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The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Report – Diesel Generators, Batteries, Chargers and Inverters

W. Keith Kahl
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Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
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THE IN-PLANT RELIABILITY DATA BASE FOR NUCLEAR PLANT COMPONENTS: INTERIM REPORT — DIESEL GENERATORS, BATTERIES, CHARGERS AND INVERTERS

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ABSTRACT

The objective of the In-Plant Reliability Data (IPRD) program is to develop a comprehensive, component-specific reliability data base for probabilistic risk assessment and for other statistical analyses relevant to component reliability evaluations. This objective is being attained through a cooperative effort with several utilities which have provided access to maintenance files and pertinent population information. This pilot data base includes (1) a component population list (for each plant) of selected electromechanical and mechanical equipment (e.g., pumps, valves, etc.), and (2) comprehensive component failure and repair histories based on corrective maintenance actions on these components.

This document is the product of a pilot study that was undertaken to demonstrate the methodology and feasibility of applying IPRDS techniques to develop and analyze the reliability characteristics of key electrical components in five nuclear power plants. These electrical components include diesel generators, batteries, battery chargers and inverters. The sources used to develop the data base and produce the component failure rates and mean repair times were the plant equipment lists, plant drawings, maintenance work requests, Final Safety Analysis Reports (FSARs), and interviews with plant personnel. The data spanned approximately 33 reactor-years of commercial operation.

1. INTRODUCTION

1.1 Program Description and Objectives

The objective of the In-Plant Reliability Data (IPRD) program is to develop a comprehensive, component-specific reliability data base for probabilistic risk assessment and for other statistical analyses relevant to component reliability evaluations. This objective is being attained through a cooperative effort with several utilities, wherein each utility provides access to the maintenance files and pertinent population information, and in return, can receive computerized listings and tapes of their component populations (equipment lists) and the component maintenance records. This pilot data base includes (1) a component population list (for each plant) of selected electromechanical and mechanical equipment, i.e., pumps (including drivers), valves (including operators), diesel generators, inverters, battery chargers and batteries, and (2) comprehensive component failure and repair histories based on corrective maintenance actions on these components.

This document is the product of a pilot study that was undertaken to demonstrate the methodology and feasibility of applying IPRDS techniques to develop and analyze the reliability characteristics of key electrical components in five nuclear power plants. These electrical components include diesel generators, batteries, battery chargers and inverters. The use of the term "electrical components" throughout this document will be in the sense of these components unless specified otherwise. The data sources used to develop the data base and produce the component failure rates and mean repair times were the plant equipment lists, plant drawings, maintenance work requests, Final Safety Analysis Reports (FSARs) and interviews with plant personnel. The data came from five nuclear power generating stations comprising five PWR units and four BWR units; and spanned approximately 33 reactor-years of commercial operation. These data were entered into a computer data management system — SAS (Statistical Analysis System). Background information on the development of this data base is reported in "The In-Plant Reliability Data Base for Nuclear Power Plant Components: Data Collection and Methodology Report," NUREG/CR-2641,[1] "The In-Plant Reliability Data Base for Nuclear Power Plant Components: Interim Data Report — The Pump Component," NUREG/CR-2886,[2] and "The In-Plant Reliability Data Base for Nuclear Plant Components: Interim Report — The Valve Component," NUREG/CR-3154.[3]

1.2 Program Scope

The IPRDS data base currently includes the population, failure, and repair records on diesel generators, batteries, battery chargers, and inverters for five plants. Approximately 700 maintenance records on these electrical components were entered in the system and Table 1 sets forth the status of them. Appendix B presents additional plant-specific information.

Table 1. Status of the data base on the electrical components (January 1984)

	IPRDS plant					
	PWR			BWR		Total
	1	2	5	3	4	
Number of maintenance records reviewed	30,000	10,000	50,000	50,000	30,000	170,000
Number of corrective maintenance (CM) records	8,000	3,000	5,000	6,000	7,000	29,000
Number of CM records for electrical components	261	151	84	107	95	698
Number of population records developed for electrical components	15	22	71	87	18	213
Time span of electrical component maintenance records (post-commercialization reactor-years)	5.1	1.3	11.5	9.2	6.2	33.2

Early in the study it became clear that there were a significant number of motor-generator (MG) sets which performed a variety of functions as battery chargers, inverters, and power supplies in two of the plants. However because of their mechanical nature, which differs greatly from their solid state counterparts, they were assembled into a separate class "MGSETS." This class of components is not included in this report due to an incomplete set of data, but they will possibly be included in a future analysis.

In addition, batteries, chargers and inverters below the 120V level have been excluded from the analysis. Only components in the essential AC power systems have been considered. Inclusion of certain dedicated electrical components (inverters, batteries, etc.) which can be found in some safety-related systems is beyond the scope of this preliminary report.

1.3 Description and Duties of the Electrical Components Considered in this Study

The electrical components under consideration serve in on-site plant power systems. They appear in the main power system and in the emergency power system. The emergency power system utilizes part of the main power system from the 4160 V level and below. This is generally the first level where essential and nonessential load distinctions are made.[1]

1.3.1 Diesel generator

The primary component of the emergency power system in most plants is the diesel-driven generator. It is designed to supply emergency AC power at the 4160 V level when normal AC power has been lost. Depending upon several factors (mostly the number of reactor units in the plant) there are multiple emergency power supply trains, each fed by a diesel generator. Most large pump motors in the plant are fed from this level. In the event of a loss of offsite power (LOSP) incident, all loads are shed from the emergency buses and only essential loads are sequentially added back after the diesel generators are on-line.

1.3.2 Chargers, batteries and inverters

The 4160 V buses feed the auxiliary transformers that typically reduce the voltage to the 600 V or 480 V level. These lower voltage level buses typically supply power to motor control centers and load centers for medium to small pump and fan motors and valve operator motors. They also feed battery chargers which provide an interface between the AC and DC power systems. These chargers rectify their AC input to 125 VDC (or 250 VDC) output for float charging the associated batteries and supplying complementary loads. The common connection for the batteries and these loads is usually the battery bus. In the event of loss of emergency bus AC power, charger output to the DC bus is lost and the batteries carry the associated loads. Primary loads on these DC buses include control circuits for AC circuit breakers and inverters for the instrument AC power system. These DC-powered inverters provide for an uninterruptible source of 120 V, single phase AC power to the plant essential instrumentation, the plant computer (a non-safety system), and in some cases an integrated control system.

In some instances, the DC power for control of a diesel generator is supplied by a station battery (125 VDC), and in some plants it is supplied by one or more dedicated batteries.[4] For each of the batteries dedicated to the diesel generator there is typically at least one dedicated charger. A dedicated battery supplies control power to the diesel and field flashing to the generator, but may not supply control power to the generator output breaker or other emergency bus feeder breakers. For this reason a diesel generator with a dedicated battery cannot supply emergency power unless both the appropriate station/unit battery and the diesel battery are available.[4] Only one IPRDS plant had dedicated batteries for electrical crank starting, all others had air start systems. These diesel generator starting batteries were included in the considered data.

Similarly some plants employ dedicated batteries to power switchgear in the switchyard. These are typically 125 VDC batteries and represent a load removed from the station power batteries. It can be difficult to locate engineering and failure information on such batteries because the switchyard is generally considered "off-site," but these batteries were included in the data system where the information was available.

Batteries and chargers of 48 and 24 VDC are also found in many plants as power supplies for nuclear instrumentation (e.g., neutron monitoring) systems and on-site telecommunications systems. In addition there are occasional batteries and chargers of lesser voltage found throughout the plant in fire protection systems or other auxiliaries, but these have been excluded from consideration in this report.

2. METHODOLOGY

The procedure used to establish the electrical component information for input to the data base involved the development of population records and the supplemental coding of failure and repair records. This chapter describes the methodology that was employed to do this.

2.1 Population (Engineering) Information

A population record was created for each identifiable member of the electrical components from the plant equipment lists and piping and instrumentation drawings (P&IDs). The FSARs for each plant were especially useful in interpreting the plant electrical diagrams and providing more complete technical information on specific components. Typically a population record was formulated with information such as the component identification number, plant system and component type (diesel generator, battery, etc.). Additional engineering information such as rated voltage, ampere-hours, and rated power was included, depending upon its applicability and availability, along with a descriptive name of the equipment. System codes were assigned according to information on the function and purpose of the component. The system codes, universal for all IPRD components, are designated in Table 2. The component identification (ID) numbers were taken from the plant electrical diagrams when possible. Unfortunately, a definitive ID was not always shown and frequently the maintenance records had to be searched for clues. The component ID is important as it is the primary vehicle for matching failure records to their appropriate piece of equipment (i.e., population records).

2.2 Failure and Repair Information

The primary source of information for the failure/repair records were the in-plant maintenance work orders. The work order text was analyzed and failure mode, failure severity, and failure cause codes were assigned. Other data reported on the maintenance order such as failure date, report number, crew size were also entered onto the record.

2.2.1 Component boundary

To accurately establish the data base it was necessary to define the boundary around the particular component of interest and to identify appropriate interfaces between the component and other systems. These definitions provide guidelines for proper sorting of the maintenance records, and are intended to assist fault tree analysts in relating the reliability statistics to basic events.

The development of appropriate boundaries for the individual components has two-fold importance. First, it makes clear the distinctions

Table 2. IPRDS generic systems list

BWR		PWR	
		Nuclear Systems—N	
N01	Reactor core	N01	Reactor core
N02	Control rod drive system	N02	Control rod drive system
N02.A	Control rod drive hydraulic system		
N03	Reactor control system	N03	Reactor control system
N04	Reactor recirculaton system	N04	Reactor coolant system
N05	Standby liquid control system	N05	Emergency boration system
N06	Reactor protection system	N06	Reactor protection system
N07	Neutron monitoring/nuclear instrumentation system	N07	Nuclear monitoring/nuclear instrumentation system
N08	Residual heat removal/low pressure safety injection system	N08	Residual heat removal/low pressure safety injection system
N09	Reactor water cleanup system	N09	Chemical and volume control system (CVCS)
		Engineered Safety System—S	
S01	Reactor core isolation cooling system		
		S02	Engineered safety features actuation system
S03	Engineered safety features	S03	Safety injection system
S03.A	High pressure coolant injection/core spray system	S03.A	High pressure safety injection subsystem
		S03.B	Safety injection tank/core flood subsystem
S03.C	Low pressure coolant injection	S03.C	Low pressure safety injection subsystem
S03.D	Low pressure core spray system		
S03.E	Automatic depressurization system		
S04	Remote shutdown system	S04	Remote shutdown system
		S05	Auxiliary feedwater system
		Containment Systems—C	
C01	Primary containment and penetrations		
C02	Reactor building	C02	Reactor building/containment and penetrations
C03	Containment heat removal	C03	Containment cooling system
		C03.A	Ice condenser system
C04	Containment isolation system	C04	Containment isolation system
C05	Containment purge system	C05	Containment purge system
C06	Standby gas treatment system		
C07	Combustible gas control system	C07	Combustible gas control system
C08	Containment ventilation system	C08	Containment ventilation system
C09	Reactor building ventilation system		
C10	Containment spray system	C10	Containment spray system
		C11	Penetration room ventilation system

Table 2 (continued)

BWR and PWR

Electrical systems—E

E01	Main power system
E01.A	Protective relaying and controls
E02	Plant AC distribution system
E02.A	Essential power system
E02.B	Non-essential power system
E02.C	HPCS power system
E02.D	Protective relaying and controls
E03	Instrumentation and control power systems
E03.A	DC power system
	vital DC power subsystem
	plant DC power subsystem
E03.B	Instrument AC power system
	vital instrument AC power subsystem
	plant instrument AC power subsystem
E04	Emergency power system
E04.A	Diesel-generator fuel oil subsystem
E04.B	Diesel-generator cooling water subsystem
E04.C	Diesel-generator air subsystem
E04.D	Diesel-generator lubrication oil subsystem
E05	Plant lighting system
E05.A	Essential lighting
E05.B	Non-essential lighting
E06	Plant computer
E07	Switchyard
E07.A	DC control power system
E07.B	Protective relaying

Power Conversion Systems—P

P01	Main steam system
P02	Turbine-generator system
P02.A	Electro-hydraulic control subsystem
P02.B	Turbine gland seal subsystem
P02.C	Turbine lubrication subsystem
P02.D	Stator (hydrogen) cooling subsystem
P02.E	Hydrogen seal oil subsystem
P03	Turbine bypass system
P04	Condenser and condensate system
P04.A	Condenser evacuation system
P04.B	Condensate cleanup/polishing system
P04.C	Condensate heater drain subsystem
P05	Feedwater system
P05.A	Feedwater heater drain subsystem
P06	Circulating water system
P07	Steam generator blowdown (PWR)
P08	Auxiliary steam system

Process Auxiliary Systems—W

W01	Radioactive waste system
W01.A	Gaseous radwaste system
	offgas subsystem (BWR)
W01.B	Liquid radwaste system
W01.C	Solid radwaste system
W02	Radiaction monitoring system
W02.A	Plant area radiation monitors
W02.B	Environmental radiation monitors
W02.C	Process radiation monitors
W03	Cooling water systems
W03.A	Reactor building cooling water system
W03.B	Turbine building cooling water system
W04	Service water systems
W04.A	Demineralized makeup water system
W04.B	Station service water system
	Essential service water system
	Non-essential service water system
W04.C	Chilled water system
W05	Refueling system
W06	Spent fuel storage system
W06.A	Fuel pool cooling and cleanup system
W07	Compressed air system
W07.A	Service air system
W07.B	Instrument air system
W08	Process sampling system
W09	Plant gas system
W09.A	Nitrogen system
W09.B	Hydrogen system

Table 2 (continued)

BWR and PWR

Plant Auxiliary Systems—X

X01	Potable and sanitary water system
X02	Fire protection system
X02.A	Water system
X02.B	Carbon dioxide system
X03	Communications system
X04	Security system
X05	Heating, ventilating, and air conditioning systems
X05.A	Control room habitability system
X05.B	Turbine building ventilation system
X05.C	Diesel building ventilation system
X05.D	Auxiliary building ventilation system
X05.E	Fuel building ventilation system
X06	Non-radioactive waste system
X06.A	Gaseous waste subsystem
X06.B	Liquid waste subsystem
X06.C	Solid waste subsystem

between the component and other parts of the system. The need exists to identify specific component boundaries so that the fault tree analyst will understand which failures were considered within a particular basic event and which were excluded. The boundary also serves to identify which maintenance actions should be assigned under given class of component. Secondary, the importance of clearly defined boundaries is crucial in the initial sorting of appropriate records from the collected set of plant data covering all components.

Generally, the approach is to consider a component "envelope" or super-component, including local ancillary piece parts that significantly affect the function of the component. This philosophy is consistent with the method employed by plant personnel in documenting a maintenance action request.

The boundaries of the four electrical components addressed in this report are outlined in the following paragraphs.

2.2.1.1 Diesel generator (DG) boundary. The boundary around the diesel generator component is described as several interfaces with other systems or components. One general criterion for demarcating this boundary is to include local systems and components that are integral to starting and sustaining the electrical generating capability of the diesel generator. The diesel engine/generator set is the focal point of the boundary.

2.2.1.1.1 Mechanical function interface (Figs. 1-3):

a. The mechanical interface encompasses the combustion air intake duct system including the outdoor snorkel or louvered vents to the outdoor air. All turbo-charging equipment including intercoolers (if present) is considered within the boundary. The exhaust system is included up to the point of outdoor discharge.

ORNL-DWG 84-14389

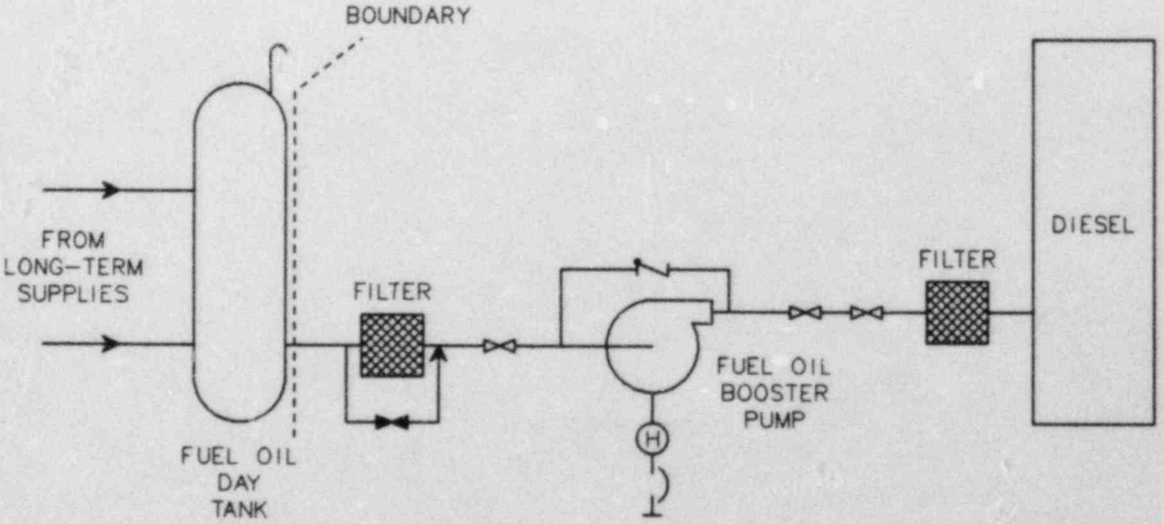

Fig. 1. Diesel generator boundary: mechanical interface of fuel oil feed system.

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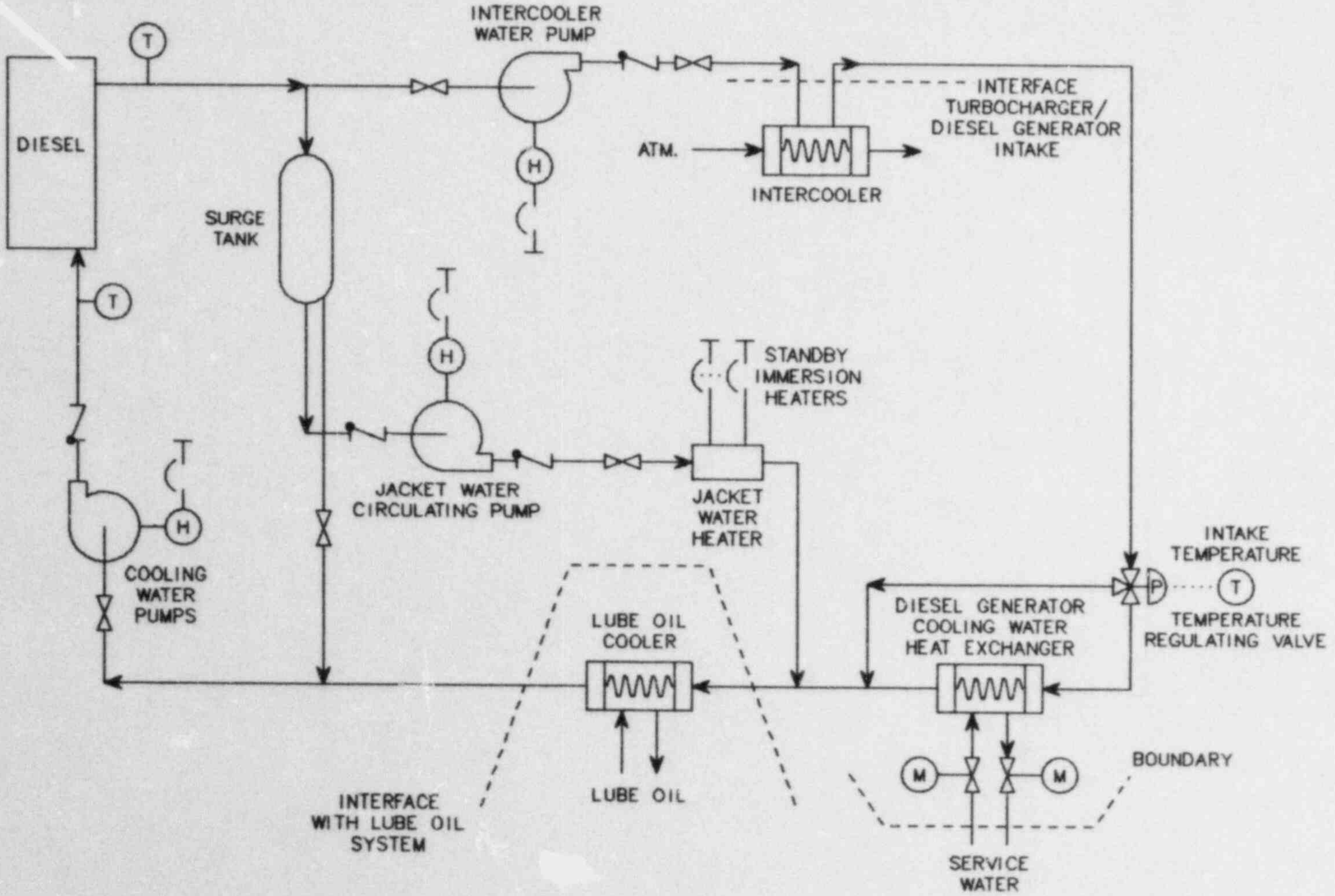

Fig. 2. Diesel generator boundary: mechanical interface of engine cooling system.

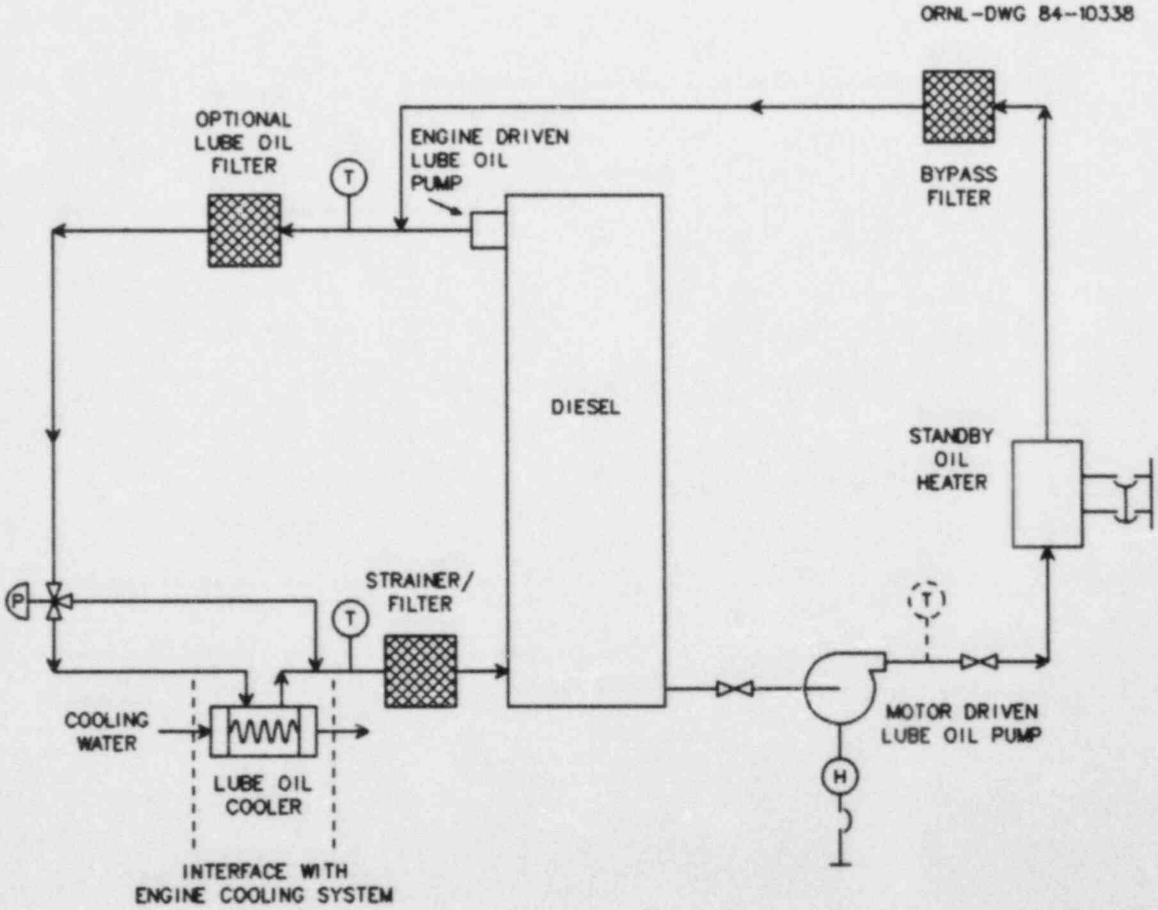

Fig. 3. Diesel generator boundary: mechanical interface of lubricating oil system.

b. The fuel oil feed system including feed and booster pumps, filters, valves, from the diesel engine up to but excluding the short-term supply (day) tank located in the diesel generator room, is within the boundary (Fig. 1).
c. The engine cooling system is within the boundary including the internal jacket coolant, the heat exchanger, and the cooling water piping to this heat exchanger up to and including the motor operated valves connecting the service water supply (Fig. 2).
d. The engine lubrication system including the lube oil sump pump, circulating pump, oil cooler, standby heater, filters, strainers and valves is within the boundary (Fig. 3).
e. Any structural supports, anchorages, and skids on which the DG is mounted are considered within the boundary.

2.2.1.1.2 Electrical function interface (Fig. 4): The electrical interface considered within this boundary includes the electrical output system from the generator section of set up to and including the connecting breaker (standby feeder breaker) to the emergency bus.

ORNL-DWG 84-10342

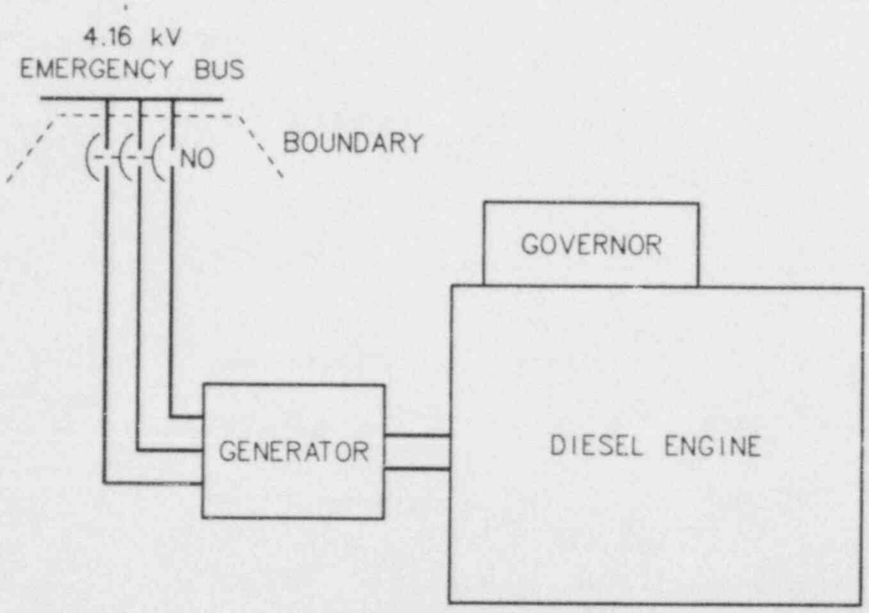

Fig. 4. Diesel generator boundary: electrical function interface.

2.2.1.1.3 Command, control, and monitoring interface (Fig. 5):

a. The command interface within the DG boundary encompasses the starting air system (or electrical start system if present), including the air accumulator tanks, filters, any integral piping and relief valves, the auxiliary compressor, and pressure switches, and instrumentation and controls.

b. The master relay (which accepts the remote emergency start signal) and all internal input contacts which commence operation of DG auxiliaries are included.

c. The control interface within the DG boundary encompasses all local controls (i.e., within the diesel generator room) including control circuits and switches which send the start signal to the DG (command interface).

d. Also included are the protective devices for shutting down the DG including relays for overcurrent, loss of field and reverse power on the generator and switches for high crankcase pressure, high coolant temperature, overspeed on the engine, etc.

e. The monitoring interface within the DG boundary encompasses local monitoring instrumentation for the DG. It is recognized that some of these items are not critical to DG operation.

2.2.1.2 Battery boundary (Fig. 6): The battery boundary is defined to include the battery container, the seismic-designed battery racks and straps, internal parts including plates and electrolyte, terminal connections including cables with lugs, posts, or connectors, and any switches or meters for normal operation of the battery. The terminal connections are up to and including the first breaker connection.

ORNL-DWG 84-10339

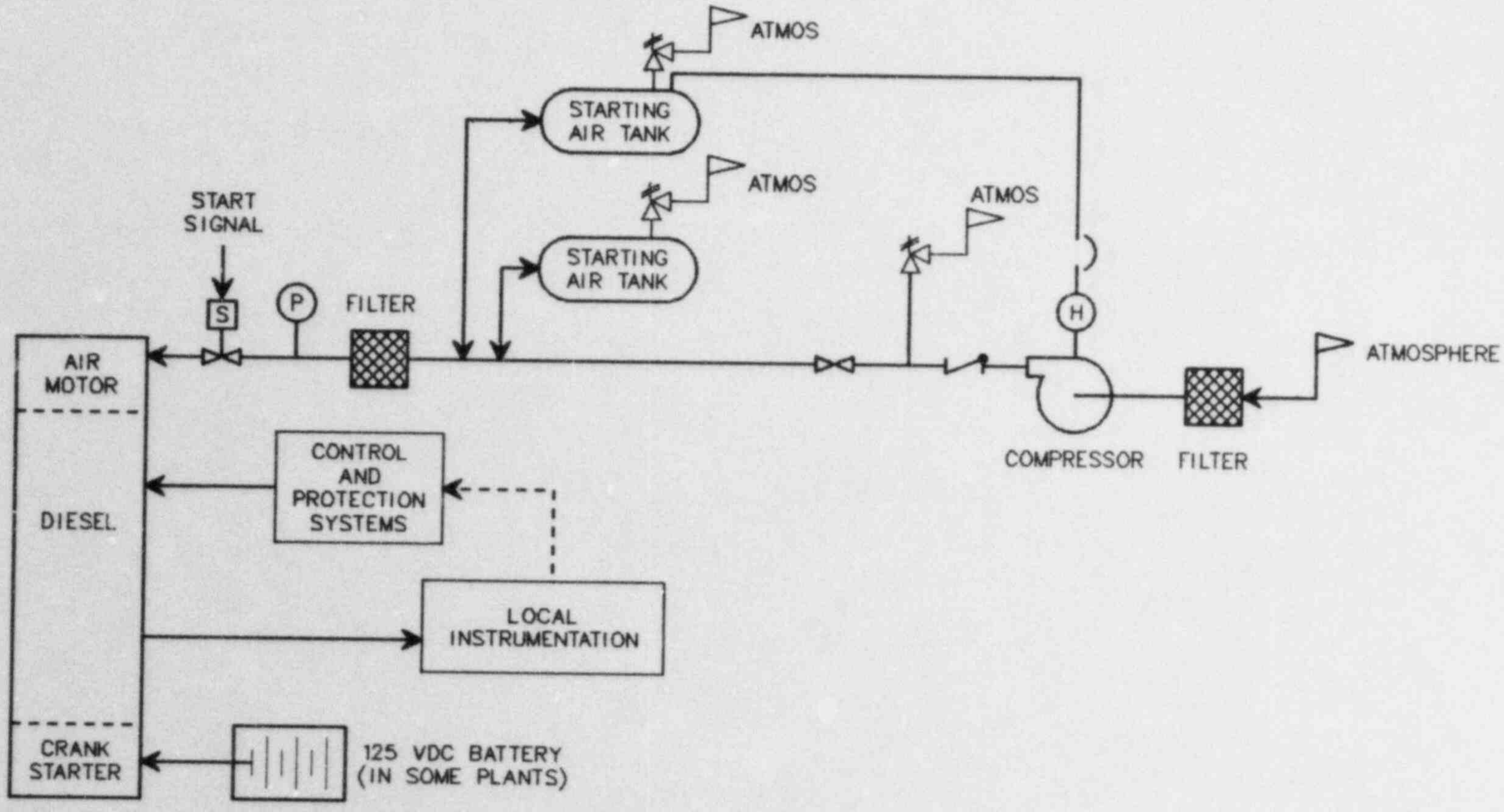

Fig. 5. Diesel generator boundary: command, control, and monitoring interface

ORNL-DWG 84-10340

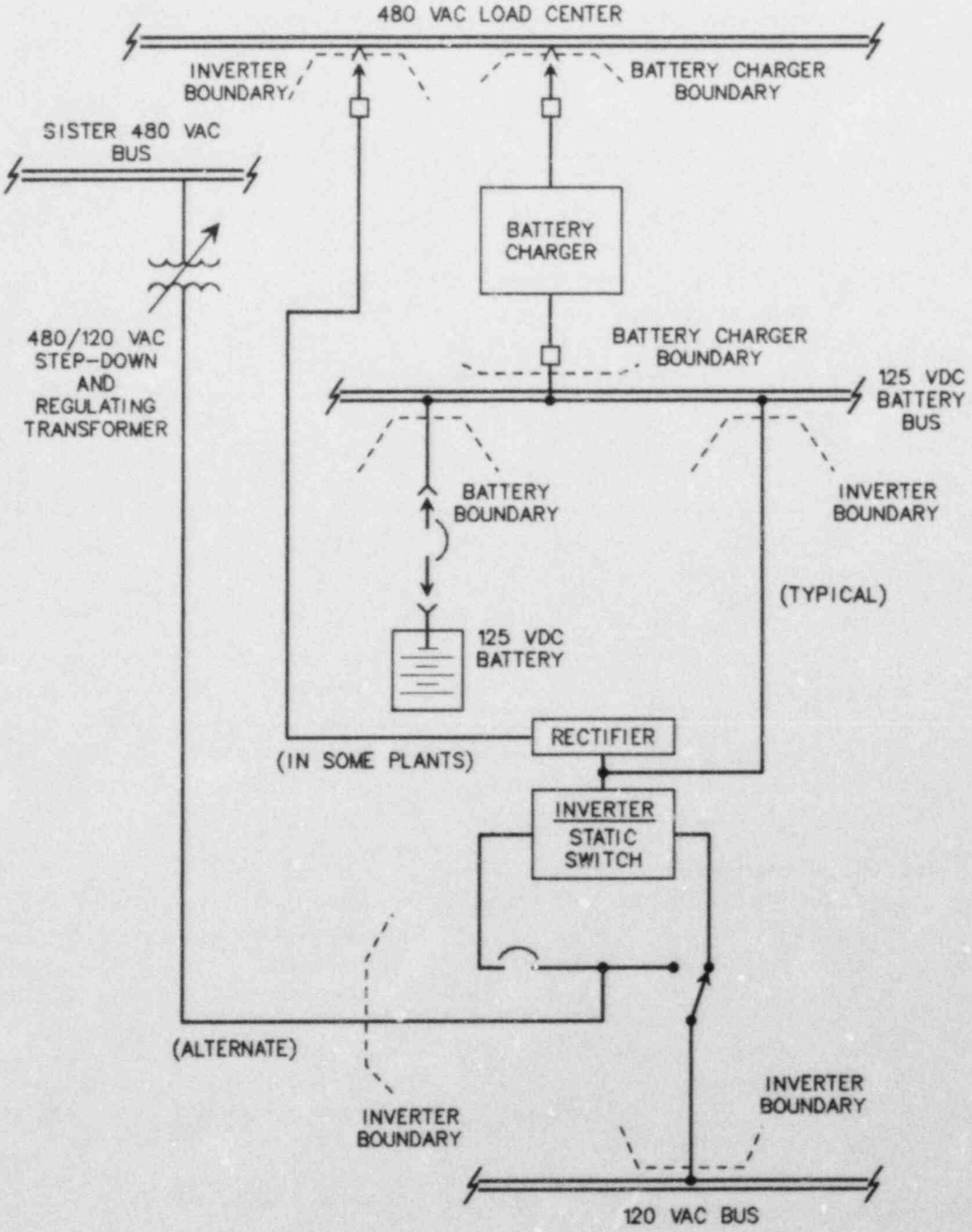

Fig. 6. Battery, charger, and inverter boundaries.

2.2.1.3 Battery charger boundary (Fig. 6): The most common type of battery charger found in newer nuclear plants is the static, solid-state charger. In older plants, electromechanical motor generator sets can frequently be found serving in a battery charging capacity. In this report only solid state equipment was considered in the battery charger category. Motor generator sets should be addressed separately for their reliability because of their structural dissimilarity to solid state equipment.

The static battery charger is typically fed from a 480 V load center (LC) or motor control center (MCC). The charger boundary is demarcated to include the connecting feeder breaker to this center (bus) and the connecting output breaker to the DC bus. Included between these two points are the electronic and nonelectronic components within the charger enclosure, the associated instrumentation, control and protective devices including meters, relays, fuses, switches, and circuit breakers.

2.2.1.4 Inverter boundary (Fig. 6): Inverters are used in the plant to invert DC power supplies into AC power for vital and nonvital loads. The most typical usage is in supplying computer power and preferred instrumentation and control power. The inverter may contain a rectifier if its normal supply is the 480 VAC bus.

As with the battery chargers, some of the encountered inverter functions were served by motor-generator (MG) or motor-motor-generator (MMG) sets. These sets were excluded from the study for similar reasons as the motor generator battery chargers (dissimilarity to solid state devices).

The inverter boundary includes connections made into multiple supply sources: (Fig. 6)

a. 125 VDC distribution bus supply: (typical)

The inverter is usually fed from the DC battery bus. The boundary includes the feeder breaker connecting the inverter/static transfer switch to the bus. The bus is not within the boundary.

b. 480 V normal or emergency bus supply: (in some plants)

The boundary includes the feeder breaker connecting the rectifier section to the bus. The rectifier is in series with the inverter/static transfer switch section.

c. Alternate regulated AC bus:

If the inverter fails, the alternate source is a second 480 V bus supply, via step and regulating transformer(s) to a bypass switch. This backup source is also employed during inverter maintenance. The boundary excludes this transformer and the connecting breaker to the alternate bus.

The boundary includes all electronic and nonelectronic components within the inverter unit, the rectifier, the static transfer switch, the associated instrumentation, and local control and protective devices (meters, relays, fuses, switches, and circuit breakers).

2.2.2 Classification of failure severity

The severity of the component failure was classified in one of the following categories.

Catastrophic: The component is completely unable to perform its function.

Degraded: The component operates at less than its specified performance level.

Incipient: The component performs within its design envelope but exhibits characteristics that, if left unattended, could develop into a degraded or catastrophic failure.

For each component, a given severity classification can have several failure modes associated with it.

2.2.3 Failure mode codes development

The failure mode codes that were developed for the electrical components were derived from a variety of sources. Important consideration was given to the primary mode(s) of operation for each component, and these are addressed individually.

Historically, the selection of failure modes for IPRDS coding has been tailored to the needs of the fault tree analyst concerned with basic events.[5-7] Such events are component specific but may be generalized as:

- loss of function of the component
- change of state without command
- failure to change state upon command.

Where practical, modes were designated as either time- or demand-related to facilitate calculation of the failure rate or failure probability. We acknowledge that in some instances the component specific failure modes may be too well defined in comparison to the gross failure modes often seen in Probabilistic Risk Assessments. However we believe that this definition affords more flexibility to the analyst whom may combine failure rates as needed to suit his immediate purpose.

2.2.3.1 Diesel generator (Table 3): The failure modes associated with catastrophic severity failures (A, B, C) are the specific cases for the diesel generator of the generalized events given above (e.g. mode A designates a failure to start). With regard to mode B ("fails to run once started") there is the belief among some failure analysts that DGs must be allowed 30 minutes of warm-up time before they should be considered as "running", and any failures within that period should be counted as a "failure to start". Hence it is given separate treatment. In addition, we recognize that in some cases the diesel will "fail to start" because it successfully started and supplied essential loads in, for example, 12 sec. instead of within the 10 sec. technical specification requirement. This is not an actual failure to start since the DG would be available under accident conditions, but the delay would mandate filing an LER as a "failure to start." LER data is not directly employed in IPRDS but nonetheless the plant maintenance work request might list the occurrence as a failure and so a separate mode (C) is assigned to describe it. Mode C also covers undesirable automatic terminations of the DG function. We recognize that in some instances a DG may experience a trip which would not occur if the diesel was in emergency operation (due to overrides). These trips would conceivably be found in the in-plant maintenance records, and the fault tree analyst should be aware of their inclusion here. Examples include items such as a manual trip which

Table 3. Diesel generator failure modes

		Time/demand related
	Catastrophic	
A:	Fails to start-fails to start despite multiple attempts	Demand
B:	Fails to run once started	Time
C:	Improper operation	Time
	a) fails to supply essential load within time specification	
	b) automatic termination of function	
	Degraded	
D:	Fails to start	Demand
	a) delayed successful start after multiple attempts	
	b) fails to supply sufficient/rated load within time spec.	
E:	Improper operation	Time
	a) fails to supply rated load	
	b) fails to maintain voltage/frequency specification	
	c) defective local switches	
	d) failure of starting air compressor	
	Incipient	
F:	Improper cooling/heating (leaks, etc.)	Time
G:	Faulty indication	Time
H:	RPM hunting	Time
I:	Vibration	Time
J:	Improper lubrication (leaks, etc.)	Time
K:	Improper fuel combustion (improper fuel feed, air feed, etc.)	Time

may be initiated by the operator if he noticed that the diesel was running hot, or vibrating excessively.

Expansion of the general failure modes into the degraded and incipient severity categories produced several new modes. Mode D describes occurrences where the diesel started and ran after multiple attempts and/or failed to supply sufficient/rated power within time specification. Mode E covers several instances where the diesel fails to supply its required rated load altogether or fails to maintain its required voltage/frequency specifications. In addition two data-driven modes were included under mode E that pertained to defective local switches and failures in the starting air compressor(s). Incipient failure modes F through K were largely derived from recurring prominent problems described in the data (e.g. oil leaks, coolant heaters malfunctioning, etc.).

All modes except modes A&D are time-related. Modes A&D describe failures to start on command and are considered demand-related. These modes have significance with regard to the standby nature of the DG as an emergency power supply.

2.2.3.2 Battery (Table 4): The catastrophic modes involve total loss of (Mode A) or inadequate (mode B) battery function availability when needed. Modes C&D, which originally described these similar conditions under test circumstances, were consolidated into A&B. The effect of the consolidation was to aggregate every failure of the battery to supply its output current at voltage. No distinction was made between such failures which might occur during emergency operation and those which might occur during performance discharge testing. We feel this is a valid approach for two reasons. Primarily, it is our contention that classification of the failure of the battery to supply output should not be based on whether the load employed to test the battery is an actual emergency load or a simulated emergency load (performance discharge test). We recognize that failure of the battery to function during an

Table 4. Battery failure modes

	Time/demand related
Catastrophic	
A: No output available	Time
B: Inadequate output available	Time
Degraded	
J: Won't hold charge	Time
K: Low cell voltage detected	Time
L: Ground detected	Time
Incipient	
E: Leakage	Time
F: Improper environment (temperature, humidity, etc.)	Time
G: Corrosion/dirty/dust contamination	Time
H: Faulty indication	Time

emergency situation can be more significant than a similar failure which occurs during a performance discharge test, since the latter is conducted during certain shutdowns (e.g. refueling) when the consequences of failure are greatly reduced.[8] The performance discharge test simulates a plant emergency load such that classification of the battery failures should be independent of the two types of loads. Secondly, we observed that frequently the maintenance records did not document under which load situation the failure discovery was made.

These catastrophic failure modes were considered time-related rather than demand-related even though the failures became evident upon loading of the batteries. However, emergency and test-related loads only yield about one demand per year. During the interim period between demands, various effects from chemical, physical, environmental and human factors contribute to the degradation of the battery's capacity to function on demand. Therefore we contend that, for purposes of this preliminary report, failure upon test is more closely related to the stresses of time than the stresses of cyclic demand. We recognize the debatable aspects of this assumption and defer on stating it conclusively at this time.

Weekly and quarterly battery cell surveillance/inspections cannot be considered as valid "demands" since they do not provide for complete assurance that the battery will perform under actual load conditions. The performance of the discharge test and the actual emergency demand situation are the only instances when the batteries perform under load, and therefore provide the only certifiable results which demonstrate the adequacy of battery state of charge.

Modes J, K, and L were all data-driven, most notably the latter. These three modes may describe similar phenomena but were separately included owing to the often unspecified circumstances surrounding the discovery of the battery problem. Typically, battery room conditions (temperature, humidity, cleanliness) are monitored for indication of impending problems. The STD-500 considers these as environmental factors which aggravate other modes of failure.[5] They are included in failure modes F and G.

2.2.3.3 Battery chargers (Table 5): The single catastrophic failure mode A describes the complete loss of the charger output to the battery bus. Modes B, C, F, and G were originally assigned to describe failures of motor-generator chargers which were subsequently excluded from consideration in this report. The degraded failure mode D covers the cases where the charger output (amperage and voltage) was not within required specifications. Mode E described failures of overheating. The incipient failure mode "faulty indication" (mode H) was data-driven by many records involving deviations in local instrument readings.

No demand-related modes are presented for battery chargers. Generally they are under constant operation and failures are necessarily time-related. Conceivable occasions for which they are subjected to demands include failure to continue or resume operation following an electrical system transient and failure to adequately recharge the batteries following plant shutdown (18 months) battery performance discharge tests. These modes were assumed not to contribute significantly, and it is our belief that demands are not a pertinent consideration for continuous duty chargers.

Table 5. Static battery charger failure modes

	Time/demand related
Catastrophic	
A: No electrical output	Time
Degraded	
D: Electrical output out of specification a) electrical output too low b) electrical output too high c) erratic electrical output	Time
Incipient	
E: Overheating	Time
H: Faulty indication	Time

2.2.3.4 Inverters. The failure modes for inverters are given in Table 6. Mode A ("no output") typically resulted from a blown fuse and represented the generalized loss of component function. We originally considered the failure to change state upon command (demand-related) which was physically suited for failures of the static transfer switch. We identified instances where this failure mode had significant impact on the plant (particularly vital instrumentation). However these were isolated occurrences during infrequent plant conditions and were lumped together with mode A failures. All of the degraded severity failure modes pertain to output parameters (e.g. voltage, current, and frequency) out of specification. The incipient failure modes cover similar problems as their counterparts for other components (e.g. overheating, faulty indication, and foreign contamination).

No demand-related modes were included for inverters for similar reasons as in battery chargers.

2.2.4 Failure cause code development

One of the characteristic features of the IPRDS is the data-driven cause coding scheme. The thrust of this approach is to let the maintenance records dictate the scheme. Typically this involves keying on certain descriptors in the failure description such as design failures, installation failures, piece parts or subcomponents, etc.

For these four electrical components, other references were reviewed first and basic lists of cause codes were generated.[5-7] This was followed by a review of the maintenance records to construct new cause codes as necessary. Finally, the supplemented list was restructured to reduce the number of codes without eliminating or obfuscating the content of

Table 6. Static inverter failure modes

		Time/demand related
	Catastrophic	
A:	No output	Time
	Degraded	
C:	Output frequency out of specification	Time
D:	Output voltage out of specification	Time
G:	Output current out of specification	Time
H:	Improper operation (unspecified deviation)	Time
	Incipient	
E:	Overheating	Time
F:	Faulty indication	Time
I:	Dirt/dust contamination	Time

significant cause categories. For each component set of codes, unique numerical identifiers were assigned. Blank entries were included to allow for subsequent expansion.

The cause code schemes have a consistent arrangement of subsets within them. These subsets may be generalized as follows:

Event/state:	Cause codes in this subset describe the event/state that is the basic cause of the failure. Examples include "design error," "personnel error," etc.
Subsystems:	These cause codes are used to describe failure or malfunction of specific subsystems included within the component boundary (e.g. for diesel generators: lubrication system, cooling system, starting system etc.)
Parts/components:	These codes are employed to further isolate and describe failures of piece parts or subcomponents of the overall component. For example, the governor of the diesel generator is a piece part of its control system.
Miscellaneous:	Cause codes describing phenomena not covered by the above categories.

The specific component cause code lists are discussed briefly in the following paragraphs.

It may be noted that the generation of cause codes for these electrical components was not significantly different from the schemes employed on the other IPRDS components. The application of the cause codes onto the failure records was oriented towards the operational history analyst as well as the needs of the fault tree analyst. Thus the failures were often coded with several cause codes which both identify the primary cause of failure and facilitate keyword searching of the failure data.

2.2.4.1 Diesel generator: The diesel generator cause codes are listed in Table 7. Because the DG is the relatively complex component (see section 2.2.1.1), there are many cause codes. Codes 00-04 describe generic events. Codes 08-11 describe a predominant phenomena: leakage of air, oil, water, etc. Codes 12-22 identify several major subsystems and auxiliaries of the diesel. The list of piece-part codes spans from 28 to 58. Several miscellaneous failure causes rounded out the list.

2.2.4.2 Battery: Table 8 provides the list of battery failure cause codes. Codes 00-04 describe generic events. Codes 08-14 pertain to failure events characteristic only to batteries including low specific gravity, plate sulphation, and cell ground. Codes 17-28 describe the few piece parts which make up batteries or can be found in the battery room. Miscellaneous codes 29-32 pick up other generic failure causes and codes 33-37 add piece parts which were not included in the earlier sequence.

2.2.4.3 Charger: Failure cause codes for battery chargers appear in Table 9. The battery chargers under consideration were solid state devices. Many of the cause codes describe common pieces found in such electronics like diodes, capacitors, and transistors. Three of the most commonly identified subcomponents were the surge suppressors, firing modules, and voltage regulators. Several codes in the list are pertinent only to motor-generator sets and are not applicable for this report.

2.2.4.4 Inverters: Table 10 gives the cause codes employed for inverter failures. As with the other components, the first several codes pertain to general failure causes. Codes 08-10 describe abnormalities in the important output parameters of voltage and frequency. Inverters loads are sensitive to minor variations in their power supply, therefore these failure codes cover important failure causes. Codes 14-31 pertain to a variety of solid state subcomponents. A few codes were added to the list that apply only to motor-generator sets and were not used for the inverters under consideration.

2.3 Match-Merging of Population Records and Failure/Repair Records

To perform the failure rate analyses using the IPRDS, it is first necessary to match failure/repair records to their appropriate component population record. This is accomplished within the data management system by "match-merging" on the plant identifier, the component class, and the component identification numbers. These multiple requirements were necessary since the components tended to have simplistic ID numbers (e.g., 1A, 2B, C-A, etc.) which were often duplicated for an entirely different kind of equipment.

Often the raw data from the in-plant records contains inaccurate and insufficient information (component ID) to match on. In previous IPRDS

Table 7. Diesel generator failure cause codes

Code type	Code No.	Code description
Event/state	00	Unknown
	01	Design error
	02	Fabrication/construction error
	03	Personnel error
	04	Procedural discrepancy
	05	Blank
	06	Blank
	07	Blank
	08	Leakage/general, unspecified
	09	Leakage/air, gas, steam
	10	Leakage/liquid coolant, hydraulic fluid
	11	Leakage/lubricant, oil, grease
Sub-systems	12	Air intake system
	13	Building environmental control system
	14	Control circuit (speed control/governor/logic channels)
	15	Cooling system
	16	Electrical systems
	17	Engine
	18	Exhaust system
	19	Fuel delivery system
	20	Generator
	21	Lubrication systems
	22	Starting system
	23	Blank
	24	Blank
	25	Blank
	26	Blank
	27	Blank
Parts/components	28	Battery
	29	Breaker
	30	Equalizer
	31	Fan
	32	Fitting/nipple/plug
	33	Governor
	34	Heater
	35	Motor
	36	Pump
	37	Recording instrument
	38	Relay
	39	Screw/bolt/fastener/weld/solder
	40	Solenoid
	41	Strainer/filter
	42	Switch/microswitch
	43	Synchronizer

Table 7 (continued)

Code type	Code No.	Code description
	44	Transducer/indicator
	45	Transducer/regulator
	46	Turbocharger
	47	Valve
	48	Wiring
	49	Brush/rigging
	50	Fuse/fuse holder
	51	Compressor
	52	Heat exchanger/cooler
	53	Gasket
	54	Flange
	55	Light/socket
	56	Sight glass
	57	Alarm/annunciator
	58	Skids/supports
Miscellaneous	59	Corrosion/erosion
	60	Cracked/pierced
	61	Foreign material containment
	62	Misaligned
	63	Out of adjustment
	64	Vibration
	65	Loose

Table 8. Battery failure cause codes

Code type	Code No.	Code description
Event/state	00	Unknown
	01	Design error
	02	Fabrication/construction error
	03	Personnel error
	04	Procedural discrepancy
	05	Blank
	06	Blank
	07	Blank
	08	Cell ground/short
	09	Cell open
	10	High specific gravity
	11	Low specific gravity/low electrolyte level
	12	Plate sulphation
	13	Seal leak
	14	Off-battery ground
	15	Blank
	16	Blank
Parts/components	17	Cable
	18	Connector/lug
	19	Container/jar
	20	Cover
	21	Inter-cell connector bolt
	22	Negative plate
	23	Positive grid
	24	Separator
	25	Terminal/post
	26	Alarm/annunciator/indicator
	27	Thermostat
	28	Fan
Miscellaneous	29	Corrosion/erosion
	30	Cracked/pierced
	31	Foreign material contamination
	32	Out of adjustment
	33	Voltmeter
	34	Ammeter
	35	Battery racks/straps/bolts
	36	Relay/contacts
	37	Switch

Table 9. Battery charger failure cause codes

Code type	Code No.	Code description
Event/state	00	Unknown
	01	Design error
	02	Fabrication/construction error
	03	Personnel error
	04	Procedural discrepancy
	05	Blank
	06	Blank
	07	Blank
	08	Abnormal output ripple
	09	Reverse current flow
	10	Blank
	11	Blank
	12	Blank
Parts/components	13	Capacitor
	14	Connectors
	15	Diode
	16	Fuse
	17	Inductor/transformer
	18	Integrated circuit (IC)
	19	Potentiometer
	20	Relay/solenoid
	21	Resistor
	22	Silicon controlled rectifier (SCR)
	23	Solder connections
	24	Switch
	25	Transistor
	26	Wiring/cable
	27	Surge suppressors
	28	Firing modules
	29	Voltage regulator
	30	Armature
	31	Bearing
	32	Brush
	33	Circuit breaker
	34	Commutator
	35	Stator
	36	Voltmeter
	37	Ammeter
	38	Blank
Miscellaneous	39	Corrosion/erosion
	40	Cracked/pierced
	41	Foreign material contamination
	42	Inadequate lubrication
	43	Misaligned
	44	Out of adjustment
	45	Under voltage trip coil/breaker
	46	Filter
	47	Lights/socket/indicators

Table 10. Inverter failure cause codes

Code type	Code No.	Code description
Event/state	00	Unknown
	01	Design error
	02	Fabrication/construction error
	03	Personnel error
	04	Procedural discrepancy
	05	Blank
	06	Blank
	07	Blank
	08	Abnormal harmonic distortion
	09	Abnormal output frequency
	10	Abnormal output voltage regulation
	11	Blank
	12	Blank
	13	Blank
Parts/components	14	Capacitor
	15	Circuit breaker/contactor
	16	Connectors
	17	Diode
	18	Fuse
	19	Inductor/transformer
	20	Integrated circuit (IC)/card
	21	Relay/solenoid
	22	Resistor
	23	Silicon controlled rectifier (SCR)
	24	Solder connections
	25	Static transfer switch
	26	Switch
	27	Transistor
	28	Wiring
	29	Alarm/annunciator/indicator
	30	Grating/synchronization board
	31	Recording instruments/meters
Miscellaneous	32	Corrosion/erosion
	33	Cracked/pierced
	34	Foreign material contamination
	35	Out of adjustment
	36	Brushes
	37	Couplings
	38	Rheostat/potentiometer

component reports the level of this incompatibility reduced the useful data for analyses and the sheer number of records prohibited further improvement within the time and funds available. However in this study the actual number of population and failure/repair records which were handled were considerably smaller. Consequently a data editing effort was undertaken after an extensive familiarization with plant equipment lists and drawings. This effort improved the quantity and quality of the final merged records set. Appendix B describes plant specific information and its limitations.

3. FAILURE RATE CALCULATIONS

3.1 Point Value Estimation

The equation used to estimate the probability of failure on demand (Q_d) is

$$Q_d = \frac{n}{D}$$

where

n = the number of failures observed and
D = the total number of demands experienced.

The equation used to estimate the failure rate (λ_t, per hour) is

$$\lambda_t = \frac{n}{T}$$

where

n = the number of failures observed and
T = the total operating time of the components.

In the data tables these values of Q_d and λ_t are listed under the column labeled "recommended." When using the recommended values, it should be re-emphasized that the IPRDS is a pilot data base. When no failures were observed ($n = 0$), the point estimates Q_d and λ_t in this column were determined using the median of a chi-square variable with one degree of freedom,[9]

$$\lambda_t = \chi^2_{0.5}(1)/2T$$

$$= 0.227/T$$

$$Q_d = \chi^2_{0.50}(1)/2D$$

$$= 0.227/D.$$

For $(D - n) < 40$, the median of a F distribution with 1 and $2D + 1$ degrees of freedom was used to calculate

$$Q_d^{50} = \frac{F_n}{2(D - n) + F_n + 1},$$

where $F_n = F_n(1, 2D + 1)$.

3.2 Interval Estimation

The confidence limits for the hourly failure rates were calculated on the assumption that the component times to failure are exponentially distributed. Although for Q_d the number of failures n is binomially distributed, the Poisson distribution may be used to approximate the distribution of this variable when the number of failures is small compared to the number of demands. The equations for estimating the 90% confidence bounds on the failure rates when $n > 0$ and $D - n \geq 40$ are:

$$\lambda_t^{5\%} = \frac{\chi^2_{0.05}\ (2n)}{2T} ,$$

$$\lambda_t^{95\%} = \frac{\chi^2_{0.95}\ (2n + 2)}{2T} ,$$

$$Q_d^{5\%} = \frac{\chi^2_{0.05}\ (2n)}{2D} , \text{ and}$$

$$Q_d^{95\%} = \frac{\chi^2_{0.95}\ (2n + 2)}{2D} ,$$

where

$\chi^2_{0.05}(2n)$ = the chi-square variate at the 0.05 level with 2n degrees of freedom and
$\chi^2_{0.95}(2n + 2)$ = the chi-square variate at the 0.95 level with $(2n + 2)$ degrees of freedom.

For the cases where $D - n < 40$, the Poisson approximation to the binominal distribution is not adequate, and the following equations are used when $n > 0$:

$$\lambda_d^{5\%} = \frac{nF_i}{D - n + 1 + nF_i} \text{ and}$$

$$\lambda_d^{95\%} = \frac{(n + 1)\ F_u}{D - n + (n + 1)\ F_u} ,$$

where

$$F_i = F_{0.05}\ (2n,\ 2D - 2n + 2) ,$$

which is the F variate at the 0.05 level with 2n and $2D - 2n + 2$ degrees of freedom, and

$$F_u = F_{0.05}\ (2n + 2,\ 2D - 2n) ,$$

which is the F variate at the 0.95 level with $2n + 2$ and $2D - 2n$ degrees of freedom.

When $n = 0$, no estimates were made for the 5% values of λ_t or Q_d. The upper confidence level when $n = 0$ was calculated using

$$\lambda_t^{95} = \chi^2_{0.95}(2)/2T \text{ and}$$

$$Q_d^{95} = \chi^2_{0.95}(2)/2D \ .$$

3.3 Component Aggregate Failure Rates

Because of the relatively short operating period of some plants, grouping of failures of similar components was considered. Typically the plant batteries considered were similar and a plant failure rate was calculated using the combined number failures and the total of operating times of the batteries. In addition, aggregate failure rates were calculated for similar components across plants by combining failures of similar components from all plants and using totals of the operating hours for the individual components.

A non-rigorous approach was utilized for computing the preliminary aggregate component failure rates across all plants. The means of the failure rates for the similar components in the various plants were examined for their relative agreement. In cases where the means of the failure rates at individual plants agreed within one order of magnitude, the individual plant data were simply aggregated. The mean and the confidence interval were determined using the same method as for components in individual plants (i.e. chi-square). Otherwise the highest and lowest mean values of the individual plant failure rates were taken as the upper and lower bounds of the aggregate failure rate. This is recognized to be a simplistic approach to documenting aggregate failure rates and is not statistically rigorous, but sufficient for the purpose at hand.

3.4 Output Data Format

The format of sample data Table 11 was selected for documenting electrical component reliability statistics of the IPRDS. The rationale behind the format is to facilitate a hierarchical display of the general electrical component classifications into specific classifications. The philosophy of this approach is similar to that found in the IEEE STD-500.[5] However the sample size of data and time frame considered in this interim data report did not allow an elaborate breakdown. Reasonable statistics could only be generated on a group level and not for individual components. Terms shown in the sample format and the tables of Appendix A are defined as follows:

Plant:	IPRDS identification number
Plant type:	BWR or PWR
Operating period:	Number of calendar years after commercialization for which data are available.
Class:	Type of component (diesel generator, battery, charger, inverter)
Volts:	Output voltage of the component (VAC or VDC)

Table 11. Sample format of output data

Component/group name:

Plant:
Plant type:
Operating period:

Class:
Volts:
Amp-hrs:
Power:

Population:
No of failures:
Population hours:
Population demands:
Maintenance frequency:

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	No. of failures	Failures/10E+3 h			No. of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic								
Degraded								
Incipient								

Amp-hrs: Output capacity of the battery (ampere-hours) or battery charger (amperes)

Power: Output power or apparent power (actually kVA) of the component (kW)

Population: Number of individual components in the group under consideration.

Number of failures: Total number of failures which can be matched with any and all of the components in the group under consideration.

Population hours: Product of the population and the number of hours in the operating period for a specific plant.

Population demands: Product of the population and the number of demands in the operating period for a specific plant. (Note: demand-related probabilities were calculated only for DGs.)

Maintenance frequency: Total number of failures divided by calendar hours.

The above variables may in some cases be designated as N/A (not applicable). If the information was not available the space is left blank.

The failure rates are broken down by failure severity and by mode within the catastrophic severity.

4. DISCUSSION OF RESULTS AND OBSERVATIONS

The primary result of this study was a demonstration of the validity of the IPRDS approach as illustrated by the failure rates. These failure rates are presented in Table 12, Figs. 7 through 14, and the Tables of Appendix A. The following sections describe the tabular and graphical presentation of this information. Additionally, the results generated in this study are compared and contrasted with other similar sources of information. A brief analysis of the available repair time data is presented. Finally there is a plant-by-plant discussion of primary modes of failures and their causes for each component class.

4.1 Presentation of Failure Data

The presentation of failure rates in this report proceeds from aggregate values to plant specific values. Bearing in mind the preliminary nature and limited scope of the source data, the figures and tables which follow should be viewed as proposed means for documenting expanded IPRDS type information. It is strongly suggested that the user recognize the limitations of the data prior to making direct use of the preliminary statistics.

Table 12 presents the IPRDS recommended (i.e. mean) catastrophic failure rates obtained and their ranges for each class of component. These mean values are computed from the aggregations of failures and population hours/demands across all plants. The high and low values represent the range of the plant specific means. In one instance (see Table 12) it was appropriate to use chi-square estimates in lieu of the range of means.

The plant specific values used to generate Table 12 are presented graphically in Figures 7 through 14. These "barbell" plots provide illustration of the aforementioned rates along with additional information about the individual populations and number of failures. In conjunction with the plant specific information in Appendix B, these plots reveal the key contributors to the aggregate value as well as the outliers which can skew results.

The sources for the plots of Figures 7-14 are the plant and class specific data tables presented in Appendix A. The format of these tables is intentionally uniform and is designed to facilitate an orderly grouping of failure rates. As mentioned earlier, the scope of the useful data in IPRDS on electrical components is somewhat limited. Therefore the level of distinction among components was necessarily imprecise. In an expansion of the data base (i.e. more participating plants) it would be possible to present finer breakdowns of components (e.g. by voltage, power, duty) and develop more specific failure rates. The tables are designed to accommodate finer designations if needed. In addition to the catastrophic failure rates by specific modes, the tables in Appendix A also provide statistics on degraded severity and incipient severity failures. A more in-depth discussion of these is presented later in this chapter.

Table 12. Aggregate catastrophic failure rates for electrical components

Component	Catastrophic mode of failure	Failure rate		
		Low	Recommended	High
Diesel generator	Failure to start, Q_d:	4.0 * 10^{-4}/d	2.9 * 10^{-3}/d	1.4 * 10^{-2}/d
	Failure to run, λ_t:	1.6 * 10^{-4}/hr	3.6 * 10^{-4}/hr	1.8 * 10^{-3}/hr
	Improper operation, λ_t:	2.2 * 10^{-3}/hr	6.1 * 10^{-3}/hr	2.1 * 10^{-2}/hr
	Combined failure to run/improper operation, λ_t:	2.2 * 10^{-3}/hr	6.4 * 10^{-3}/hr	2.1 * 10^{-2}/hr
Battery	No output, λ_t:	3.0 * 10^{-8}/hr[a]	6.4 * 10^{-7}/hr	3.0 * 10^{-6}/hr[a]
	Inadequate output, λ_t:	4.9 * 10^{-7}/hr	3.2 * 10^{-6}/hr	7.5 * 10^{-6}/hr
Battery charger	No output, λ_t:	1.4 * 10^{-6}/hr	5.5 * 10^{-6}/hr	1.8 * 10^{-5}/hr
Inverter	No output, λ_t:	8.5 * 10^{-6}/hr	2.1 * 10^{-5}/hr	1.9 * 10^{-4}/hr

[a] Chi-square estimates.

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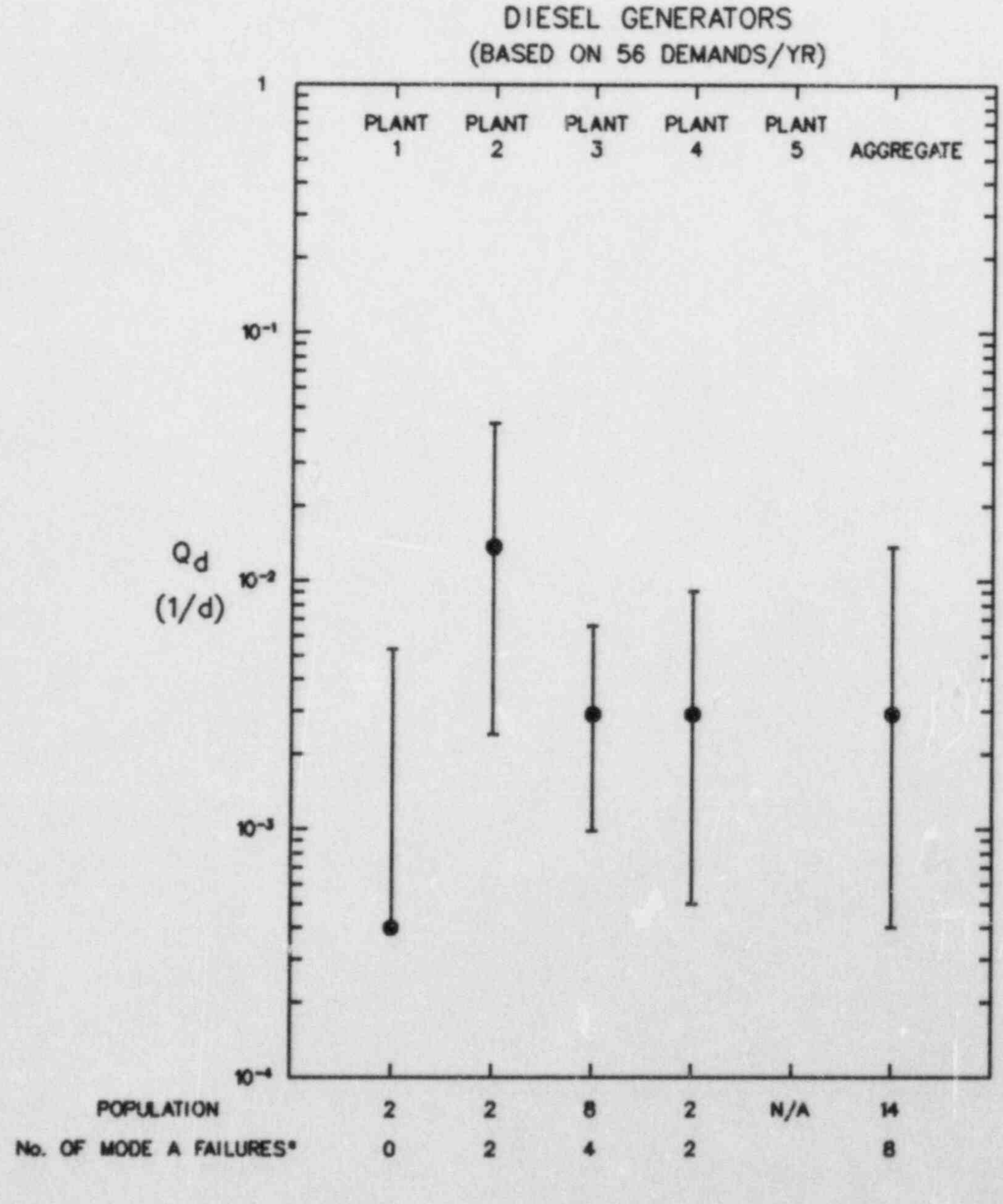

*MODE A = FAILURE TO START

Fig. 7. Diesel generator catastrophic failure rate for failure to start: specific plants and aggregate.

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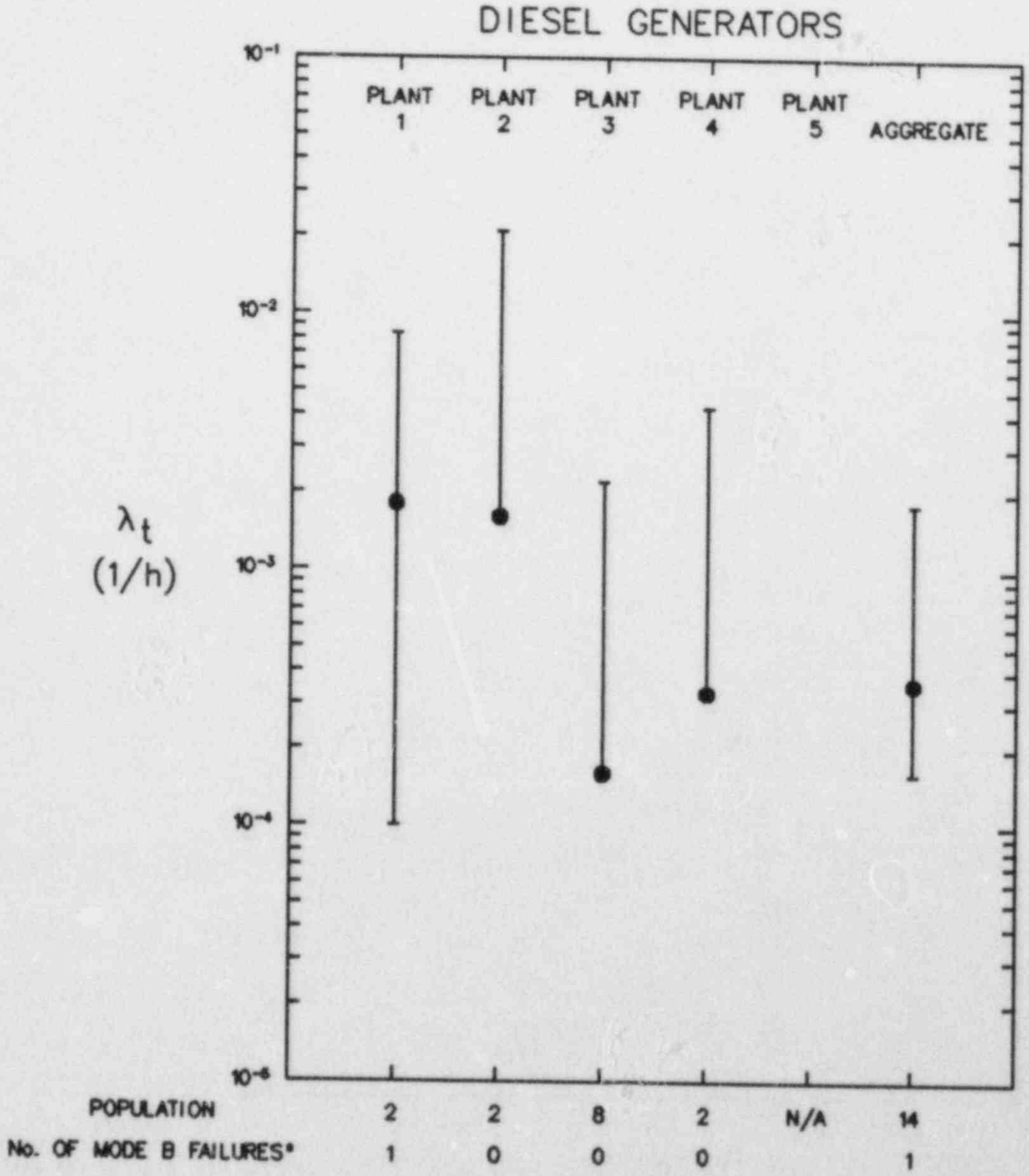

*MODE B = FAILURE TO RUN ONCE STARTED

Fig. 8. Diesel generator catastrophic failure rate for failure to run: specific plants and aggregate.

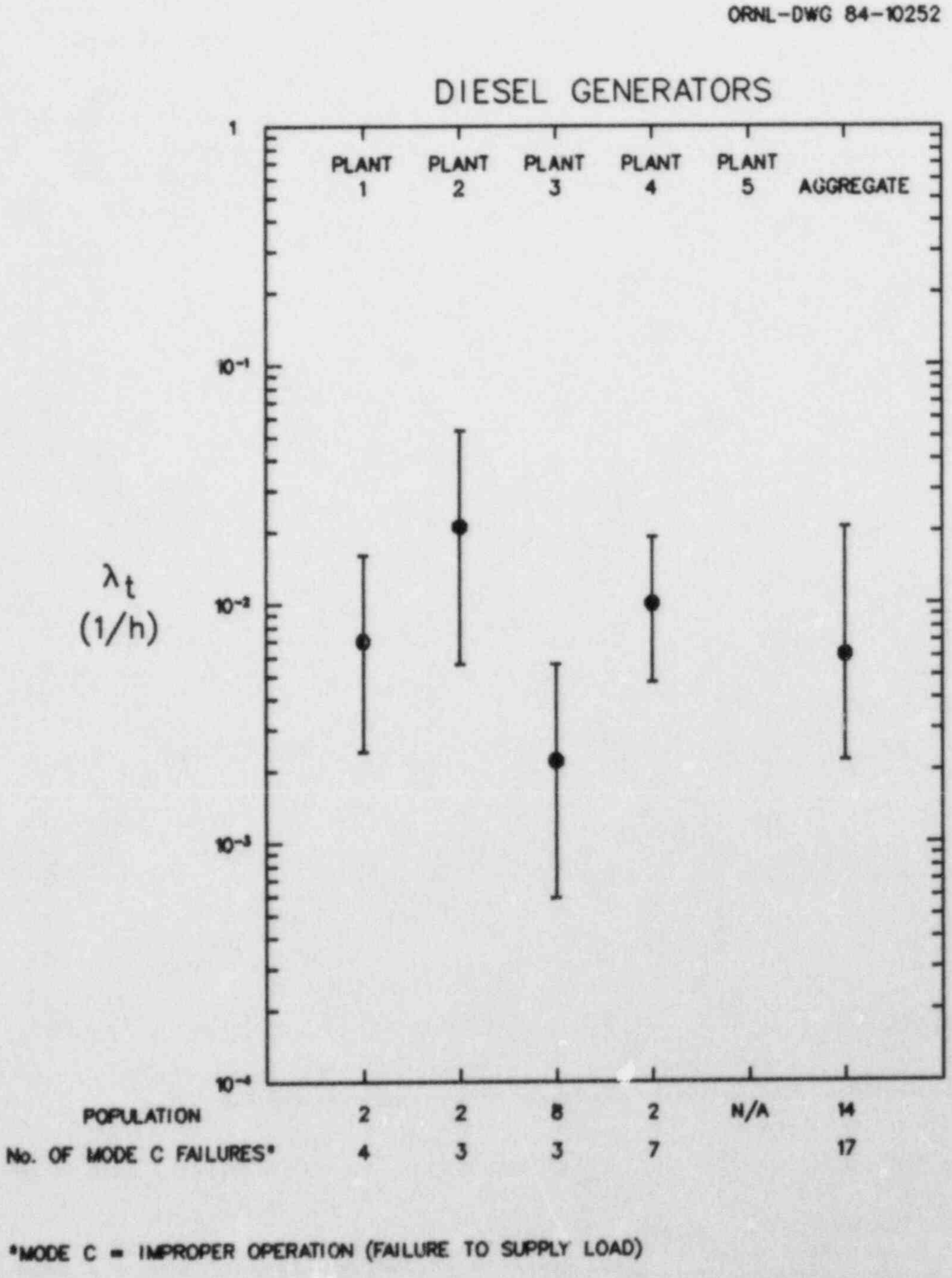

Fig. 9. Diesel generator catastrophic failure rate for improper operation: specific plants and aggregate.

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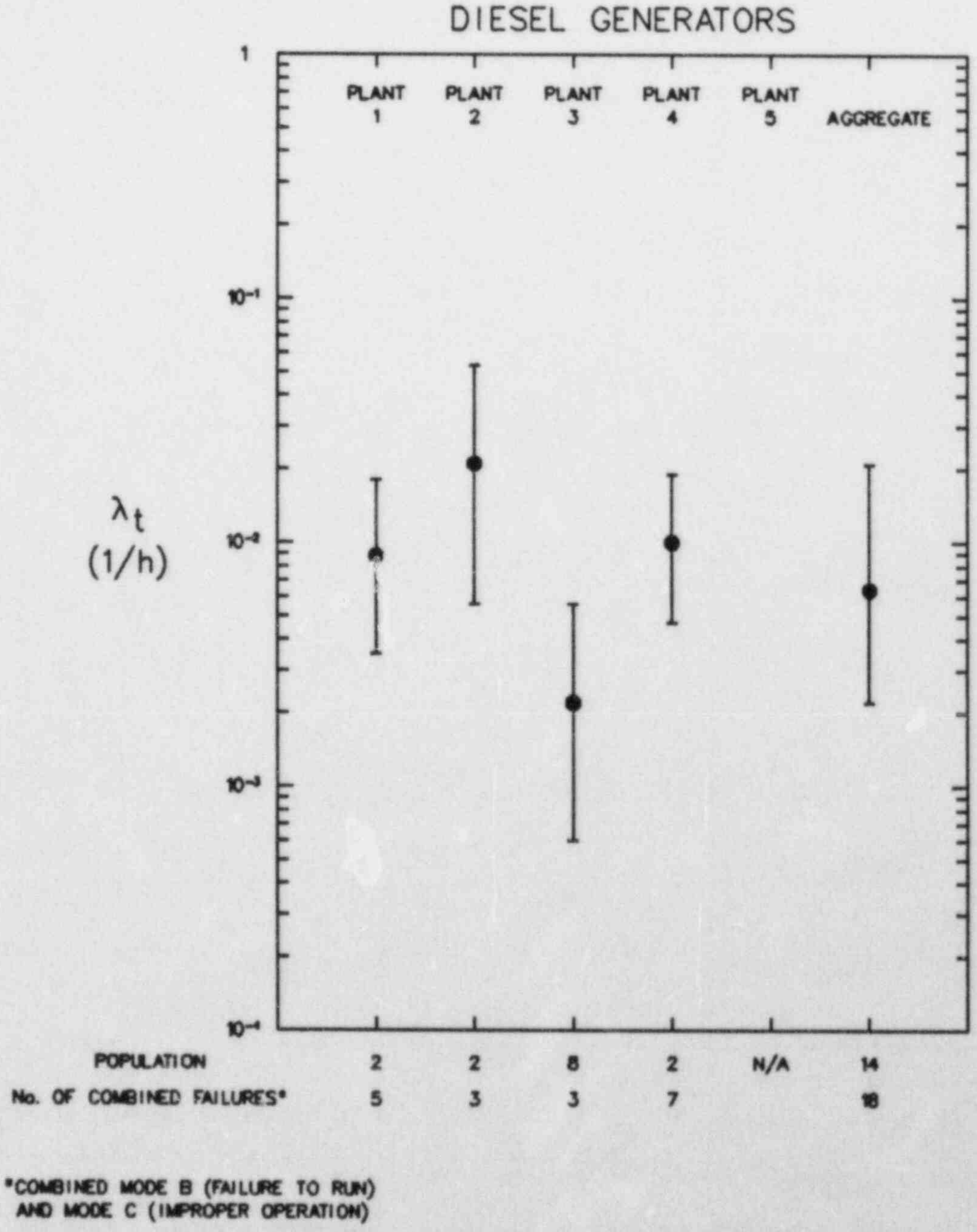


Fig. 10. Diesel generator catastrophic failure rate for combined failure to run/improper operation: specific plants and aggregate.

ORNL-DWG 84-10253

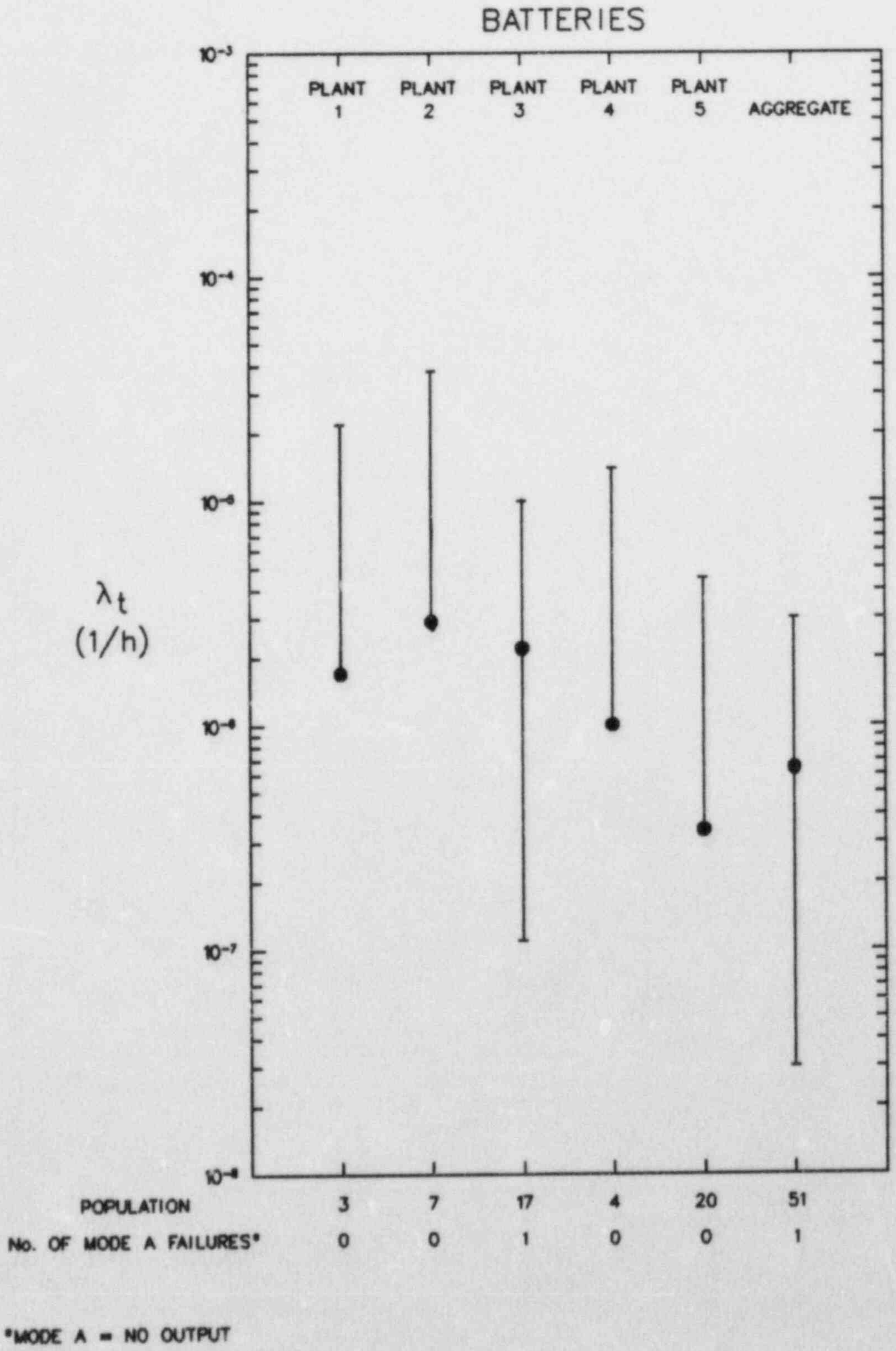


Fig. 11 Battery catastrophic failure rate for no output: specific plants and aggregate.

ORNL-DWG 84-10254

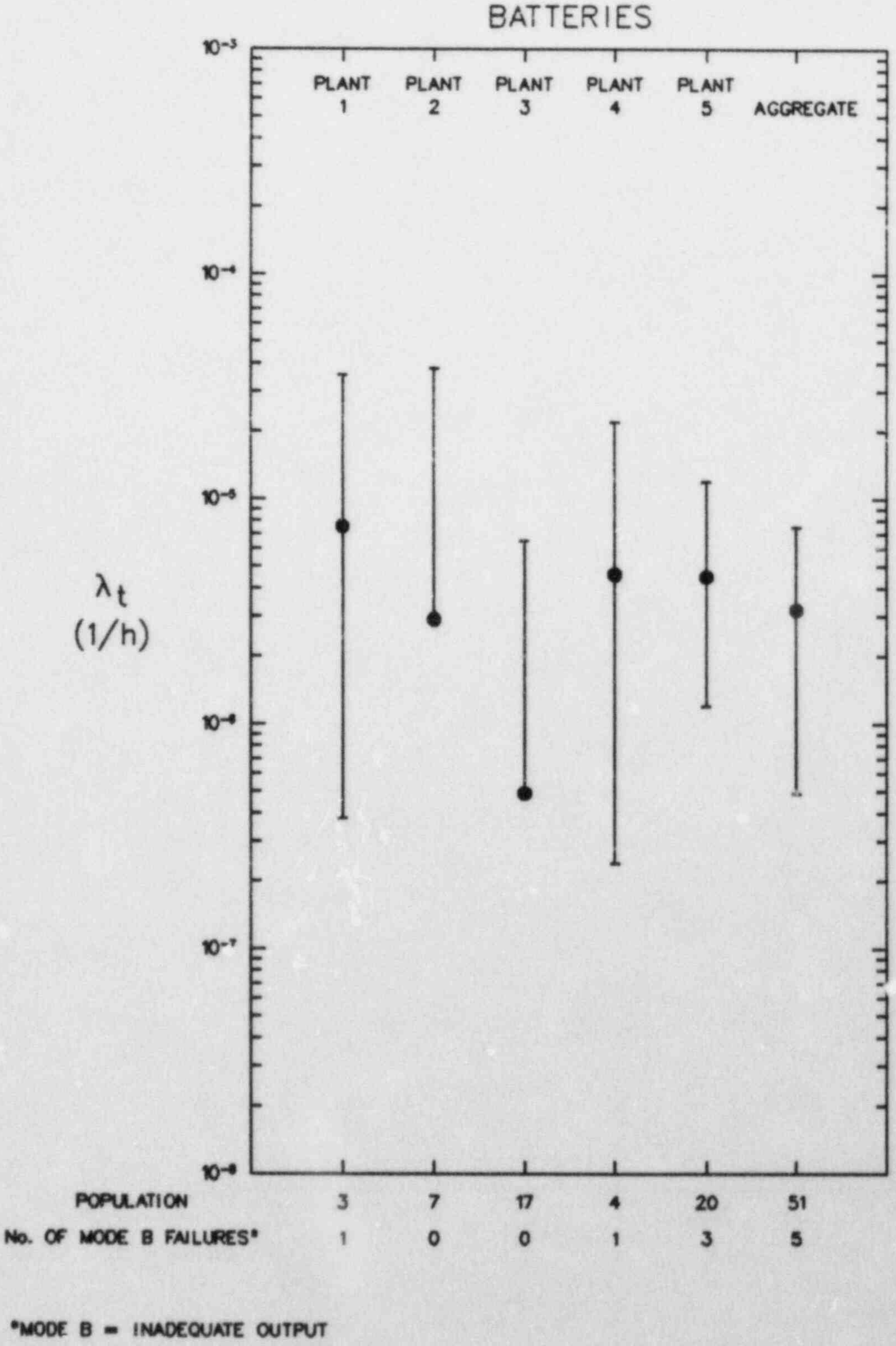
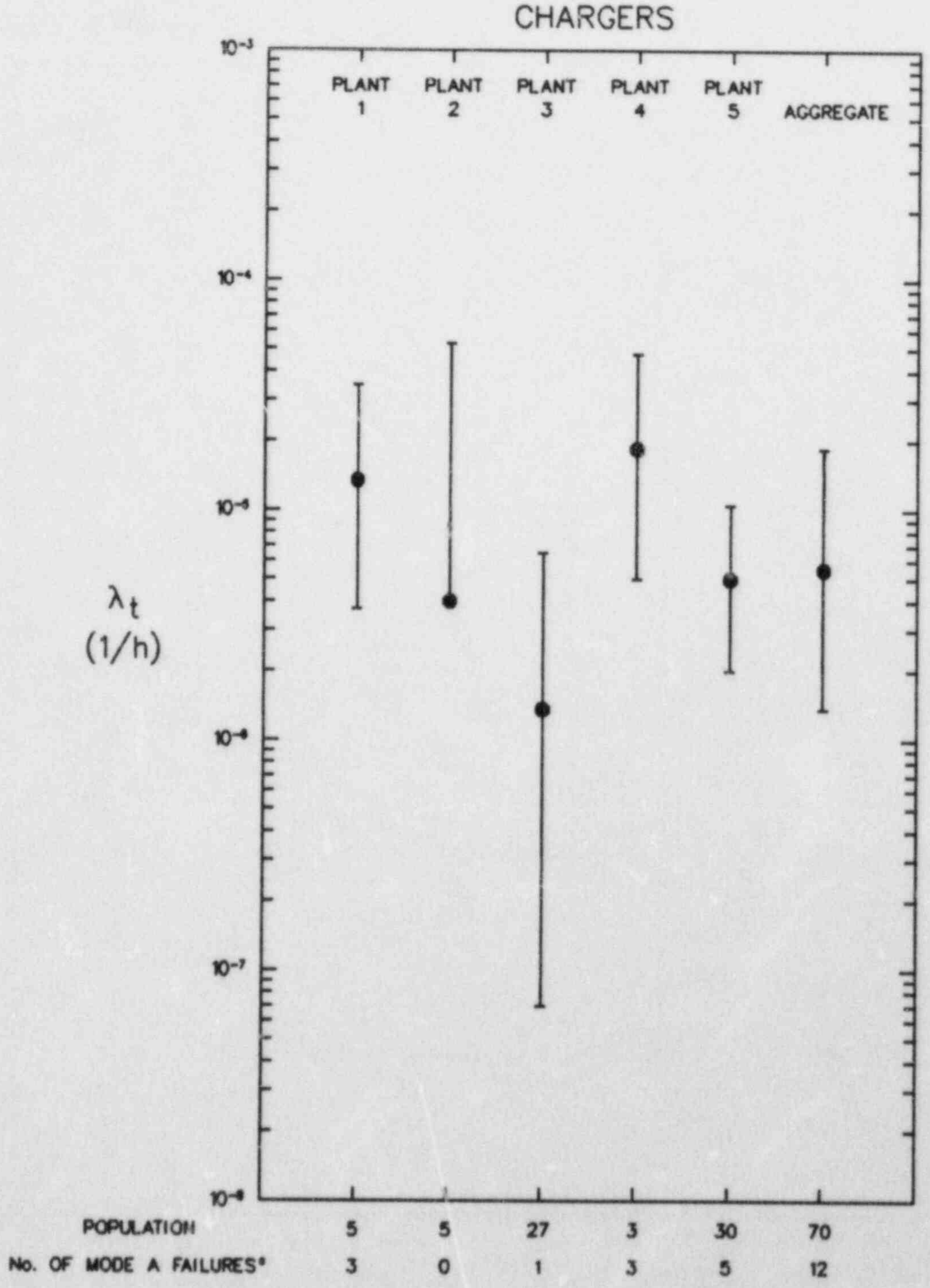


Fig. 12. Battery catastrophic failure rate for inadequate output: specific plants and aggregate.

ORNL-DWG 84-10249



*MODE A = NO ELECTRICAL OUTPUT

Fig. 13. Static battery charger catastrophic failure rate for no output: specific plants and aggregates.

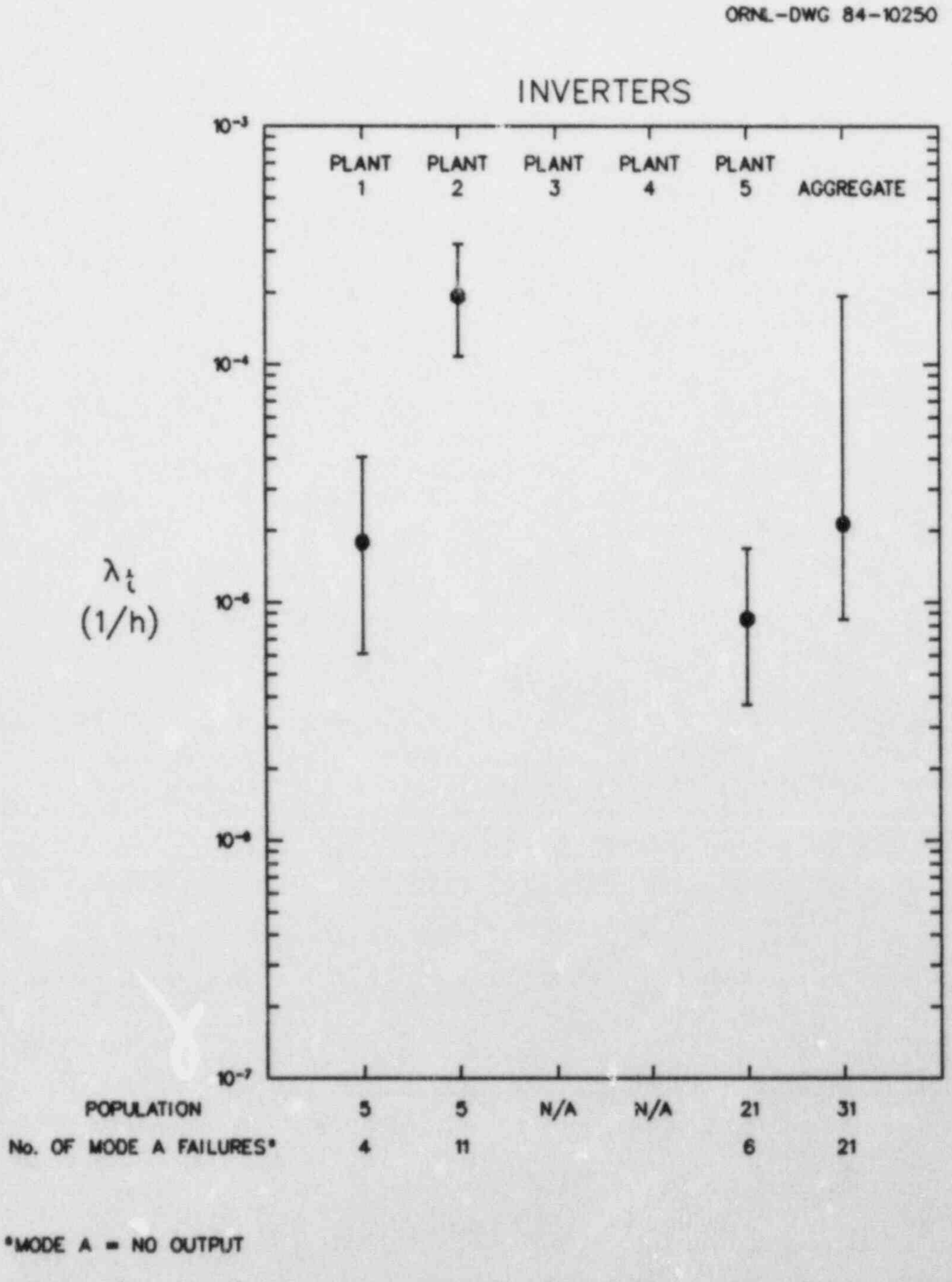


Fig. 14. Static inverter catastrophic failure rate for no output: specific plants and aggregates.

The bases for computing failure rates varied for the components. Diesel generator demand failure probabilities were calculated assuming 56 start demands per year per diesel. This is the composite average number of demands cited in Reference 10 and we believe it to be a reasonable estimation for the typical nuclear station DG. In addition the time-related failure rates for DGs were based upon an assumed run time of 1 hour per start demand (i.e. 56 hours/year). This basis is essentially consistent with other DG reliability studies, principally the LER report (Ref. 11). We recognize that with the variety of nuclear plants in the United States, there are some with more demands per year and some with less. However for the particular IPRDS plants, the best available information indicates that the 56 demands/year estimate is appropriate. Furthermore we appreciate the difficulty involved in obtaining valid operation periods for computing "failure to run" statistics. We fully acknowledge that a failure rate based on many single hour periods may not truly reflect the failure to run probability for extended period running.

Batteries, chargers and inverters were assumed to have been operational during all calendar hours for which post-commercialization plant data were available. Demand-related failure probabilities were not deemed applicable to the latter group of components.

4.2 Observations and Comparison with other Data Sources

A review of the failure statistics computed from the IPRDS data permits some observations to be made. In addition, other data references were reviewed to provide a meaningful basis for comparison. These comments are presented by class of component. Tables 13-16 and Figures 15-19 illustrate the comparisons.

4.2.1 Diesel generators

Because of the importance of emergency on-site power supplies in accident scenarios and the role of the DG in those supplies, there has been much research done on DG reliability. The scope of this report did not allow an in-depth analysis of the subject and the reader is referred to References 4, 10, and 11 for a broader discussion.

The catastrophic failure rates for diesel generators considered three key modes of failure: failure to start, failure to run once started, and improper operation. The first two modes are commonly considered in DG reliability studies and the third was created to cover other instances where the DG may have started and run but did not supply its loads, stopped unintentionally, etc. As with most other studies of DG failures, the principal mode for concern is failure to start (DGs tend to be very reliable once in a running mode). The IPRDS mean value calculated for "failure to start" is $2.9*10^{-3}$/demand. Comparison with other references is illustrated in Table 13 and reveals the IPRDS estimate for "failure to start" to be one order of magnitude lower than the values given in other studies. Figure 15 plots the mean values and the upper and lower bounds (as available). It should be noted that the mean IPRDS

Table 13. Comparison of diesel generator failure rates with other sources

Mode	Mean failure rate				
	IPRDS	EPRI[a] NP-2433	LERs[b]	WASH[c] 1400	ORNL/[d] TM-8545
Failure to start, Q_d:	$2.9 * 10^{-3}$/d	$1.7 * 10^{-2}$/d	$1.0 * 10^{-2}$/d	$3.1 * 10^{-2}$/d	$2.5 * 10^{-2}$/d
Failure to run, λ_t:	$6.4 * 10^{-3}$/hr[e]	N/A	$6 * 10^{-3}$/hr	$3 * 10^{-3}$/hr	$2.3 * 10^{-3}$/hr

[a] Ref. 10.

[b] Ref. 11, based on 52 demands/yr.

[c] Ref. 12.

[d] Ref. 4.

[e] Modes B and C combined.

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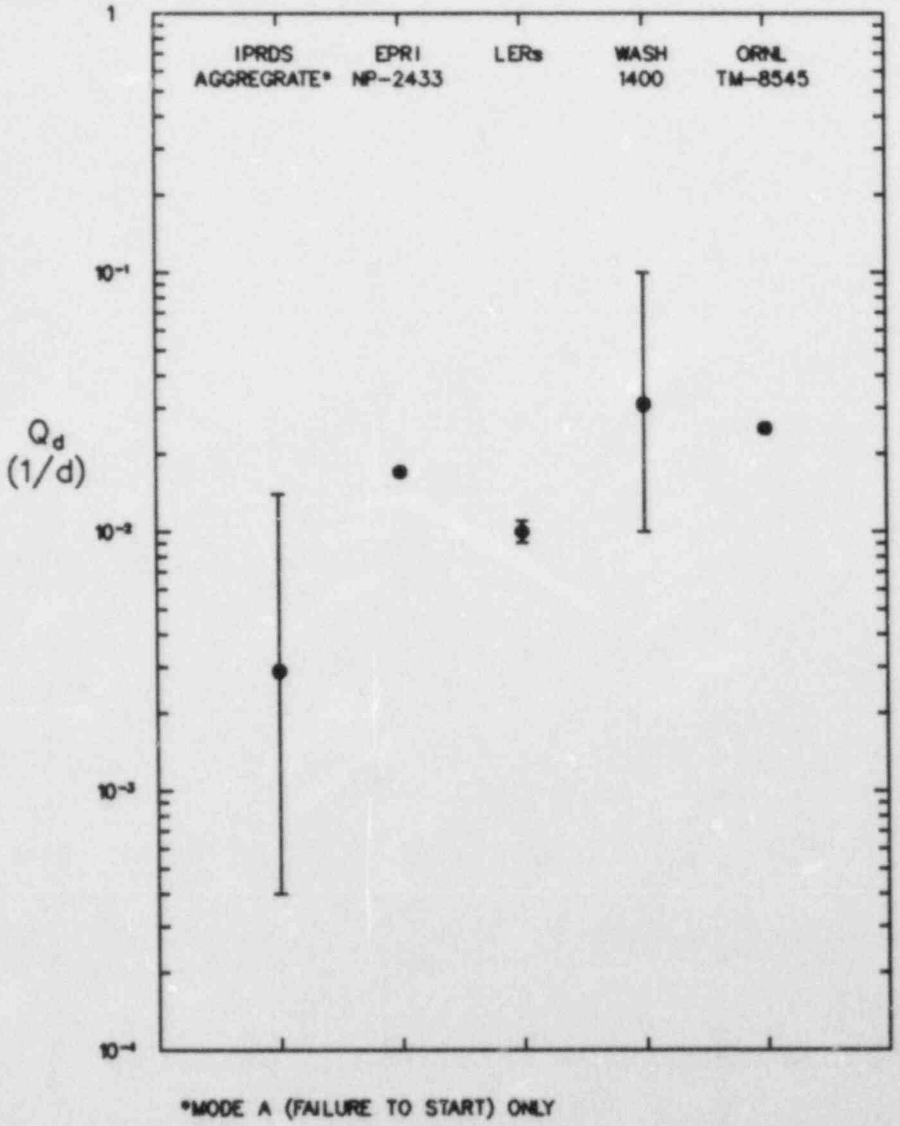

Fig. 15. Diesel generator catastrophic failure rate for failure to start: comparison with other references.

aggregate value did not fall within the lower bounds of either the LER study (Ref. 11, weekly testing) or WASH-1400 (Ref. 12). However the upper band did overlap somewhat with the lower bands of these sources. The EPRI report (Ref. 10) gave upper and lower bounds for individual plant failure rates but only a point estimate for the composite. Similarly the ORNL report (Ref. 4) only provided a point estimate of DG failures to start.

A mean value of $3.6*10^{-4}$/h was calculated for "failure to run" and a mean value of $6.1*10^{-3}$/h was calculated for "improper operation." Clearly the "failure to run" mode was more discriminating than "improper operation" in defining failures, hence the lower value. In reviewing the other sources it became evident that a lumped consideration of failures to operate is standard practice. Therefore we have presented in Table 12 the individual failure rates for IPRDS modes as well as a combined "failure to run"/"improper operation" failure rate. It is this combined failure rate ($6.4*10^{-3}$/h) which was used in comparing values from the other references (Table 13), and it averaged about twice those values. Figure 16 illustrates that the point value estimates from other sources fall within the lower band of the IPRDS combined failure rate. The EPRI report (Ref. 10) did not include a point estimate for failure to run for the composite case.

With regard to the observed differences between IPRDS estimates and others, we offer some possible explanations. The failure to start estimate may be affected by a possible, although improbable, underestimation

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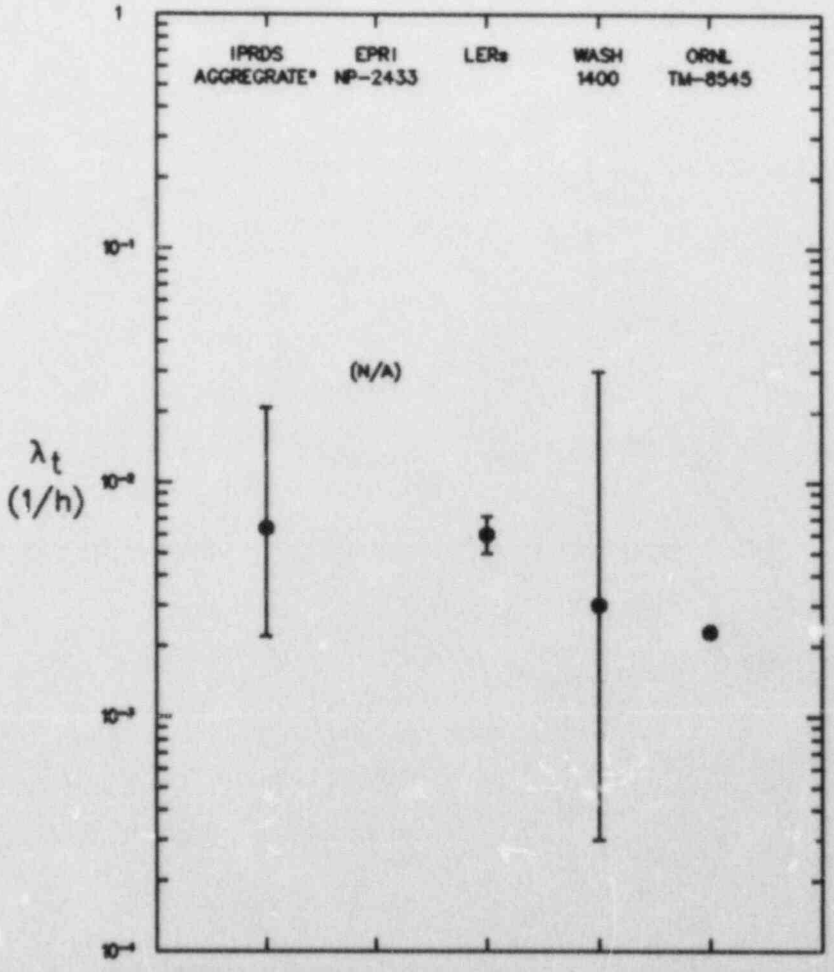


*COMBINED MODE B (FAILURE TO RUN) AND MODE C (IMPROPER OPERATION)

Fig. 16. Diesel generator catastrophic failure rate for failure to run: comparison with other references.

of the actual number of start failures. Three of the cited DG references relied upon Licensee Event Reports (LERs) as a contributing data source. Because of technical specification requirements concerning diesel generators, several failures to start and supply load may be documented as LERs in a relatively short period of time. It is conceivable that only one maintenance work request might be generated as a result of these if the multiple failures stemmed from a single cause. Another factor possibly affecting both "failure to start" and "failure to run" rates is that often the text of the maintenance work request did not indicate the kind of failure, only the repair action to be performed.

4.2.2 Batteries

The mean value for "no output" failures was calculated at $6.4*10^{-7}$/h and the mean value figured for "inadequate output" failures was $3.2*10^{-6}$/h. Fewer references were found (than with DGs) to compare these values against. Table 14 and Figure 17 present a useful comparison with some qualifications noted below.

The Reactor Safety Study (WASH-1400) assessed the battery failure rate at $3*10^{-6}$/h and considered only total losses of battery function (catastrophic). The upper and lower bounds did not overlap with any other references. WASH-1400 disregarded "internal shorts" and "shorts to ground" as being easily detected and incurring negligible fault duration time. We grouped such faults under degraded severity failures.

For large storage batteries, IEEE STD-500 (1984, Ref. 5) cites an overall catastrophic failure rate of $1*10^{-8}$/h which is very low. Another report concerning probabilistic safety analyses of DC power requirements for nuclear plants puts the time-related rate closer to $1*10^{-6}$/h.[13]

An informal report prepared by Idaho National Engineering Laboratory (INEL, Oct. 1982) describes a review of Licensee Event Reports (LERs) for battery and battery charger failures in commercial U.S. nuclear power plants from January 1976 to December 1981.[14] This review did not investigate populations of batteries and chargers nor did it delve into service hours. Hence no failure rates were estimated and the comparison was not possible. However the report did document gross indications of failure trends, and some of these may be discussed in a later report.

4.2.3 Chargers

Only one catastrophic mode of failure for battery chargers ("no output") is included and the failure rate calculated was $5.5*10^{-6}$/h. The WASH-1400 report provides a comparative rate of $3*10^{-6}$/h for "no function" failures under the general category of high power (>1 amp, >28 volts) solid state devices. Reference 13 cites a probability of $2.9*10^{-6}$/h for loss of charger function. The IEEE STD-500 (1984, Ref. 5) lists a catastrophic failure rate of $4.9*10^{-7}$/h for battery chargers. Table 15 and Fig. 18 illustrate the compatibility of all the point estimates and error bands.

In the same LER data summary report discussed in the preceding section (Ref. 14), battery charger failure trends were quantified, but likewise no failure rates were estimated.

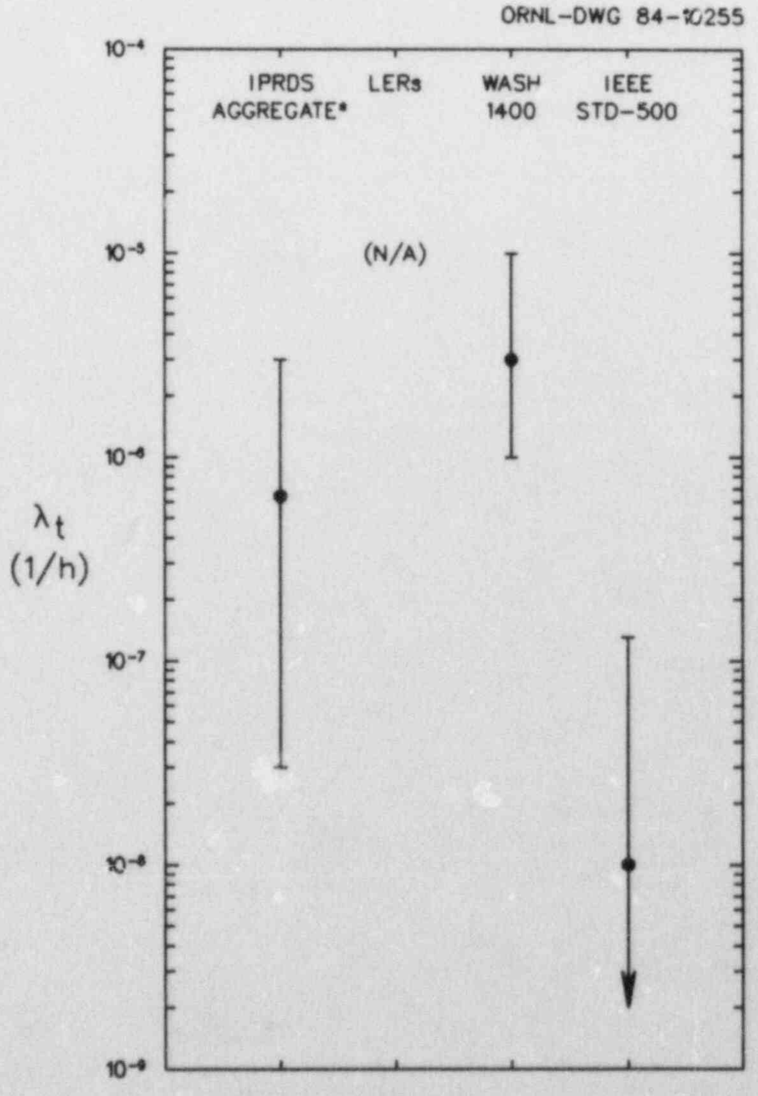
Table 14. Comparison of battery failure rates with other sources

Mode	Mean failure rate			
	IPRDS	LERs[a]	WASH-1400[b]	IEEE[c] STD-500
No output, λ_t:	$6.4 * 10^{-7}$/hr	N/A	$3 * 10^{-6}$/hr	$1 * 10^{-8}$/hr
Inadequate output, λ_t:	$3.2 * 10^{-6}$/hr	N/A	N/A	(included above)

[a] Ref. 14, failure rates not estimated.

[b] Ref. 12.

[c] Ref. 5.



*MODE A (NO OUTPUT) ONLY

Fig. 17. Battery catastrophic failure rate for no output: comparison with other references.

Table 15. Comparison of static battery charger failure rate with other sources

Mode	Mean failure rate			
	IPRDS	LERs[a]	WASH-1400[b]	IEEE[c] STD-500
No output, λ_t:	$5.5 * 10^{-6}$/hr	N/A	$3 * 10^{-6}$/hr	$4.9 * 10^{-7}$/hr

[a] Ref. 14, failure rates not estimated.

[b] Ref. 12.

[c] Ref. 5.

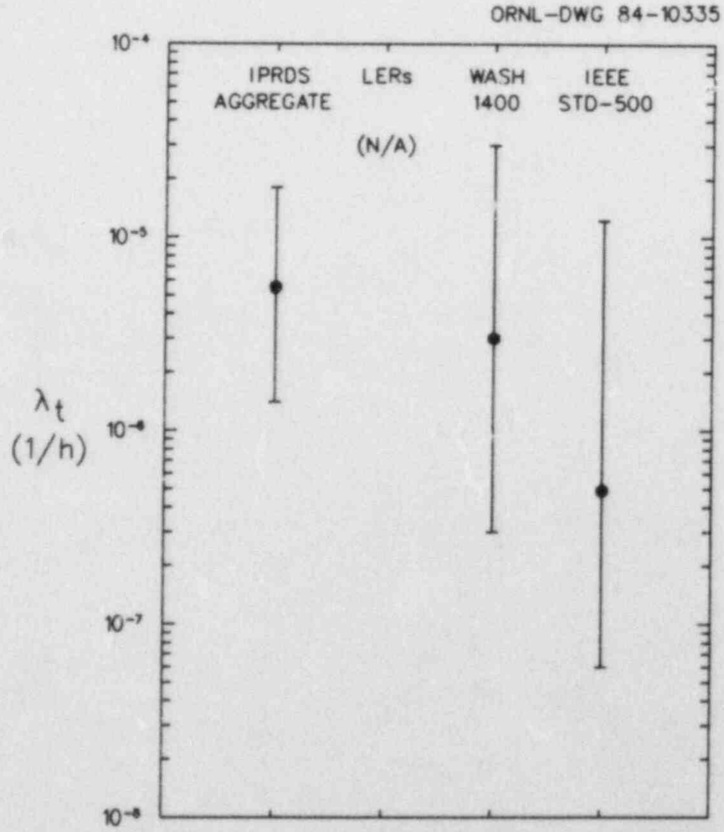


Fig. 18. Static battery charger catastrophic failure rate for no output: comparison with other references.

4.2.4 Inverters

The mean value for the catastrophic ("no output") failure rate was calculated at $2.1*10^{-5}$/h. This rate reflected data from three plants only, one of which had an inordinately high number of catastrophic failures over a short time span. This tended to drive the computed value higher than one might otherwise expect.

Comparing values in Table 16, an LER data summary draft report on inverters calculated a rate of $8.9*10^{-6}$/h.[15] Again the WASH-1400 generic value for solid state devices is $3*10^{-6}$/h. The IEEE STD-500 recommends a value of $6.9*10^{-6}$/h for single-phase static inverters (the predominant type in IPRDS data). The computed value from IPRDS data compares somewhat higher than these (Fig. 19). The entire LER band falls within the lower bound of the IPRDS estimate.

Table 16. Comparison of static inverter failures rates with other sources

Mode	IPRDS	LERs[a]	WASH-1400[b]	IEEE STD-500[c]
No output, λ_t:	$2.1 * 10^{-5}$/hr	$8.9 * 10^{-6}$/hr	$3 * 10^{-6}$/hr	$6.9 * 10^{-6}$/hr

[a] Ref. 15.

[b] Ref. 12.

[c] Ref. 5.

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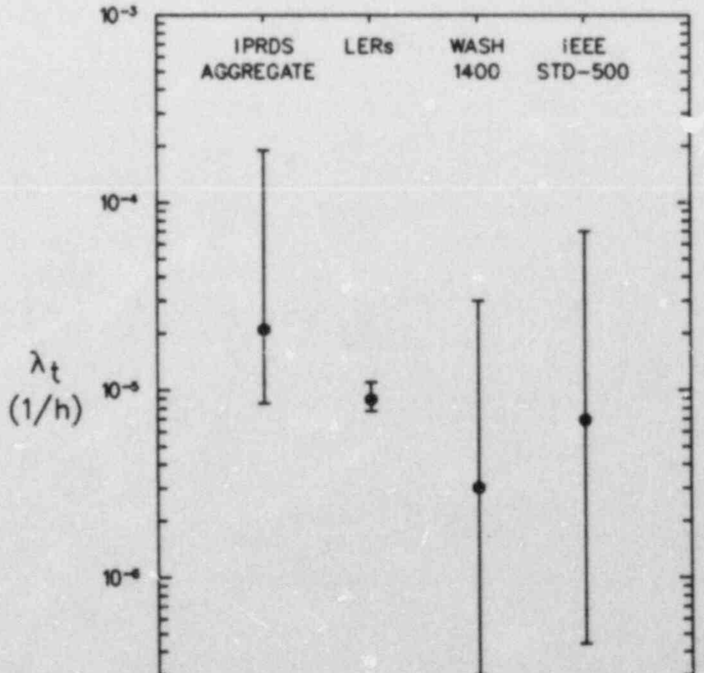

Fig. 19. Static inverter catastrophic failure rate for no output: comparison with other references.

The LER data summary report considered static inverter failures reported from January 1976 through December 1982.[15] The principal difference between that study and our analysis is their inclusion of dedicated inverters found in low pressure coolant injection (LPCI) systems. "Inoperable" was the only mode considered in estimating the failure rate in the LER-based study and it dominated nearly all events as the predominant mode of failure (98%).

The primary cause of inverter failure in the LERs was "electrical malfunction" (61%). Summarizing by subcomponent causes of failure, 53% of the events were "unknown", 15% involved fuses, 12% involved capacitors, and 10% involved control cards. These trends compare very well with IPRDS results (see Sect. 4.4).

4.3 Repair Data

Repair data were available from Plants 1, 2, and 5. The repair data encoded into the IPRDS consisted of repair time and repair category. The size and nature (e.g. electrical, mechanical) of the repair crew were only occasionally available and were not input. The repair category was assigned (from Table 2.6 in Ref. 1) according to the specific repair action described in the maintenance request. The repair times included only the corrective maintenance portion of the total component downtime. Therefore the reported repair time probably underestimates the component unavailable time. It is conceivable, especially for these electrical components, that the differences between the repair time and the overall unavailable time may be significant.

An important consideration in evaluating repair times is the urgency of the repair. The repair time is likely to be longer if it is performed during a planned outage, rather than one which is necessary to end a forced outage. Perhaps industry adoption of a common repair urgency or priority index for the maintenance request would assist data analysts in reviewing the historical operating records of individual components and coordinating them with plant status data taken from operator logs.

The arithmetic mean, minimum, maximum and median repair time values for electrical components are presented in Tables 17–20. Where applicable comparisons were available, mean value ranges from other references are also shown. In several cases, the mean repair time was apparently influenced by a small number of failures exhibiting uncharacteristic, lengthy repair times. The median value can be useful in identifying these cases.

Table 17. Diesel generator repair times

Plant	Number of failures with repair times	Repair time statistics (h)				Reference value (h)	Reference sources
		Mean	Minimum	Maximum	Median		
1	112	22	0.5	501	3	7–20	5,10
2	35	13	1	38	8	7–20	5,10

Table 18. Battery repair times

Plant	Number of failures with repair times	Repair time statistics (h)				Reference value (h)	Reference sources
		Mean	Minimum	Maximum	Median		
1	20	9	1	35	4	0.5–1	5
2	9	7	3	16	4	0.5–1	5
5	32	19	1	200	7	0.5–1	5

Table 19. Charger repair times

Plant	Number of failures with repair times	Repair time statistics (h)				Reference value (h)	Reference sources
		Mean	Minimum	Maximum	Median		
1	9	5	2	7	5	4–80	5
2	4	5	2	10	4	4–80	5
5	22	18	1	152	10	4–80	5

Table 20. Inverter repair times

Plant	Number of failures with repair times	Repair time statistics (h)				Reference value (h)	Reference sources
		Mean	Minimum	Maximum	Median		
1	30	8	1	48	4	2.5	5
2	19	40	1	350	8	2.5	5
5	9	10	2	16	8	2.5	5

4.4 Predominant Modes and Causes of Failure

The computerized data management system permitted tabulations of the frequency of severity, mode, and cause codes in the records for trend analyses. Trends imply that a consistency in behavior is observed over a period of time. For this reason, we considered all available data (including pre-commercialization) to provide maximum coverage. Discussion of before and after commercialization trends that were observed in the records is noted where appropriate and significant.

4.4.1 Diesel generators

As a class, DGs offered the largest number of records for analysis with Plants 1 and 4 covering the most years. Individual plants exhibited a typical breakdown of severities of failure (catastrophic - 10%, degraded - 30%, incipient - 60%) as shown in Table 21.

Table 21. Diesel generator failures by severity and mode

	Plant 1	Plant 2	Plant 3	Plant 4	Total
Catastrophic					
A: Fails to start-fails to start despite multiple attempts	1	6	5	2	14
B: Fails to run once started	1				1
C: Improper operation	5	5	3	7	20
Degraded					
D: Fails to start	1		1	1	3
E: Improper operation	38	14	47	13	112
Incipient					
F: Improper cooling/heating (leaks, etc.)	25	6	4	2	37
G: Faulty indication	26	18	9	9	62
H: RPM hunting	1			2	3
I: Vibration	19	2	1	1	23
J: Improper lubrication (leaks, etc.)	29	4	6	5	44
K: Improper fuel combination (improper fuel feed, air feed, etc.)	15	4	1	5	25

Plant 1 data contained 7 catastrophic failures of which the bulk were mode C (improper operation). No leading causes for Mode C failures were immediately visible. For all the catastrophic failures (modes A, B, and C) the primary causes appeared to involve local control circuitry. There were 39 degraded severity failures in Plant 1 with almost all of them driven by mode E (improper operation) failures. The contributing cause in most of the these was failure/replacement of a particular vendor's model of control switch. These were somewhat evenly distributed throughout the pre- and post-commercialization periods. In 1978 a large number of the switches were changed out and the failures tapered off. Plant 1 had 115 incipient failures that were slightly more prevalent in the pre-commercialization period. Of these, 25 were mode F (improper cooling, leaks) failures which declined in frequency after commercial operation began. Most of these failures were driven by malfunctions and leaks in the immersion water heaters used to keep warm coolant circulating through the DG jacket during standby. There were 26 mode G (faulty indication) mostly occuring in early plant years. These failures were mostly caused by malfunctions of local switches, transducers, and indicators in the control system. There were 19 documented records of mode I (vibration) failures which tended to involve loosening of fasteners and flanges. There were 29 mode J (improper lubrication) failures identified and evenly distributed across all years of the data. The controlling causes of these failures were dominated by gasket and flange leaks around the circulating pump of the lubrication oil system. Fifteen failures were mode K (improper fuel/air feed) and were largely attributed to inadequate maintenance of the air intake system.

Plant 2 had 11 catastrophic failures for the short two year span of data. Similarly there were 14 degraded failures. Of the catastrophic failures, 6 were by mode A (failure to start) and 5 were by mode C (improper operation). A review of the data revealed air start motor failures and feeder breaker failures as principal contributing causes to the catastrophic failures. The degraded failures were exclusively driven by mode E failures (improper operation). These failures were dominated by difficulties with the air start system, specifically, compressor gasket and pressure switch failures. Plant 2 had 34 incipient severity failures, mostly mode G (faulty indication) failures. The bulk of the mode G failures occurred prior to commercialization and were driven by minor difficulties with various alarms and indicators. There were 6 mode F (improper cooling) failures mostly involving the adjustment or cleaning of the heater and heat exchanger in the lubrication oil loop. There were lesser numbers of mode I (vibration), J (improper lubrication), and K (improper fuel/air feed) failures. These generally involved minor routine maintenance of fuel and lube oil filters.

Plant 3 data documented 8 catastrophic failures, 48 degraded failures and 21 incipient failures. The catastrophic failures were driven by 5 mode A failures and 3 mode C failures. The mode A (failure to start) failures usually involved breaker and relay failures in the start system circuits. The mode C (improper operation) failures involved two control circuit failures and one lube oil pump bearing failure. The degraded failures were exclusively dominated by mode E (improper operation) failures as with the other plants. For Plant 3 the principal contributing cause of these failures was blown head gaskets on the air start system compressors. A year-by-year tabulation revealed that this problem worsened considerably after commercial operation began. The incipient failures contained 9 mode G (faulty indication) failures. These were mostly due to relay failures in indicators on the control system. Also there were 6 mode J (improper lubrication) "failures" which chiefly involved normal adding or changing of the lube oil. Four failures involved improper cooling (mode F) and described cleaning maintenance on the interfacing heat exchanger between the cooling water and lube oil systems.

Plant 4 experienced a total of 9 catastrophic failures. Nearly all of these were mode C (improper operation) failures driven by malfunctioning breakers and relays in the control system (governor) and generator section. The 2 mode A (failure to start) failures were of unknown cause. There were a total of 14 degraded failures of which 13 were mode E (improper operation) failures. The primary contributing cause was failure of the dead-line relay. Plant 4 had 24 incipient failures. There were 9 mode G (faulty indication) involving the governor actuator, protective relays, and indicators. Five failures were mode J (improper lubrication) and were caused by low oil level. Five other incipient failures were mode K (improper fuel/air feed) and involved repairs to the air intake louvers and filters.

Considering the overall data, some general trends can be identified. First, almost all catastrophic failures involved a failure to start or a failure to supply load. The latter case tended to stem from feeder breaker malfunctions and the start failures involved either the air motors or the command circuits. Secondly, the degraded severity category was over-whelmingly dominated by "improper operation" mode of failure. This mode covers a variety of maladies and a review of the records illustrated plant specific trends. In Plant 1 these failures were driven by failures of a particular type of control switch used in the plant. In Plants 2 and 3 the cause was failures of gaskets on the starting air compressors. Plant 4 degraded failures were largely due to failures of the dead-line relay. Thirdly among the incipient failures in all plants, the predominant mode was faulty indication. This mode also covered a broad group of failure types since indication included alarms and instrumentation which are found in many subsystems of the DG. It is difficult to generalize about this group but it was observed that a significant fraction of these failures could be attributed to instrument drift.

4.4.2 Batteries

There is a trend in the higher percentage of degraded failures versus incipient failures across all plants (Table 22). We surmise this is a component specific effect. In principle, batteries are surveyed and inspected on a regular and relatively frequent basis. Thus one would expect almost no catastrophic failures and a considerably larger fraction of incipient failures, which is the case.

In Plant 1, the sole catastrophic failure stemmed from an apparent human error where the charger was turned off and the battery subsequently ran down. Plant 1 degraded failures were driven by post-commercial

Table 22. Battery failures by severity and mode

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Total
Catastrophic						
A: No output			1			1
B: Inadequate output	1	2		1	3	7
Degraded						
J: Won't hold charge	2		2	3	1	8
K: Low cell voltage detected	4	2		4	1	11
L: Ground detected	11	2	1	2	17	33
Incipient						
E: Leakage	2		4			6
F: Improper environment (temperature, humidity, etc.)	1			2		3
G: Corrosion/dirty/dust contamination	5	1	1		8	15
H: Faulty indication	3	7		2	10	22

period cell grounds and shorts which were easily cleared. Incipient failures were caused by a variety of factors, most notably dirt and dust in the pre-commercial years of operational testing.

In Plant 2, the limited span of data described pre-commercialization problems with two cases inadequate output due to low specific gravity and a number of instances of local voltmeter out-of-adjustment failures.

Plant 3 had one catastrophic failure involving the breakage of a terminal post and cell, probably human error-related. Several degraded failures in the pre-commercialization period described cell replacements for unknown reasons. Plant 3 also had a small number of incipient failures which were driven by improper installation of the seismic racks and restraints, producing stress cracks in the jars.

Plant 4 also experienced a single catastrophic failure that was human factor related (monthly surveillance discrepancy). Degraded failures were divided among the modes J (won't hold charge), K (low cell voltage detected) and L (ground detected). Most failures associated with the latter two modes were produced by undervoltage alarms and were resolved by adjustment of charger set points. The small number of incipient failures were due to battery room thermostat failures.

Plant 5 with its large population of batteries contained only three catastrophic failures, all described in insufficient detail to comment upon. There were many degraded failures driven by mode L and distributed across the pre- and post-commercialization periods. The primary cause of these failures was documented as high resistance-type ground such as moisture. Incipient failures were exclusively driven by modes G (corrosion, dirt, dust) and H (faulty indication). The mode G failures were addressed by routine cleaning and restrapping of the batteries indicating responses to an apparently under-controlled environment in the battery rooms also found in the degraded group.

4.4.3 Chargers

As a class, battery chargers did not have much failure data on any particular plant. To facilitate a general trend analysis, the data from all plants were combined and sorted on mode and cause codes. Therefore the discussion will be on chargers as a class, with plant specific trends noted where significant (Table 23).

There was only one identified catastrophic mode of failure (A, no electrical output). There were 18 such failures, with the largest number from Plant 5. The primary cause contributing to these was dirty switch contacts. Plant 1 followed with 5 mode A failures. For Plants 1-4 the contributing causes appeared to be common failures of small electronic devices (e.g. fuses, diodes, resistors).

There was also only one identified degraded mode of failure found (D, electrical output out of specification). This mode accounted for 29 failures with the largest number also originating in Plant 5. The dominant cause of these failures appears to be out-of-adjustment in several piece parts.

There was only one identified mode E failure (over heating), and there were 14 mode H failures (faulty indication). These incipient severity failures were distributed across all plants. The prime culprit

Table 23. Static battery charger failures by severity and mode

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Total
Catastrophic						
A: No electrical output	5		2	3	8	18
Degraded						
D: Electrical output out of specification	6	4	1	3	15	29
Incipient						
E: Overheating					1	1
H: Faulty indication	2	3	2	4	3	14

was typically drift of the local voltmeter on the charger output. Secondary causes involved malfunctioning indicator lights and alarms.

Class-wide frequency counts of cause codes for all modes revealed that many charger failures were simple and easily adjusted deviations from specifications. Most of the modern static battery chargers lend themselves to ready maintenance and replacement of key solid state components such as voltage regulator cards, surge suppressors, firing modules, etc. Many of the failures were caused by fouling of contacts which could be easily cleaned. With back-up systems including the battery itself and other power buses, there is not much of a catastrophic system effect from a charger failure. It is likely that maintenance on them is exclusively corrective (i.e. "run to failure"), therefore it is not surprising to see larger percentages of catastrophic and degraded failures.

4.4.4 Inverters

The amount of failure data on inverters was good for Plants 1, 2, and 5. Plant 3 data for this component was discarded for lack of credible component identification and no inverter data were available from Plant 4 (Table 24).

Plant 1 experienced nearly all inverter failures after commercialization. There were five documented mode A (no output-catastrophic) failures, resulting largely from blown fuses. There were 17 degraded failures driven mostly by mode H (improper operation) failures. No single significant contributing cause could be discerned. Plant 1 had a uniform year-to-year distribution of incipient failures stemming from faulty indication (mode F). The texts of the maintenance records on these indicated a plant effort to trouble shoot inverter problems with recording instruments.

Plant 2 exhibited an unusually high number of catastrophic mode A (no output) failures for its short time span of data. There were 23 such failures identified, distributed throughout several inverters in the uninterruptible power supplies (UPS). The primary causes of the failures were blown fuses and capacitors. There were 25 degraded failures nearly all occurring pre-commercialization. Most of the failures were mode C and D (output frequency and volts out of specification) and involved fuses, capacitors, and the phase lock circuitry. There were also a significant number of mode H failures (improper operation) stemming from a malfunctioning air-flow relay (no further details). There were 11 incipient failures mostly resulting from faulty indication (mode F) failures in the pre-commercial period and mode I failures (dust, dirt) afterwards. The contributing causes involved setpoint drift and loose connections in alarm relays.

Plant 5 inverters experienced a total of 7 catastrophic mode A failures. The causes of these failures were varied and involved blown fuses, bad voltage regulator, oscillator, and dwell angle cards. Some of the failures involved malfunctions of the static switch, leading to inadvertent swapping of power supplies. There were smaller numbers of degraded and incipient failures which appeared to be insignificant.

Table 24. Static inverter failures by severity and mode

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Total
Catastrophic						
A: No output	5	23	-	N/A	7	35
Degraded						
C: Output frequency out of specification		6		N/A		6
D: Output voltage out of specification	1	10	-	N/A	2	13
G: Output current out of specification	5	1		N/A		6
H: Improper operation (unspecified deviation)	11	8	-	N/A	2	21
Incipient						
E: Overheating				N/A		
F: Faulty indication	10	8		N/A	3	21
I: Dirt/dust contamination	2	3		N/A		5

As a class, inverter failure causes were dominated by blown fuses, diodes, and capacitors. Circuit card problems were common. It appeared that the nature of these electronic devices does not lend itself to much preventative maintenance. Most of the corrective maintenance on inverters appeared to be uncomplicated.

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Appendix A. STATISTICAL TABLES ON SELECTED ELECTRICAL COMPONENTS

Table A1. In-plant reliability data system

Component/group name: Aggregate Diesel Generators

Plant: All
Plant type: All

Class: DSLGEN
Volts: 4160 VAC
Amp-hrs: N/A
Power: All

Population: 14
No. of failures: 238
Population hours: 2801
Population demands: 2801
Maintenance frequency: 543/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	No. of failures	Failures/10E+3 h			No. of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	18	2.2	6.4	21.0	8	0.4	2.9	14.0
(A)					8	0.4	2.9	14.0
(B)	1	0.16	0.36	1.8				
(C)	17	2.2	6.1	21.0				
Degraded	88	19.0	31.0	62.0	2	0.4	0.71	1.6
Incipient	122	7.2	44.0	137.0				

Table A2. In-Plant reliability data system

Component/group name: Plant 1 Diesel Generators

Plant: 1
Plant Type: PWR
Operating Period: 5.1 years

Class: DSLGEN
Volts: 4160 VAC
Amp-hrs: N/A
Power: 4418 kW

Population: 2
No. of Failures: 117
Population hours: 571
Population Demands: 571
Maintenance frequency: 1309/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+3 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	5	3.5	8.8	18.0	0		0.40	5.3
(A)					0		0.40	5.3
(B)	1	0.1	1.8	8.3				
(C)	4	2.4	7.0	16.0				
Degraded	34	44.0	60.0	79.0	0		0.40	5.3
Incipient	78	112.0	137.0	165.0				

Table A3. In-Plant reliability data system

Component/group name: Plant 2 Diesel Generators

Plant: 2	Class: DSLGEN	Population: 2
Plant Type: PWR	Volts: 4160 VAC	No. of Failures: 27
Operating Period: 1.3 years	Amp-hrs: N/A	Population hours: 146
	Power: 2850 kW	Population Demands: 146
		Maintenance frequency: 1185/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+3 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
[illegible]strophic	3	5.6	21.0	53	2	2.4	14	43
(A)					2	2.4	14	43
(B)	0		1.6	21				
(C)	3	5.6	21.0	53				
Degraded	9	32.0	62.0	108	0		1.6	21
Incipient	13	53.0	89.0	142				

Table A4. In-Plant reliability data system

Component/group name: Plant 3 Diesel Generators

Plant: 3
Plant Type: BWR
Operating Period: 3.1 years

Class: DSLGEN
Volts: 4160 VAC
Amp-hrs: N/A
Power: 2850 kW

Population: 8
No. of Failures: 50
Population hours: 1390
Population Demands: 1390
Maintenance frequency: 230/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+3 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	3	0.59	2.2	5.6	4	0.98	2.9	6.6
(A)					4	0.98	2.9	6.6
(B)	0		0.16	2.2				
(C)	3	0.59	2.2	5.6				
Degraded	32	17.0	23.0	31.0	1	0.04	0.72	3.4
Incipient	10	3.9	7.2	12.0				

Table A5. In-Plant reliability data system

Component/group name: Plant 4 Diesel Generators

Plant: 4
Plant Type: BWR
Operating Period: 6.2 years

Class: DSLGEN
Volts: 4160 VAC
Amp-hrs: N/A
Power: 2500 kW

Population: 2
No. of Failures: 44
Population hours: 694
Population Demands: 694
Maintenance frequency: 405/10E+6 hrs

	Time-related failure rates				Demand-related failure probabilities			
Failure severity (by mode)	Number of failures	Failures/10E+3 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	7	4.7	10.0	19.0	2	0.51	2.9	9.1
(A)					2	0.51	2.9	9.1
(B)	0		0.33	4.3				
(C)	7	4.7	10.0	19.0				
Degraded	13	11.0	19.0	30.0	1	0.07	1.4	6.8
Incipient	21	20.0	30.0	43.0				

Table A6. In-plant reliability data system

Component/group name: Aggregate Batteries

Plant: All
Plant type: All

Class: Battery
Volts: All
Amp-hrs: All
Power: N/A

Population: 51
No. of failures: 71
Population hours: 1,564,315
Population demands: N/A
Maintenance frequency: 45/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	No. of failures	Failures/10E+6 h			No. of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	6	1.7[a]	3.8	7.6[a]				
(A)	1	0.03[a]	0.64	3.0[a]				
(B)	5	0.49	3.2	7.5				
Degraded	36	6.5	23.0	90.0				
Incipient	29	11.0	19.0	75.0				

[a] Chi-square estimates.

Table A7. In-Plant reliability data system

Component/group name: Plant 1 Batteries

Plant: 1
Plant Type: PWR
Operating Period: 5.1 years

Class: Battery
Volts: All
Amp-hrs: All
Power: N/A

Population: 3
No. of Failures: 19
Population hours: 134,025
Population Demands: N/A
Maintenance frequency: 142/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	1	0.38	7.5	35				
(A)	0		1.7	22				
(B)	1	0.38	7.5	35				
Degraded	12	52	90	145				
Incipient	6	20	45	88				

Table A8. In-Plant reliability data system

Component/group name: Plant 2 Batteries

Plant: 2	Class: Battery	Population: 7
Plant Type: PWR	Volts: All	No. of Failures: 9
Operating Period: 1.3 years	Amp-hrs: All	Population hours: 79,730
	Power: N/A	Population Demands: N/A
		Maintenance frequency: 113/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	0		2.9	38				
(A)	0		2.9	38				
(B)	0		2.9	38				
Degraded	3	10	38	97				
Incipient	6	33	75	149				

Table A9. In-Plant reliability data system

Component/group name: Plant 3 Batteries

Plant: 3	Class: Battery	Population: 17
Plant Type: BWR	Volts: All	No. of Failures: 9
Operating Period: 3.1 years	Amp-hrs: All	Population hours: 461,720
	Power: N/A	Population Demands: 57
		Maintenance frequency: 19/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	1	0.11	2.2	10				
(A)	1	0.11	2.2	10				
(B)	0		0.49	6.5				
Degraded	3	1.8	6.5	17				
Incipient	5	4.3	11	23				

Table A10. In-Plant reliability data system

Component/group name: Plant 4 Batteries

Plant: 4	Class: Battery	Population: 4
Plant Type: BWR	Volts: All	No. of Failures: 12
Operating Period: 6.2 years	Amp-hrs: All	Population hours: 217,240
	Power: N/A	Population Demands: N/A
		Maintenance frequency: 55/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	1	0.24	4.6	22				
(A)	0		1.0	14				
(B)	1	0.24	4.6	22				
Degraded	8	18	37	66				
Incipient	3	3.8	14	36				

Table A11. In-Plant reliability data system

Component/group name: Plant 5 Batteries

Plant: 5	Class: Battery	Population: 20
Plant Type: PWR	Volts: 125 VDC	No. of Failures: 22
Operating Period: 3.8 years	Amp-hrs: All	Population hours: 671,600
	Power: N/A	Population Demands: N/A
		Maintenance frequency: 33/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	3	1.2	4.5	12				
(A)	0		0	4.5				
(B)	3	1.2	4.5	12				
Degraded	10	8.1	15	25				
Incipient	9	7.0	13	23				

Table A12. In-plant reliability data system

Component/group name: Aggregate Chargers

Plant: All
Plant type: All

Class: Charger
Volts: All
Amp-hrs: All
Power:

Population: 70
No. of failures: 41
Population hours: 2,183,975
Population demands: N/A
Maintenance frequency: 19/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	No. of failures	Failures/10E+6 h			No. of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	12	1.4	5.5	18.4				
(A)	12	1.4	5.5	18.4				
Degraded	20	1.4	9.2	18.0				
Incipient	9	1.4	4.1	53.0				

Table A13. In-Plant reliability data system

Component/group name: Plant 1 Chargers

Plant: 1
Plant Type: PWR
Operating Period: 5.1 years

Class: Charger
Volts: All
Amp-hrs: All
Power:

Population: 5
No. of Failures: 8
Population hours: 223,375
Population Demands: N/A
Maintenance frequency: 36/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	3	3.7	13.0	35.0				
(A)	3	3.7	13.0	35.0				
Degraded	4	6.1	18.0	41.0				
Incipient	1	0.23	4.5	21.0				

Table A14. In-Plant reliability data system

Component/group name: Plant 2 Chargers

Plant: 2
Plant Type: PWR
Operating Period: 1.3 years

Class: Charger
Volts: All
Amp-hrs: All
Power: All

Population: 5
No. of Failures: 4
Population hours: 56,950
Population Demands: N/A
Maintenance frequency: 70/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	0		4.0	53.0				
Degraded	1	0.90	18.0	83.0				
Incipient	3	14.0	53.0	136.0				

Table A15. In-Plant reliability data system

Component/group name: Plant 3 Chargers

Plant: 3	Class: Charger	Population: 27
Plant Type: BWR	Volts: All	No. of Failures: 3
Operating Period: 3.1 years	Amp-hrs:	Population hours: 733,320
	Power:	Population Demands: N/A
		Maintenance frequency: 4/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	1	0.07	1.4	6.5				
(A)	1	0.07	1.4	6.5				
Degraded	1	0.07	1.4	6.5				
Incipient	1	0.07	1.4	6.5				

Table A16. In-Plant reliability data system

Component/group name: Plant 4 Chargers

Plant: 4
Plant Type: BWR
Operating Period: 6.2 years

Class: Charger
Volts: All
Amp-hrs:
Power: All

Population: 3
No. of Failures: 5
Population hours: 162,930
Population Demands: N/A
Maintenance frequency: 31/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	3	5.0	18.0	48.0				
(A)	3	5.0	18.0	48.0				
Degraded	2	2.2	12.0	39.0				
Incipient	0		1.4	18.0				

Table A17. In-Plant reliability data system

Component/group name: Plant 5 Chargers

Plant: 5
Plant Type: PWR
Operating Period: 3.8 years

Class: Charger
Volts: 125 VDC
Amp-hrs:
Power:

Population: 30
No. of Failures: 21
Population hours: 1,007,400
Population Demands: N/A
Maintenance frequency: 21/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	5	2.0	5.0	10.0				
(A)	5	2.0	5.0	10.0				
Degraded	12	6.9	12.0	19.0				
Incipient	4	1.4	4.0	9.1				

Table A18. In-plant reliability data system

Component/group name: Aggregate Inverters

Plant: All	Class: Inverter	Population: 31
Plant type: All	Volts: 120 VAC	No. of failures: 60
	Amp-hrs: N/A	Population hours: 985,505
	Power:	Population demands: N/A
		Maintenance frequency: 61/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	No. of failures	Failures/10E+6 h			No. of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	21	8.5	21.0	193.0				
(A)	21	8.5	21.0	193.0				
Degraded	22	5.7	22.0	70.0				
Incipient	17	4.3	17.0	70.0				

Table A19. In-Plant reliability data system

Component/group name: Plant 1 Inverters

Plant: 1
Plant Type: PWR
Operating Period: 5.1 years

Class: Inverter
Volts: 120 VAC
Amp-hrs: N/A
Power: All

Population: 5
No. of Failures: 28
Population hours: 223,375
Population Demands: 306
Maintenance frequency: 125/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	4	6.12	17.9	41.0				
(A)	4	6.12	17.9	41.0				
Degraded	14	37.9	62.7	98.0				
Incipient	10	24.3	44.8	76.0				

Table A20. In-Plant reliability data system

Component/group name: Plant 2 Inverters

Plant: 2	Class: Inverter	Population: 5
Plant Type: PWR	Volts: 120 VAC	No. of Failures: 19
Operating Period: 1.3 years	Amp-hrs: N/A	Population hours: 56,950
	Power: All	Population Demands: N/A
		Maintenance frequency: 334/10E+6 hrs

Failure severity (by mode) failures	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	11	108.0	193.0	320.0				
(A)	11	108.0	193.0	320.0				
Degraded	4	24.0	70.0	160.0				
Incipient	4	24.0	70.0	160.0				

Table A21. In-Plant reliability data system

Component/group name: Plant 5 Inverters

Plant: 5	Class: Inverter	Population: 21
Plant Type: PWR	Volts: 120 VAC	No. of Failures: 13
Operating Period: 3.8 years	Amp-hrs: N/A	Population hours: 705,180
	Power: All	Population Demands: 966
		Maintenance frequency: 18/10E+6 hrs

Failure severity (by mode)	Time-related failure rates				Demand-related failure probabilities			
	Number of failures	Failures/10E+6 h			Number of failures	Failures/10E+3 demands		
		Low	Recommended	High		Low	Recommended	High
Catastrophic	6	3.7	8.5	17.0				
(A)	6	3.7	8.5	17.0				
Degraded	4	1.9	5.7	13.0				
Incipient	3	1.2	4.3	11.0				

Appendix B. PLANT SPECIFIC INFORMATION

Appendix B. PLANT SPECIFIC INFORMATION

The IPRD program, in conjunction with IEEE, obtains plant data under an agreement to use the information for beneficial analyses and to maintain anonymity of the participants. Below are some general statements about the sources for the electrical component information. Table B-1 provides more specific statistics. All available records have been included.

Plant 1

Plant 1 is a single unit PWR. The population and engineering information was largely assembled from plant piping and instrumentation drawings in the FSAR. Correspondence with plant personnel provided some supplementary information. Failure/repair records were generated from component and system maintenance summary cards.

For diesel generators, Plant 1 had 177 failure/repair (F/R) records for 2 population records, of which 174 records were matched. For batteries, there were 34 F/R records for 3 population records, of which 31 matched. For chargers, there were 16 F/R records for 5 population records and 12 were matched. Plant 1 had 34 F/R records for 5 inverter population records, 30 of which were matched.

Plant 1 data spanned 7.3 reactor-years total, including 5.1 reactor-years of post-commercialization operating data. Considering only the latter period significantly reduced the number of applicable F/R records for matching.

Plant 2

Plant 2 is a single unit PWR. The population information was assembled from information in the plant's FSAR. Failure/repair records originated from plant supplied computer listings.

For diesel generators, there were 62 F/R records for 2 population records, 51 records were matched. For batteries, Plant 2 had 18 F/R records for 8 population records, of which 17 matched. There were seven charger F/R records for seven population records and all were matched. Plant 2 had 64 F/R records for inverters and 5 population records. All inverter F/R records were matched.

Plant 2 data covered a total of 2.2 reactor-years including 1.3 reactor-years of post-commercialization operating data. Considering only the latter period reduces the number of applicable F/R records for matching significantly.

Plant 3

Plant 3 is a multi-unit BWR. The population records were generated from information found in the FSAR. Failure/repair records were generated from the plant's monthly operating reports. These generally did not contain the degree of specific information found in the individual maintenance work requests.

Plant 3 diesel generators had 80 failure/repair records for 8 population records, of which 65 matched. For batteries, there were 10 F/R records for 26 population records, 9 of which were matched. For

Table. B-1. Information on Plant Specific Records

	IPRDS Plant					
	PWR			BWR		Total
	1	2	5	3	4	
Number of maintenance records reviewed	30,000	10,000	50,000	50,000	30,000	170,000
Number of corrective maintenance (CM) records	8,000	3,000	5,000	6,000	7,000	29,000
Number of CM records for electrical components:	261	151	84	107	95	698
Diesel generators	177	62	n/a	80	50	369
Batteries	34	18	43	10	14	119
Battery chargers	16	7	27	4	10	64
Inverters	34	64	14	3	0	115
MG sets				10	21	31
Number of population records developed for electrical components:	15	22	71	87	18	213
Diesel generators	2	2	n/a	8	2	14
Batteries	3	8	20	26	6	63
Battery chargers	5	7	30	45	5	92
Inverters	5	5	21	0	0	31
MG sets				10	5	15
Time span of electrical component maintenance records (reactor-years)	7.3	2.2	11.5	9.3	6.2	36.5

N/A: no data were available.

chargers there were 4 F/R records for 45 population records, with 3 records matching. No inverter population records could be developed.

The data on Plant 3 spanned a total of 9.3 reactor-years. Approximately all of the data was post-commercialization.

Plant 4

Plant 4 is a single unit BWR. The FSAR for the plant provided much of the information for creating the population records. Failure and repair records were developed from the original maintenance work requests.

Plant 4 had 50 diesel generator F/R records for 2 population records, of which 47 were matched. For batteries, there were 14 F/R records for six population records with twelve records matching. For chargers there were ten F/R records for five population records, seven of which were matched. Plant 4 did not have inverter data.

The data from Plant 4 covered 6.2 reactor-years, all of which was post-commercialization.

Plant 5

Plant 5 is a PWR. The population records were generated from plant P&IDs, information found in the FSAR and communication with ORNL engineers who had extensive familiarity with the plant's electrical system.

For batteries there were 43 F/R records for 20 population records, 22 of which matched. For chargers, there were 27 F/R records for 30 population records with 21 records matching. There were 14 inverter failure/repair records for 21 population records with 13 records matching.

The data from Plant 5 spanned approximately 11.5 reactor-years of data, with roughly all of it being post-commercialization.

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13. ABSTRACT (200 words or less)

The objective of the In-Plant Reliability Data (IPRD) program is to develop a comprehensive, component-specific reliability data base for probabilistic risk assessment and for other statistical analyses relevant to component reliability evaluations. This objective is being attained through a cooperative effort with several utilities which have provided access to maintenance files and pertinent population information. This pilot data base includes (1) a component population list (for each plant) of selected electromechanical and mechanical equipment (e.g., pumps, valves, etc.), and (2) comprehensive component failure and repair histories based on corrective maintenance actions on these components.

This document is the product of a pilot study that was undertaken to demonstrate the methodology and feasibility of applying IPRDS techniques to develop and analyze the reliability characteristics of key electrical components in five nuclear power plants. These electrical components include diesel generators, batteries, battery chargers and inverters. The sources used to develop the data base and produce the component failure rates and mean repair times were the plant equipment lists, plant drawings, maintenance work requests, Final Safety Analysis Reports (FSARs), and interviews with plant personnel. The data spanned approximately 33 reactor-years of commercial operation.

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