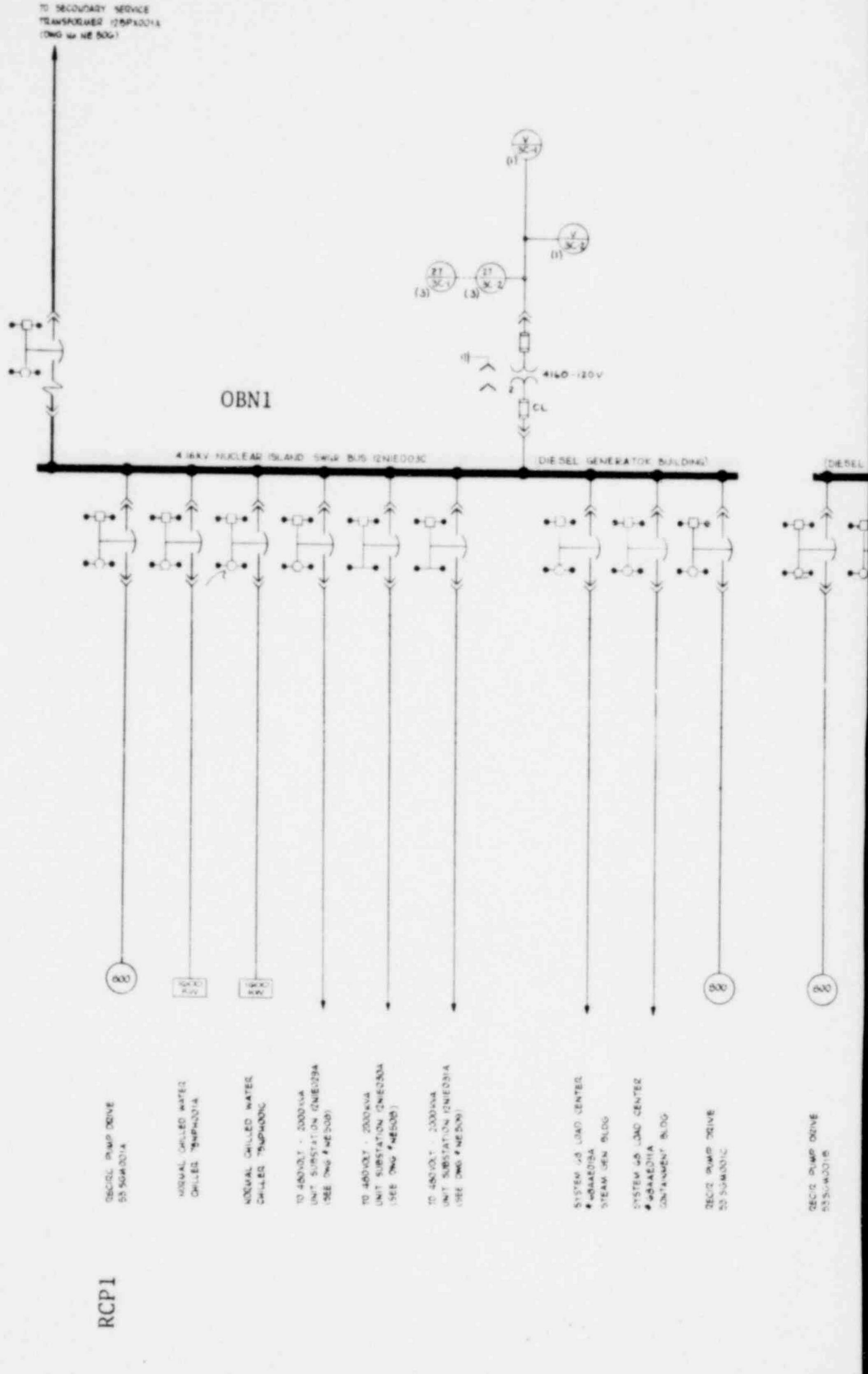
TO SECONDARY SERVICE
TRANSFORMER 12BPX001A
OBN1
4160-120V
CL
4.16KV NUCLEAR ISLAND SWGR BUS 12NIE003C
DIESEL GENERATOR BUILDING
600
600
600
RECIRC PUMP DRIVE
NORMAL CHILLED WATER
NORMAL CHILLED WATER
TO 480VOLT - 2000KVA
UNIT SUBSTATION
TO 480VOLT - 2000KVA
UNIT SUBSTATION
TO 480VOLT - 2000KVA
UNIT SUBSTATION
SYSTEM LOAD CENTER
STEAM GEN BLDG
SYSTEM LOAD CENTER
CONTAINMENT BLDG
RECIRC PUMP DRIVE
RECIRC PUMP DRIVE
RCP1

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and RPS switchyards are connected to the grid through four separate transmission lines.

Larger loads like the AFWP's are connected directly to the diesel buses. Power to 480 V loads is provided by unit substation transformers connected to the diesel buses, as shown in Figure 3. For example, loads fed at this voltage level are the primary pony motors (PP) and the intermediate pony motors (IP) or the auxiliary feedwater pump coolers (AFWPC).

When the main generator is operating, the Safety-Related AC Power System receives power from the plant power supply. In the event of a turbine or reactor trip in the absence of an electrical fault, the generator load-break switch (GLBS) is automatically opened. The unit service station transformers remain connected to the PPS and provide uninterrupted power. An electrical fault in the main generator causes the tripping of the associated 161 kV circuit breakers located in the generating switchyard and loss of the power supply from the unit-station service transformers.

Upon loss of the PPS, the following automatic actions are initiated:

1. Tripping of the supply circuit breakers from the unit station service transformers.
2. Tripping of the non-class IE motor loads.
3. Delayed closing of the RPS circuit breakers from the reserve transformers.

Independently of the transfer to the RPS the diesel generators are started, but the supply breakers of the associated diesel buses remain open. Once the restoration of the voltage by means of the RPS has been successful, the diesel generators are stopped manually, but they remain

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ready to start and to supply power.

Upon loss of the RPS, the following automatic actions are initiated:

(a) Tripping of the circuit breakers connecting the class IE switchgear buses to the reserve transformers.

(b) Closing of the diesel generator circuit breakers (CBDG1 and CBDG2).

After restoration of the voltage at the 4.16 kV class IE switchgear buses, automatic sequential loading is performed, as required to maintain safe shutdown of the plant.

3.2. The 125 Volt DC Power System

Class IE loads supplied by the 125 V DC Power System are divided into two redundant groups. Each group receives power from a separate and independent 125 volt DC battery supply (BAT1 and BAT2). DC power is required for control of the 4.16 kV circuit breakers and the 480 V load center circuit breakers. It is supplied from BAT1 or BAT2 in correspondence with the associated branch of the Safety-Related AC Power System (Figure 5).

Each battery supply is furnished with two 125 volt solid-state battery chargers. Each charger is of adequate capacity to restore the battery from design minimum charge to the full charge within 12 hours while supplying power to the steady-state loads during normal operation.

One battery charger is continuously connected. During a loss of AC power, the battery charger is automatically re-energized when AC power is restored. The other battery charger is used as a standby. The DC crcuit breaker is normally closed to connect the standby battery charger to the DC distribution bus.

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3.3. The Diverse Power System

This system was added more recently [1] and provides a separate and diverse power source for the pony motors of the main heat transfer path 3 (MHTP3). Power to the 480 V AC pony motors PP3 and IP3 is supplied from a 250 volt battery system (BAT3) via the diverse power inverter (DPI), the diverse power 250 volt/480 volt transformer (DPTR) and the diverse power AC bus (DPB). There are two battery chargers; one is fed from the normal AC power distribution system, and the other can be fed from either DB1 or DB2 (Figure 5).

One battery charger is continuously connected to its 480 V load center and to the associated 250 V DC bus (DCB3). During a loss of power, the battery charger is automatically re-energized when AC power is restored. The other battery charger is used as a standby. The DC circuit breaker of the standby unit is normally open, and is closed manually of feeding of DCB3 via this unit is necessary. In the event of the loss of all offsite AC power sources and one diesel bus, a transfer switch can be used to manually connect the diverse power supply to the available diesel bus.

3.4. The 120 Volt Vital AC Power System

The system is divided into three separate groups, each receiving AC power from a separate inverter through a static transfer switch. The normal source of power for the three distribution buses of the vital AC power system are the inverters which are supplied from the battery systems described in the two previous sections. Power can also be provided from back-up Class IE 480 V motor control centers. If an inverter or its DC power source fails, the associated distribution bus is transferred automatically by the static transfer switch to the back-up motor control center. The transfer is accomplished at high speed, so that performance ov vital control and instrumentation is not degraded. Amongst others, the vital AC power system supplies AC power to the plant protection system (PPS).

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4.0 FAULT TREE ANALYSIS OF THE POWER SUPPLY FOR THE SHUTDOWN HEAT REMOVAL SYSTEM

Based upon the success of power supply as defined in Section 2.2, and upon the initiator groups to be treated, basic fault trees were set up. In order to keep track of the influence of loss of off-site power, all fault trees were constructed in such a way as to directly deliver the unavailability contribution from loss of off-site power and the failure of one diesel to provide electrical power via its associated buses. Furthermore, the trees allow for a comparison of the situations before and after using the diverse power supply. Subsequently, the systems are referred to as previous design (PD), with no diverse power supply, and as new design (ND), with diverse power supply.

Consequently, the basic fault trees were constructed with reference to the following top events:

1. No power on one of the two diesel buses (Figure 6).
2. Failure of forced recirculation, 3 MHTP's available at reactor shutdown, PD (Figure 7).
3. Failure of forced recirculation/loss of off-site power, 3 MHTP's available at reactor shutdown, ND (Figure 8).
4. Failure of forced recirculation, 2 MHTP's available at reactor shutdown, ND (Figure 9).
5. Failure of forced recirculation, 1 MHTP available at reactor shutdown, ND, PD (Figure 10).
6. Failure of the auxiliary feedwater pumps, main feedwater system not available at reactor shutdown (Figure 11).

The top of the tree given in Figure 6 was chosen in order to realize the fact that both electrical AFWP's are necessary to deliver sufficient

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Fig. 6. No power on either one of the two diesel buses upon reactor shutdown.

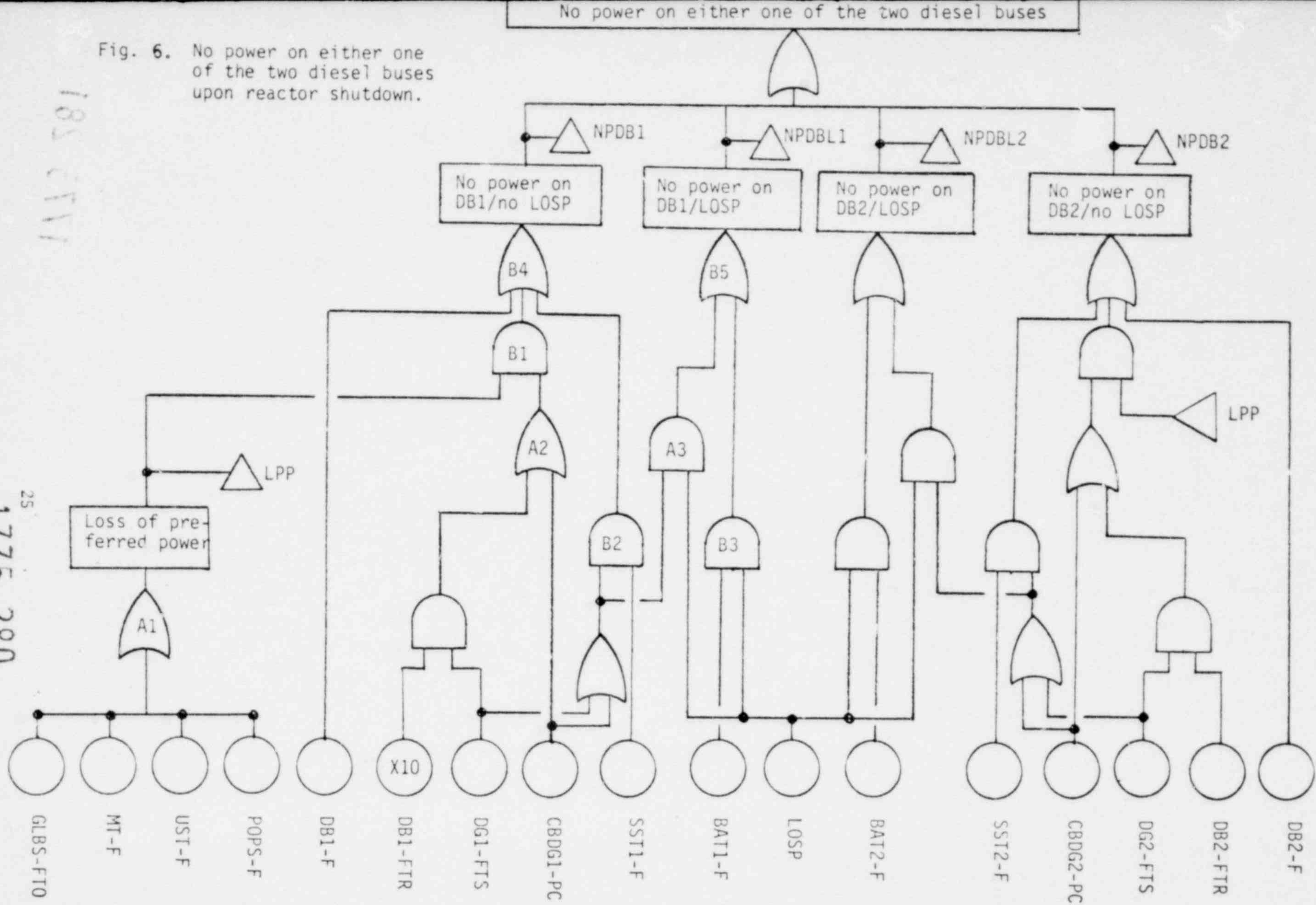

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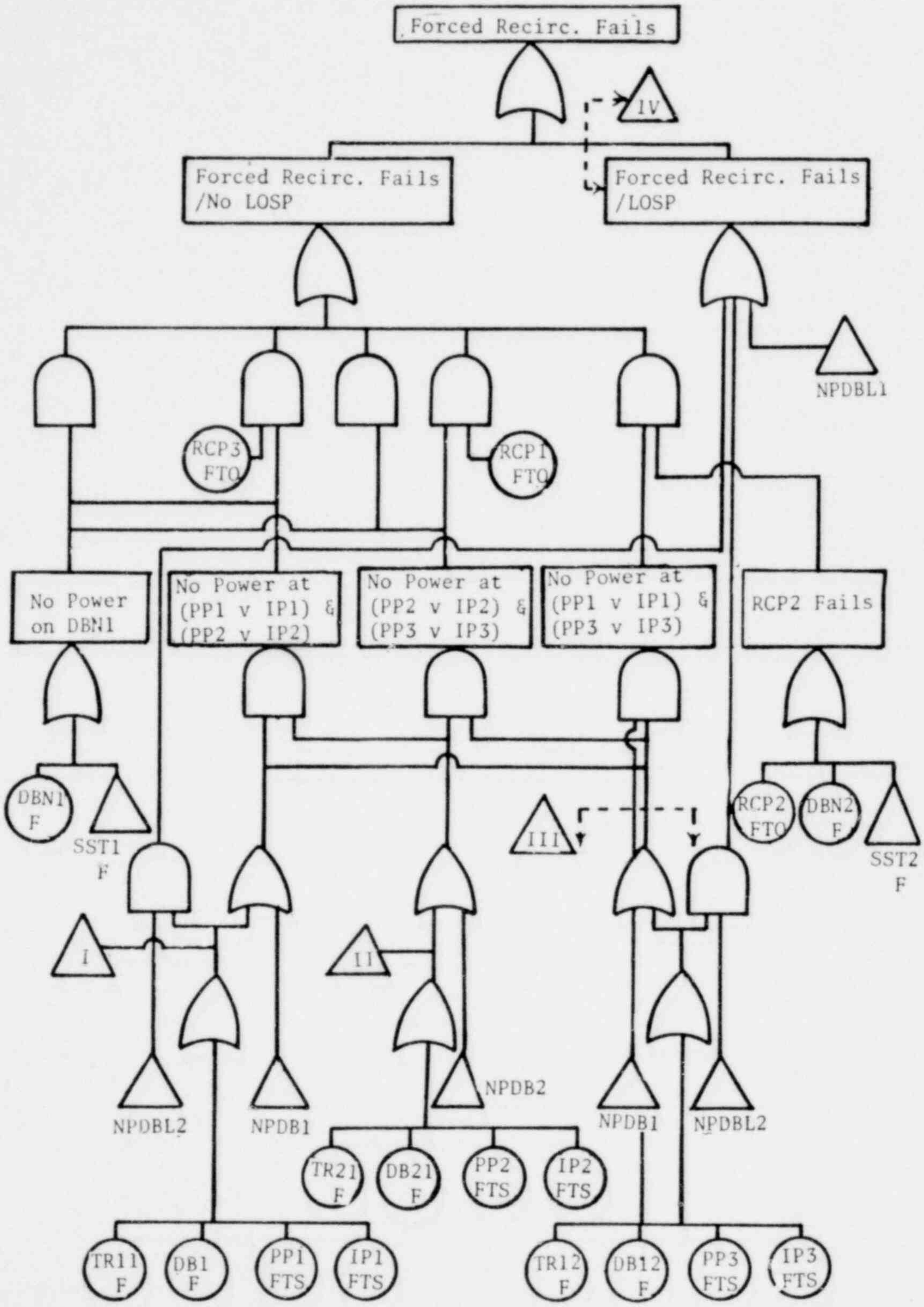
Figure 7. Fault tree, Forced Recirculation Fails, 3 MHTP's Available at Reactor Shutdown, PD.



Note: For ND replace these parts by subtrees given in Figures 8 and 9

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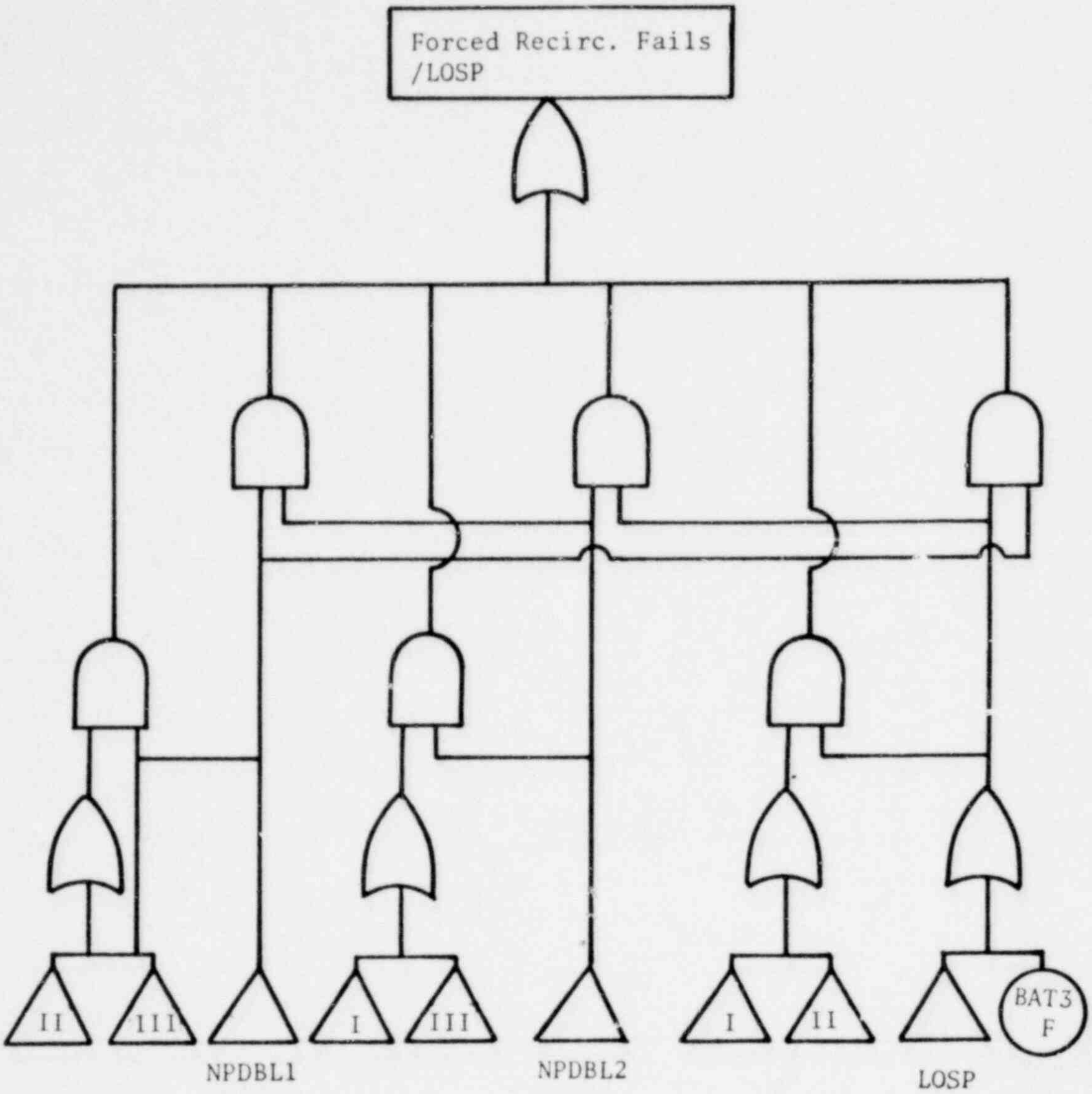

Figure 8.

Fault Tree, Forced Recirculation Fails/LOSP, 3 MHTP's Available at Reactor Shutdown, ND.

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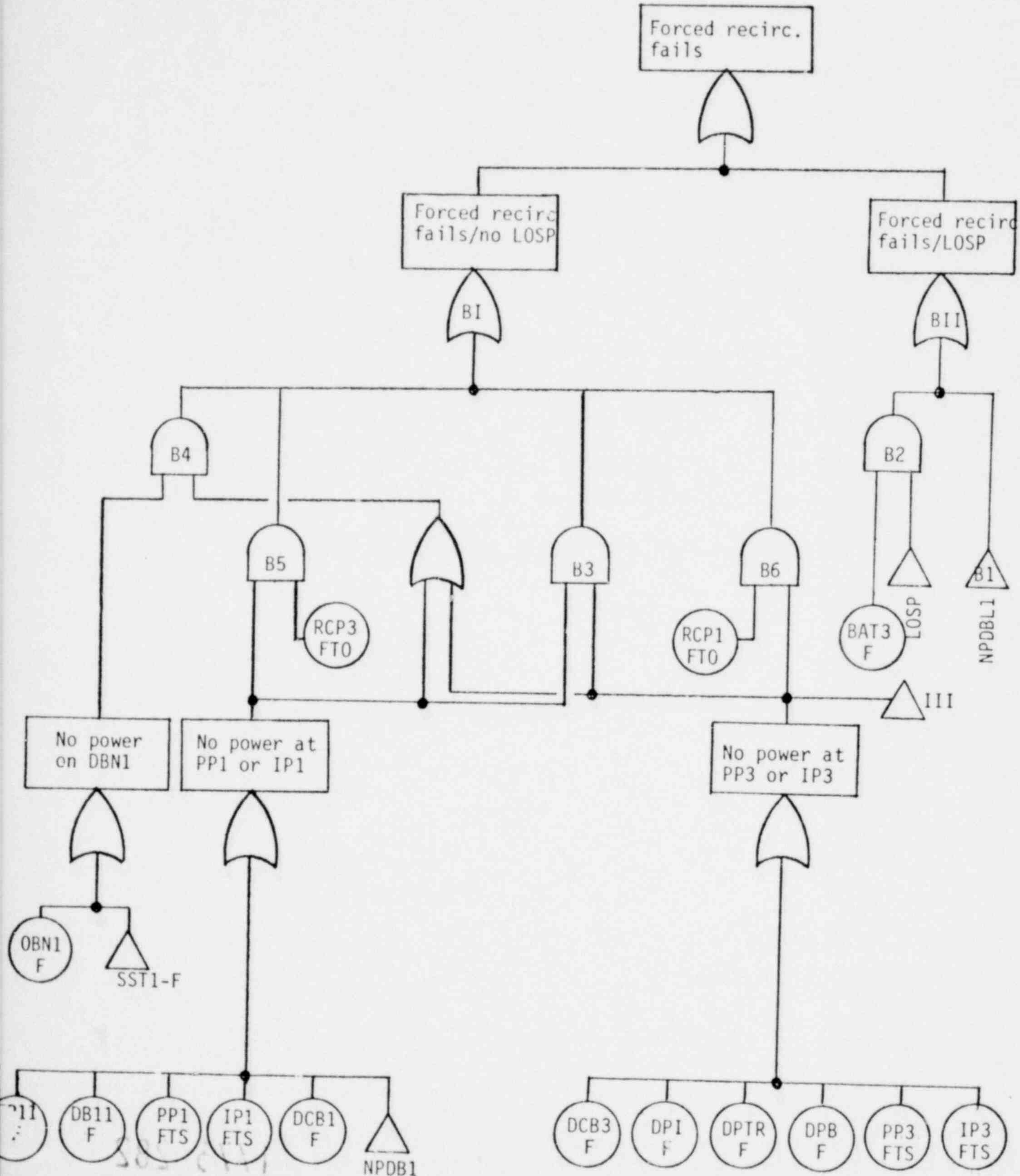
Fig. 9. Loss of forced recirculation at reactor shutdown with 2 MHTPs available.



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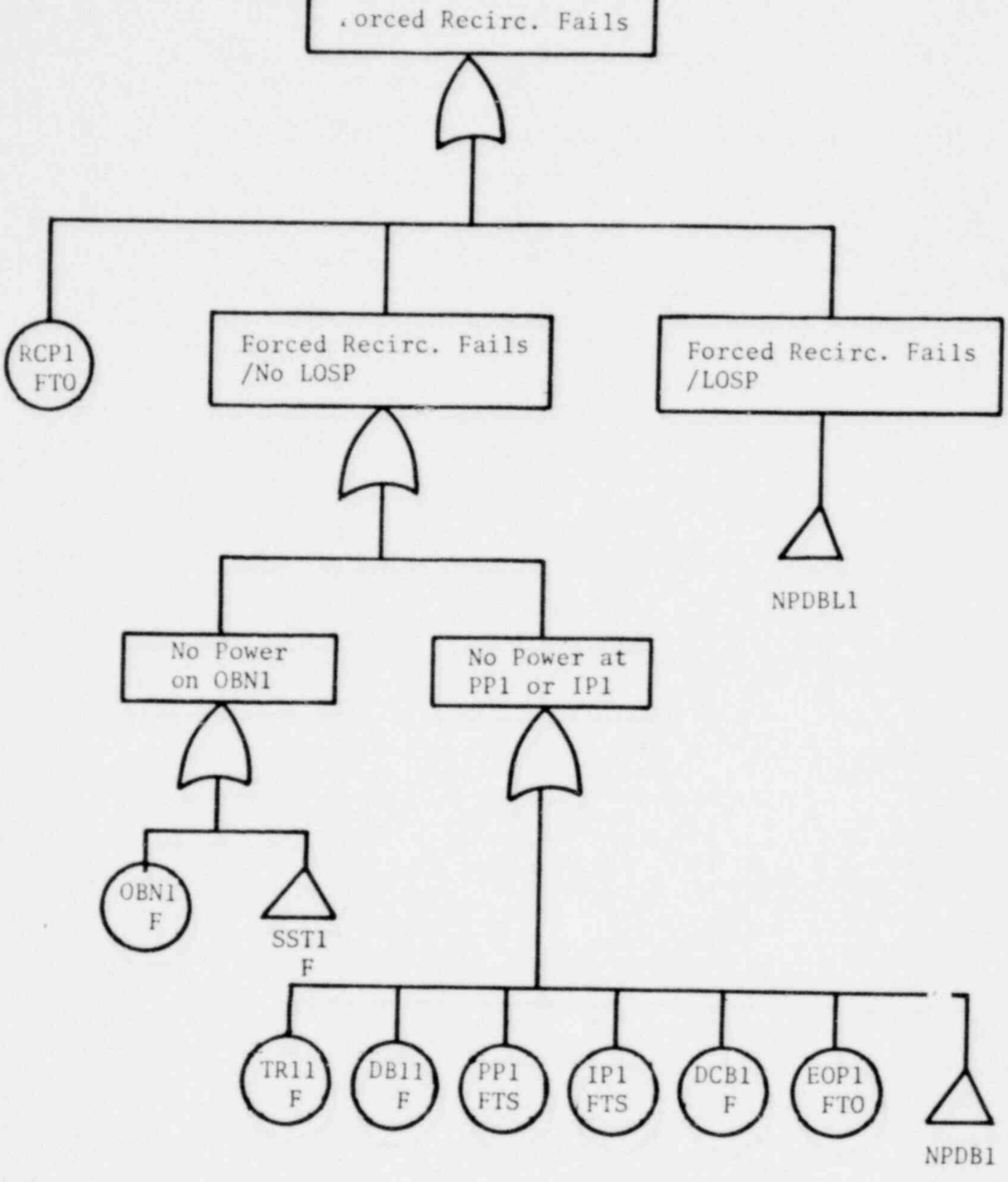

Figure 10.

Fault Tree, Forced Recirculation Fails, Only MHTP1 Available at Reactor Shutdown, NP, PD.

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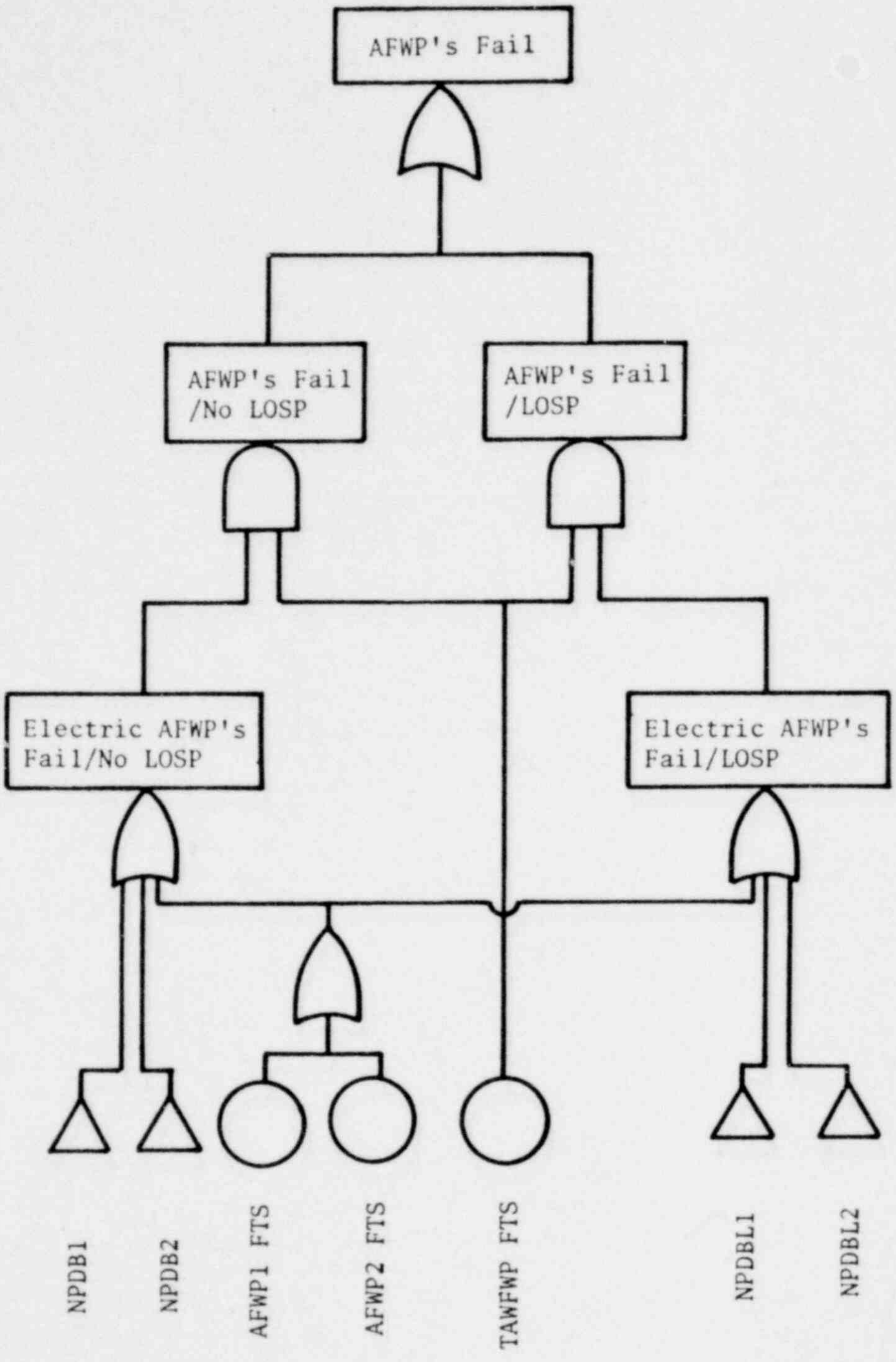

Figure 11. Fault Tree, Auxiliary Feedwater Pumps Fail.

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cooling water. Hence, the loss of one diesel bus already calls for operation of the TAFWP. In addition, the loss of one diesel bus plays an important role for 2-loop or 1-loop reactor shutdowns. For these cases the sub-top events NPDB1, NPDBL1, NPDB2, and NPDBL2 were used in conjunction with the associated fault trees showing "forced recirculation fails" as the top event.

Considering the fault trees of Figures 8 and 9, the tree shown in Figure 7 can also be used for the 3-loop shutdown, ND. In a similar way the tree of Figure 9 can also be transferred to the 2-loop shutdown, PD. Thus, the basic fault trees can be used for all of the different cases which must be investigated. More detailed information is given in the subsequent chapters.

4.1. The Fault Trees

The fault trees are almost self-explanatory. In the following sections, some basic information is given to help the understanding. For abbreviations, see the Nomenclature. Where other expressions are used, as in the PSAR, the additional remarks given in parentheses relate directly to Figures 1 through 5 (Figures 8.3-46 through 8.3-50 of the PSAR, status March 1977 [1]).

Top Event: Power on One of the Two Diesel Buses Not Available (Figure 6)

On loss of preferred power (LPP) the diesel buses are transferred to the reserve power. If that power source should also be lost, a failure to start of diesel generator 1 (DG1-FTS) would lead to the event "no power on DB1/ no LOSP" (NPDB1). As the diesel is already started at LPP, a premature closure of the circuit breakers generates the same event (CBDG1-PC). Failure of the station service transformer (SST1-F) means a cut-off of the off-site power supply to DB1. In combination with DG1-FTS or CBDG1-PC we get another contribution to the event NPDB1.

Loss of offsite power has the same effect as SST1-F. Consequently, its occurrence together with DG1-FTS or CBDG1-PC means loss of DB1 as before, but is now considered as contribution to the event "no power on DB1/LOSP" (NPDBL1). The second contributor to that event is the failure of the associated 125 V DC battery supply, because it would disable the diesel generator circuit breaker. This fault tree was used as an input to the other trees which are used to consider the different local power supply configurations (at the equipment level). In addition it served for the estimation of diesel bus availabilities under varying input failure rates.

Top Event: Forced Recirculation Fails

For the shutdown with 3 MHTP's available, Figure 7 represents the fault tree of the PD. According to the definition of the success of power supply for establishing forced circulation, credit is given to the natural circulation ability of the steam/water loops only (Section 2.2). Hence, the failure-to-operate probability of the recirculation pumps was considered, because it determines the frequency of request for power supply to the primary and intermediate sodium pumps of those MHTP's not affected by the failure of the recirculation pumps. The failure-to-start probabilities of the primary and intermediate pump pony motors are understood to reflect failure of the individual power supplies stemming from load breaker or control circuit malfunction.

Considering the diverse power supply, i.e. ND, subtrees III and IV must be replaced by the configurations as given in Figures 8 and 9, which represent the top events: "forced recirculation fails/LOSP" and "no power at PP3 or IP3." As can be seen from Figure 8, there is now no direct contribution from NPDBL1 to the top event "forced recirculation fails/LOSP," and the top event is reached only in combination with local power supply failures (subtrees I through III) in one of the redundancy groups not affected by NPDBL.

Figure 9 shows the complete fault tree for the shutdown, with 2 MHTP's available, ND. Taking now subtree III from Figure 7, reflecting the diesel power supply of the primary and intermediate pumps of MHTP3, we would get the 2 MHTP shutdown case for the PD. It can easily be seen that the event NPDB1 would now immediately lead to the top event.

In Figure 10, the fault tree for the shutdown with only 1 MHTP available is given. In contrast to the 2 MHTP case, failure of the RCP is not backed up by the primary and intermediate sodium pumps, because according to the definition of success, one loop natural circulation of the steam/water loop is considered insufficient for adequate cooldown of the reactor core.

Figure 11 shows the tree for the top event "auxiliary feedwater pumps fail." This top event means the failure of the feedwater supply and consequently the failure of the SHRS for those cases where the main feedwater supply is not available at reactor shutdown.

4.2. Analyses

When estimating the unavailabilities of the top events for the various cases considered it turned out that two of them worth closer investigation:

(a) Reactor shutdown with 2 MHTP's available; because of the a priori reduced redundancy, failure of one diesel bus due to LOSP already leads to the top event, i.e. forced recirculation fails.

(b) Reactor shutdown due to loss of MFWP's or MC; the feedwater supply has to be provided by the AFWS either by means of both electrical AFWP's or the turbine-driven AFWP.

Both cases are similar in that the loss of one diesel bus leads to the FTS event of those electrical pump motors, which are necessary either to provide feedwater or to establish the forced recirculation. Depending on the credit given to the TAFWP or the natural circulation ability, this may lead to insufficient cooling of the core after shutdown.

Therefore, a more detailed investigation of Cases (a) and (b) has been performed by means of quantitative analysis of the fault trees given in Figures 6 and 9. As can be seen from their configuration, estimates of the top event probabilities of the other trees can easily be performed using the results of these analyses.

The calculations have been performed using the program CRESS 2 (Calculation of the Reliability of Systems by Simulation) [7]. This program can be used for the analysis of systems which call for the use of different types of input data, such as:

(i) Failure, instantaneous repair, repair time.

(ii) Failure, repair begun at subsequent inspection, repair time.

(iii) Failure upon demand.

Hence, it is especially suited for calculating the average unavailability, as is being investigated in the present work. The printout provides the minimal cut sets which contributed to the system outage and the reliability or availability of subtree top events which are of special interest. The standard deviation for the average unavailability of the system (the top event) is calculated by the approximate formula

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$$S = \frac{1}{N - 1} \sum_{i} \left| (n_i - n)^2 \right|^{\frac{1}{2}},$$

where

N = the number of trials,

n_i = the unavailability in the i^{th} trial, and

n = the average unavailability.

4.3. Failure Rates

The failure rates of the electrical power system were taken from WASH-1400 [9]. The repair times of distribution buses and transformers were based upon Reference [10]. The failure data of the pumps are in accordance with those used in the previous UCLA analysis [2], and the failure rate of the emergency oil pump was taken from [4].

A list of the failure data used for the baseline case is given in Table 3. It is indicated in parentheses where the figures include mechanical failure rates.

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AFWP-FTS	$Q = 3 \times 10^{-4}$	
AFWP-FTS	$Q = 1.3 \times 10^{-3}$	(including pump failure)
BAT-F	$\lambda = 3 \times 10^{-6}/h$	RT = 5 hr
CBDG-PC	$\lambda = 10^{-6}/h$	RT = 5 hr
DB-F	$\lambda = 2.3 \times 10^{-6}/h$	RT = 5 hr
DB-FTR	$Q = 10^{-3}$	
DG-FTS	$Q = 3 \times 10^{-2}$	
EOP-FTO	$\lambda = 6 \times 10^{-6}$	RT = 10 hr (pump failure)
GLBS-FTO	$Q = 10^{-3}$	
IP-FTS	$Q = 3 \times 10^{-4}$	
IP-FTS	$Q = 1.3 \times 10^{-3}$	(including pump failure)
LOSP, LPP	$Q = 10^{-3}$	
MT-F	$\lambda = 2 \times 10^{-6}/h$	RT = 10 hr
OBN-F	$\lambda = 2.3 \times 10^{-6}/h$	RT = 5 hr
PP-FTS	$Q = 3 \times 10^{-4}$	
PP-FTS	$Q = 1.3 \times 10^{-3}$	(including pump failure)
RCP-FTO	$\lambda = 3.9 \times 10^{-5}$	RT = 170 hr (pump failure)
SST-F	$\lambda = 2 \times 10^{-6}/h$	RT = 10 hr
TAFWP-FTS	$Q = 10^{-3}$	(pump failure)
TR-F, UST-F	$\lambda = 2 \times 10^{-6}/h$	RT = 10 hr

Table 3. Failure date, baseline case

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5.0 RESULTS

According to the definition of success given in Section 2.2., i.e. the availability of standby electrical power at reactor shutdown, success for the initiator groups 2 through 4 is governed by the availability of at least one diesel bus. The same holds for initiator group 1 when investigating the PD. Consequently, a sensitivity analysis was performed on the basis of the fault tree given in Figure 6, including the loss of off-site power in conjunction with component failure of one redundancy group (top events of subtrees "no power on DB1/LOSP" and "no power on DB2/LOSP," respectively). This concept was extended to the investigation of the loss of forced recirculation at reactor shutdown with 2 MHTP's available (Figure 9). The results are given in Section 5.1 and allow detailed insight into the percentage contribution of component failure combiantions to the unavailability of the main standby electrical power distribution buses (diesel buses) and to the local power distribution, according to the variation of component failure rates.

In Section 5.2 we discuss the unavailabilities of the SHRS and the probabilities of SHRS failure per year according to the initiator groups considered. Results are also given taking into account mechanical failure of the pumps. This enables a comparison of the influences of mechanical versus electrical component failures on the reliability of the system to be made, together with a rough estimate of the total system reliability so far as the contribution of motors and pumps is concerned. The analysis has not been extended to include the passive systems.

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5.1. Sensitivity Analyses

Standby Electrical Power at Reactor Shutdown

As can be seen from Table 4, the largest change in the results for the cases considered is achieved when the diesel failure rates are increased by a factor of 2. Taking the failure rate of one diesel as a conservative estimate for the CMF, a doubling of the single failure rate must be performed for those cases where the loss of one diesel bus already leads to the top event. Hence the figure of 6.57×10^{-5} can be interpreted as the unavailability of one diesel bus when taking into account the contribution of the CMF to the single failure rate of the diesel. It can also be seen that increasing the diesel failure rate mainly influences the event "no power on DB/LOSP." As to be expected, failure-to-start of the diesel is of special importance for the LOSP event. Table 5 shows a rise of the percentage contribution from 88.3 to 94.8.

The results are also rather sensitive to failure of the diesel buses. The data taken for the baseline case represents failure rates due to short and open circuits of the buses during operation and the associated repair times. Additional problems may arise from load sequencing under normal or abnormal grid conditions. For the latter case, recent experience showed difficulties in adapting the setting of undervoltage relays to certain undervoltage conditions of the grid and to the set point margins, which are necessary to allow voltage dips in the course of load sequencing without dropping the associated loads [8]. Two main problems were observed:

1. On completion of load sequencing some motors were not energized as a consequence of load shed signals caused by voltage dips

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Cases	No power on one DB/no LOSP	No power on one DB/LOSP	No power on one DB	No power on 1/2 DB's
Baseline Case	5.69×10^{-6}	3.26×10^{-5}	3.83×10^{-5}	7.39×10^{-5}
Diesel Generatorsx2	6.29×10^{-6}	5.95×10^{-5}	6.57×10^{-5}	1.25×10^{-4}
Circuit Breakersx3	8.56×10^{-6}	3.16×10^{-5}	4.02×10^{-5}	8.04×10^{-5}
Diesel Busesx3	1.61×10^{-5}	2.98×10^{-5}	4.59×10^{-5}	9.18×10^{-5}

Table 4. Unavailability of diesel buses at reactor shutdown

Gates	Definition of gates/description of event combinations	Baseline Case	Diesel Generator x2	Circuit Breakers x3	Diesel Buses x3
x10	DB1-F	13.1	8.3	12.3	33.3
B1	LPP $\wedge$ [(DB1 $\wedge$ DG1) $\vee$ CBDG1]	<0.5	<0.5	10.0	<0.5
B2	[DG1 $\vee$ CBDG1] $\wedge$ SST1	1.0	1.0	0.6	<0.5
B4	no power on DB1/no LOSP	15.4	10.0	21.3	35.1
B3	BAT1 $\wedge$ LOSP	1.0	2.3	2.9	1.7
A3	[DG1 $\vee$ CBDG1] $\wedge$ LOSP	87.3	92.5	75.8	63.2
B5	no power on DB1/LOSP	88.3	94.8	78.7	64.9

Note: Summation may differ from 100% depending on roundoff errors and system configuration.

Table 5. Percentage contributions to the unavailability of one of the two diesel buses

(implying too close a setting of the undervoltage relays).

2. Blown control fuses caused failure of the motor controllers and hence a failure of the associated motors to start (implying too wide a setting of the undervoltage relays).

Both failure types have a common mode effect, in that they may lead to a common failure of supply voltage to several pieces of equipment depending on the actual dynamics of the transient and the actual reaction of the individual undervoltage relays or fuses. The sensitivity of this common mode effect at the level of the main distribution of standby power was investigated by raiding the DB failure rates by a factor of 3. This leads to an increase of the event "no power on one DB/no LOSP" to 1.61×10^{-5}, a figure which now comes rather close to the event "no power on one DB/LOSP" (Table 4). The percentage contribution of the no LOSP case rises from 15.4 to 35.1, as shown in Table 5.

The effect of this type of CMF at the local power distribution level can be estimated from Table 7, Case 2. The figure of 2.17×10^{-4} can be regarded as an estimate of forced recirculation unavailability, taking into account CMF caused by load sequencing or diesel starting failure.

Raising the failure rates of the circuit breakers by a factor of 3 just leads to a shift of the percentage contribution of the event "no power on one DB/no LOSP" from 15.4 to 21.3 and for the event "no power on one DB/LOSP" from 88.3 to 78.7 without remarkably affecting the diesel bus unavailability (4.02×10^{-5} versus 3.83×10^{-5} for the baseline case).

In Table 6 the contribution of the component failures to the top event is shown. Grouping is done with reference to no loss of off-site power, loss of off-site power, and loss of preferred power. The figures

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Groups	Involved Components	Code	Baseline Case	Diesel Generators x2	Circuit Breakers x3	Diesel Buses x3
No loss of offsite power	DB1-F	x10	519	546	503	1604
	DB2-F	x19	499	531	535	1612
	SST1-F, DG1-FTS	x9,x7	17	28	8	11
	SST2-F, DG2-FTS	x18,x15	20	37	15	20
	GLBS-FTO, CBDG1-PC	x1,x8			10	
	SST2-F, CBDG2-PC	x18,x14			3	
	GLBS-FTO, CBDG2-PC	x1,x14			8	
Loss of off-site power	LOSP, DG1-FTS	x13,x7	47	96	36	39
	LOSP, DG2-FTS	x13,x15	38	67	51	45
	LOSP, CBDG1-PC	x13,x8		3		
	LOSP, CBDG2-PC				4	
	LOSP, BAT1-F	x13,x11	6	3	3	4
	LOSP, BAT2-F	x13,x12	10	5	6	3
Loss of pre-ferred power	LPOPS, CBDG1-PC	x4,x8	5	3	7	5
	LPOPS, CBDG2-PC	x4,x14	3	5	10	3

Table 6. Loss of power at one of the two diesel buses. Minimal cut sets

No.	Cases	Forced Recirc. fails/no LOSP	Forced Recirc. fails/LOSP	Forced Recirc. fails
1	Baseline case	7.94×10^{-6}	3.21×10^{-5}	4.01×10^{-5}
2	El. comp.x3 Diesel gen.x2	1.32×10^{-5}	2.03×10^{-4}	2.17×10^{-4}
3	Baseline case + pumps	4.82×10^{-5}	3.44×10^{-5}	8.26×10^{-5}
4	El. comp.x3 Diesel gen.x2 + pumps	5.13×10^{-5}	1.55×10^{-4}	2.06×10^{-4}

Table 7. Unavailability of forced recirculation at reactor shutdown with 2 MHTP's available

represent the number of failures actually computed by the program. The total number of trials for every case remained constant, so that direct comparison of the indicated failure numbers provides a picture of the individual contributions of different event combinations to the top event. It is important to note the influence of the operational mode (active or stand-by) and the repair time upon the unavailability. Though 536 trials led to failure of "DB1/no LOSP" and only 53 trials to failure of "DB1/LOSP" (baseline case), the percentage contribution to the unavailability shows a relation of 15.4 to 88.3 (Table 5).

Forced Recirculation upon Two Loop Shutdown

The unavailability of the forced recirculation for the baseline case was calculated to be 4×10^{-5} (Table 7). This is the unavailability of electrical power at those primary and intermediate sodium pump pony motors, which must begin operation in order to establish forced recirculation, considering the mechanical failure of the RCP's. Increasing the failure rates of the electrical power system components by a factor of 3 and the starting probability of the diesel by a factor of 2 results in a rise of the unavailability to establish forced recirculation by a factor of 5 (estimate on CMF sensitivity in the previous section).

Case 3 includes the mechanical failure rates of the primary and intermediate pumps. Hence, the result represents the unavailability of forced recirculation due to active components. As can be seen, the unavailability rises by a factor of two as compared to the baseline case. It is interesting to note that considering the pump failure rates in conjunction with the estimate on CMF sensitivity (Case 4) leads only to a shift of the contribution of the two gates BI and BII ("forced recirculation fails/no LOSP" from 1.32×10^{-5} to 5.13×10^{-5}, "forced recir-

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culation fails/LOSP" from 2.03×10^{-4} to 1.55×10^{-4}) without affecting the total unavailability.

Table 8 shows the contributions to the top event as generated by the gates B1 to B6 (see also Figure 9). The main contributor to BII (forced recirculation fails/LOSP) is the unavailability of DB1 (NPDBL1), while B2 (representing loss of power to the emergency oil pump) is of little importance. The components involved in the event NPDBL1 can be seen from Table 9, group 1.

The most important contributions to BI (forced recirculation fails /no LOSP) stem from failures of the recirculation pumps in conjunction with loss of electrical power to the primary and intermediate sodium pumps (B5 and B6). As can be seen from Case 3, consideration of mechanical pump failures led to a situation where the contribution to the top event originating from mechanical pump failures and originating from failures of the electrical system is about 50% each. Power supply failure to the recirculation pumps is of little influence (B4). Comparing Cases 1 and 3 or 2 and 4, respectively (B5 and B6) yields a contribution of the local power supply and NPDB1 of between 30% and 40% to the unavailability of the primary and intermediate pumps.

Actual contributions of the components to failure of the system can be seen from Table 9. The numbers of failures given there are taken directly from the computer output (i.e., the total number of system failures given in the last line is the one observed during the associated computer run). As that number is roughly the same, the figures given in the columns can be regarded as the relative contributions to the top event. The subdivision in Table 9 is related to the following event combinations:

Gates	Definition of gates/description of event combinations	Baseline Case	El. Comp.x3 Diesel Gen.x2	Baseline Case + Pumps	El. Comp.x3 Diesel Gen.x2 + Pumps
B3	(PP1 $\vee$ IP1) $\wedge$ (PP3 $\vee$ IP3)	0.9	0.6	13.4	7.7
B4	DBN1 $\wedge$ (PP1 $\vee$ IP1 $\vee$ PP3 $\vee$ IP3)	1.0	0.9	0.5	0.9
B5	RCP3 $\wedge$ (PP1 $\vee$ IP1)	9.6	2.4	22.2	8.7
B6	RCP1 $\wedge$ (PP3 $\vee$ IP3)	8.4	2.2	22.3	7.6
BI	Forced rec. fails/no LOSP	19.9	6.1	58.4	24.9
B1	NPDBL1	77.4	88.2	40.7	71.0
B2	LOSP $\wedge$ BAT3	2.8	5.7	1.0	4.1
BII	Forced rec. fails/LOSP	80.2	93.9	41.7	75.1

Note: Summation may differ from 100% depending on roundoff errors and system configuration

Table 8. Percentage contributions to the unavailability of forced recirculation at reactor shut-down with 2 MHTP's available

TABLE 9. LOSS OF FORCED RECIRCULATION AT REACTOR SHUTDOWN WITH 2 MHTP'S AVAILABLE. MINIMAL CUT SETS

Groups	Involved Components	Code	Baseline Case	El. Comp.x3 Diesel Gen.x2	Baseline Case + Pumps	El. Comp.x3 Diesel Gen.x2 + Pumps
Failure of the main electrical power system	SST1-F, DG1-FTS	x9,x7	50	62	15	38
	LOSP, BAT1-F	x13,x11	9	16		11
	LOSP, CBDG1-PC	x13,x8	4	7		4
	LOSP, DG1-FTS	x13,x7	121	169	49	101
	LOSP, BAT3-F	x13,x28	7	20	3	16
Local power supply PPs, IPs, RCPs	PP1-FTS or IP1-FTS, DPI-F or DPTR-F	x23,x26	13	3	8	26
	PP1-FTS or IP1-FTS, DCB3-F or DPB-F	x24,x27	7			3
	PP1-FTS or IP1-FTS PP3-FTS or IP3-FTS	x,24,x25	5		26	16
	RCP1-FTO PP3-FTS or IP3-FTS	x29,x25	37	10	84	32
	RCP1-FTO DPIF or DPTR-F	x29,x26	54	69	43	56
	RCP1-FTO DCB3-F or DPB-F	x29,x27	15	14	6	11
	RCP3-FTO PP1-FTS or IP1-FTS	x21,x24	41	12	79	33
	RCP3-FTO, TR11-F	x21,x23	5	3		5
	RCP3-FTO DB11-F or DCB1-F	x21,x22	13	11	5	7
	RCP3-FTO, DB1-F	x21,x10	15	8	4	
	PP3-FTS or IP3-FTS SST1-F	x25,x9			3	3
	PP3-FTS or IP3-FTS DB11-F or DCB1-F	x25,x22			7	7
Local power supply, PPs, IPs, RCPs, EOPs	EOP1-FTO PP3-FTS or IP3-FTS	x30,x25			9	6
	EOP1-FTO, RCP3-FTO	x30,x21			27	10
	EOP2-FTO PP1-FTS or IP1-FTS	x31,x24			10	7
	EOP3-FTO, RCP1-FTO	x31,x29			25	9
Number of system failures			400	403	407	398

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Group 1. Failure of the main electrical power system (power supply including diesel buses).

Group 2. Failure of the local power system (Cases 1 and 2); pump failure or failure of the local power system (Cases 3 and 4).

Group 3. Pump failure in conjunction with EOP's or failure of the local power system (Cases 3 and 4 only).

5.2. Unavailabilities and Failure Probabilities per Year of the SHRS Electrical Power Supply

Table 10 shows the gain of the availability of the SHRS power supply as achieved by the new design. As the design change was concerned with the power supply of the primary and intermediate pumps of loop 3, major improvements can be expected for initiator groups 1 and 2 (IG1 and IG2) only. Reactor shutdown with 1 MHTP available is affected as far as the available loop is the one fed by the diverse power supply, which as a mean occurs with a frequency of 1/3 of all one-loop shutdowns. The figures given in the tables relate to the one-loop shutdowns with electrical power supply provided from one of the diesel generators.

As can be seen from the table, the unavailability of power supply under LOSP conditions is governed, with one exception (IG1, ND) by the loss of one diesel bus, i.e. 3.26×10^{-5} (for IG4 we get $3.26 \times 10^{-5} \times 2 = 6.52 \times 10^{-5}$), because both electrical AFWP's are needed for sufficient feedwater supply). Furthermore, the loss of one diesel bus determines the total unavailability for IG1/PD and IG2/PD, ND. As the event "loss of one diesel bus/LOSP" does not lead to the unavailability of the 3 MHTP's reactor shutdown for ND, we got an improvement of about 2 orders of magnitude for the availability of the SHRS in the case of regular

initiator group		loss of forced recirculation or feedwater supply					
		baseline case, new design			baseline case, previous design		
		no LOSP	LOSP	TOTAL	no LOSP	LOSP	TOTAL
1	3 MHTPs available	1.00×10^{-8}	8.00×10^{-8}	9.00×10^{-8}	1.00×10^{-8}	3.26×10^{-5}	3.26×10^{-5}
2	2 MHTPs available	7.94×10^{-6}	3.26×10^{-5}	4.01×10^{-5}	1.36×10^{-5}	3.26×10^{-5}	4.62×10^{-5}
3	1 MHTP available	6.41×10^{-4}	3.26×10^{-5}	7.27×10^{-3}	6.41×10^{-4}	3.26×10^{-5}	7.27×10^{-3}
4	loss of MFWS or MC	6.11×10^{-7}	6.52×10^{-8}	6.76×10^{-7}	no design change		
		6.11×10^{-4}	6.52×10^{-5}	6.76×10^{-4}			
		(el. AFWPs only)					

Table 10. Unavailability of SHRS due to loss of electrical power supply

reactor shutdown. Taking into account the initiator frequency of that event (7 yr^{-1}) this fact is to be considered an important step towards a low failure probability per year of the SHRS power supply (Table 11). In comparison with the PD one can also see that now the availability of the SHRS power supply for the 2-loop shutdown is the same as previously for the 3-loop shutdown.

For IG3, the total availability is more or less determined by the RCP (UA = 6.6×10^{-3}), because according to the definition of success natural recirculation in one steam/water loop was considered insufficient (see also Figure 10). It will be seen that our conservative assumption, just in this one case, leads to an unavailability figure which would call for improvement of the system, all the other situations being handled satisfactorily. As a consequence, it would be advisable to more specifically investigate the one-loop shutdown case, from the points of view of initiator frequency as well as the cooling capability. This is also emphasized by the figures shown in Table 11.

Initiator group 4 seems to be of little importance (Table 10). Indeed, as far as the redundancy of the AFWP' is concerned, the availability is sufficiently high. In contrast to the "loss of recirculation" one has to be careful when extrapolating from the availability of the pumps to that of the system, because the AFWS is highly intermeshed, so that valve or pipe failures are much more dominant compared to the MHTP's.

In order to get an indication of the influence of the power supply versus mechanical failure of the pumps, additional estimates were made, including those failures. As can be seen from Table 12, the influence changes from about 5 for IG1 to 1.2 for IG3. This is due to the reduced redundancies of the system from a 3-loop shutdown to the 1-loop shutdown,

	initiator group	initiator frequency yr^{-1}	Loss of forced recirculation	
			new design yr^{-1}	previous design yr^{-1}
1	3 MHTPs available	7.207	6.47×10^{-7}	2.3×10^{-4}
2	2 MHTPs available	1.844	7.34×10^{-5}	8.7×10^{-5}
3	1 MHTP available	0.116	8.47×10^{-4}	8.47×10^{-4}

Table 11. Comparison of SHRS failure probabilities per year due to loss of electrical power supply, ND and PD

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	initiator group	initiator frequencies yr^{-1}	loss of forced recirculation or feedwater supply			
			loss of electrical power supply		loss of electrical power supply or pump failure	
			UA	FP, yr^{-1}	UA	FP, yr^{-1}
1	3 MHTPs available	7.207	9.00×10^{-8}	6.49×10^{-7}	4.70×10^{-7}	3.39×10^{-6}
2	2 MHTPs available	1.844	4.01×10^{-5}	7.39×10^{-5}	8.26×10^{-5}	1.52×10^{-4}
3	1 MHTP available	0.116	7.30×10^{-3}	8.47×10^{-4}	9.27×10^{-3}	1.08×10^{-3}
4	loss of MFWS or MC	0.370	6.76×10^{-7}	2.50×10^{-7}	2.67×10^{-6}	9.88×10^{-7}
5	LOSP and CMF of diesels*	0.185	1×10^{-2}	1.85×10^{-3}	-	-

* LOSP and failure of one diesel contained in UAs belonging to initiator groups 1 through 4

Table 12. Unavailabilities and failure probabilities per year of SHRS due to loss of electrical power supply or pump failure.

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which caused more and more influence of RCP failure as compared to the failure of the power supply of the IP's and PP's. The overall picture shows that IG5 (LOSP and CMF of diesels) still delivers the most important contribution to the failure probability per year (1.85×10^{-3} versus 1.08×10^{-3} for the 1-loop shutdown case including mechanical pump failures). This result must be seen, again, with our conservative assumption on natural recirculation capability. For example, if it could be shown that forced recirculation in the primary loop by means of one of the PP's is sufficient to ensure cooldown of the core (provided that the integrity of the coolant circuits is retained), we would get for IG5 the situation LOSP and CMF of diesels and PP3 FTS, i.e. considering the electrical power supply

$$0.185 \times 10^{-2} \times 1.3 \times 10^{-3} = 2.4 \times 10^{-6}\ yr^{-1}.$$

For similar assumptions (one PP and one IP sufficient, given the mechanical integrity of the associated loops), we would achieve for IG5

$$0.116 \times 2 \times 1.3 \times 10^{-3} = 3 \times 10^{-4}\ yr^{-1},$$

i.e. that initiator group would now deliver the dominant contribution to the SHRS failure probability per year. In any case, it can be seen that the ND could lead to further improvement of the SHRS availability, dependent upon the actual natural recirculation behavior of the coolant loops.

5.3. Comparison with Other Results

Comparison with results gained so far by other investigators [2-4] is difficult, because our analyses were directed towards the aspect of a reliable power supply. In addition, the LOSP event was treated differently with respect to the initiator groups, and with respect to the credit given to natural circulation cooling capability. Dependent on the presumptions we get greater or lesser demands placed upon the availability of the pumps in the coolant circuits. Therefore, our results are determined by the availability figures of those pumps and their associated power supplies. The passive structure parts are of little influence. Hence, the results given in Table 12, IG1, 2, 3, and 5 (loss of electrical power supply or pump failure) can be considered as estimates for the availability of the SHRS. Because of the reasons given in the previous section, this cannot be done with respect for IG4. Taking for the unavailability of the AFWS the figure estimated by BNL, i.e. 3.1×10^{-4} for the initiating event "loss of main feedwater not due to loss of off-site AC power" we would get for IG4

$$0.370 \times 3.1 \times 10^{-4} = 2.73 \times 10^{-5} \text{ yr}^{-1}.$$

Comparing this figure with the contribution of the other IG's given in Table 13 shows the dominant role of IG3 and IG5, which results in a failure probability per year of the SHRS of 3.08×10^{-3} yr^{-1}. Though amongst the IG's there is a shift of the contribution to the overall result (depending on different presumptions), this figure compares well with 2.9×10^{-3} yr^{-1} as achieved by BNL or greater than 10^{-3} as achieved by the NUS.

A comparison with the results of previous UCLA analyses [2] is given in Table 13. The figures clearly show that the rising requirements for pump and power supply availability depending upon the cooling capability of natural circulation. In the analyses given in Reference [2] two loop natural recirculation capability was assumed, whereas the investigations in this report are based upon two loop natural recirculation capability of the steam/water loops only (column 3). This calls for operation of the pumps according to the configurations allowed by the definition of success, and leads to the failure probabilities per year

	nat. circ. heat removal capability / initiator group	previous UCLA results/ /		results of this report	
		full capability (nominal date)	no capability of 1 MHTP	no capability of * prim. and/or int. MHTPs	no capability of 1 MHTP
1	3 MHTPs available	1.6×10^{-8}	small	3.4×10^{-6}	small
2	2 MHTPs available	1.2×10^{-7}	1.1×10^{-6}	1.5×10^{-4}	small
3	1 MHTPs available	2.5×10^{-6}	9.8×10^{-5}	1.1×10^{-3}	3×10^{-4}

*corresponding to loss of forced recirculation according to the definition of success of power supply

Table 13. Comparison of SHRS failure probabilities per year under various assumptions on natural circulation capability.

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being larger. The increase is between 2 orders of magnitude for the 3-loop shutdown to 1 order of magnitude for the 1-loop shutdown. An estimate for IG3 based on less stringet assumptions (see Section 5.2) is given in column 4.

6.0 CONCLUSION

The requirements for the power supply of the SHRS upon reactor shutdown were investigated on the bases of a conservative assumption on the natural recirculation capability of the main heat transfer paths, i.e. only natural recirculation of two steam/water loops in conjunction with forced recirculation of the two associated primary and intermediate loops was considered sufficient for appropriate cooldown of the core after reactor shutdown from full power operation. Under these assumptions, we get a failure probability per year of the SHRS power supply of 2.7×10^{-3} yr^{-1}, which is determined primarily by the contribution of the two initiators "loss of off-site power" and "reactor shutdown with only one main heat transfer path available." Including mechanical pump failures in our calculation (and neglecting failure of passive mechanical components), we estimated the overall SHRS failure probability to be 3.1×10^{-3} yr^{-1}.

The modification of the electrical power supply design by the introduction of the diverse power supply (DC) for feeding of the primary pumps and the intermediate pumps of loop 3 brought a substantial improvement for reactor shutdowns with three main heat transfer paths available, i.e. from 2.3×10^{-4} yr^{-1} to 6.5×10^{-7} yr^{-1}. A reduction of the dominant contribution to the SHRS power supply failure probability caused by "loss of off-site power and common mode failure of the diesel" will be achieved by means of the diverse power supply, if less conservative assumptions on natural recirculation capability can be justified. Considering forced recirculation in one primary loop sufficient for cooldown of the core, we would get a figure of 3.4×10^{-6} yr^{-1} for the sequence loss of off-site power <u>and</u> common mode failure of diesels <u>and</u> failure of primary pump 3, i.e. the common mode failure of diesels would not be at all important in

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the context of establishing sufficient coolant recirculation after reactor shutdown. With similar assumptions, we would get a failure probability per year of the SHRS of 3×10^{-4} for reactor shutdowns with one main heat transfer path available. This means a reduction of the failure probability by a factor of 3. On the other hand, that sequence becomes now dominant and determines the overall failure probability per year of the SHRS. As we also estimated a dominant contribution from the same sequence for our baselines case, further investigation is advisable. In particular, an improved estimation of the initiator frequency and of the actual possibilities of reactor cooldown by means of one main heat transfer path is desirable.

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