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GOVERNMENT OF INDIA

AERB TECHNICAL DOCUMENT

COMPENDIUM OF STANDARD GENERIC RELIABILITY DATABASE FOR PROBABILISTIC SAFETY ASSESSMENT OF NUCLEAR POWER PLANTS

ATOMIC ENERGY REGULATORY BOARD

AERB TECHNICAL DOCUMENT NO. AERB/NPP/TD/O-1

COMPENDIUM
OF
STANDARD GENERIC RELIABILITY DATABASE
FOR
PROBABILISTIC SAFETY ASSESSMENT
OF
NUCLEAR POWER PLANTS

Atomic Energy Regulatory Board
Mumbai 400 094
India

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Price:

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FOREWORD

The Atomic Energy Regulatory Board (AERB) constituted by the Government of India vide Statutory Order No. 4772 dated November 15, 1983 is entrusted with the responsibility of enforcing safety and carrying out regulatory functions envisaged under the Atomic Energy Act, 1962. AERB is responsible for enforcing safety in all atomic energy related activities within India, as well as for enforcing the provisions of the Factories Act, 1948 in the units of the Department of Atomic Energy (DAE) that are under the purview of AERB. In discharging these responsibilities, AERB has been drawing up codes, standards, guides, manuals and other safety related technical documents to facilitate the concerned organisations in implementing the relevant safety regulations.

AERB is in the process of developing a manual to provide Guidelines for the performance and review of probabilistic safety assessment (PSA) of nuclear power plants and other nuclear facilities. It was realised that there is a need to have a standard generic database for PSA studies which could be used in the absence of plant specific data. Towards this AERB commissioned this study to compile a generic reliability database from various sources for components being used in Indian nuclear facilities. This technical document is intended to supplement the manual on guidelines for probabilistic safety assessment.

The document has been prepared by Shri A.K. Babar, Former Head, PSA section, Reactor Safety Division, BARC. Subsequently, it was reviewed by the PSA committee of AERB and experts in this field from various units of DAE. AERB thank all the individuals who helped in the drafting and finalisation of this technical document.

(S. K. Sharma)
Chairman, AERB

DEFINITIONS

Availability

The fraction of time in which an entity is capable of performing its intended purpose.

Basic Event

An event in a logic model, which represents the state in which a component or a group of components is unavailable. Generally, basic events are component failures, operator errors, adverse environmental conditions etc. However, they can also relate to operation, maintenance, etc.

Catastrophic Event

Any event, which could potentially cause the loss of primary system function(s) resulting in significant damage to the system or its environment and/or cause the loss of life or limb.

Common Cause Failure (CCF)

The failure of a number of devices or components to perform their functions, as a result of a single specific event or cause.

Component

The smallest part of a system necessary and sufficient to consider for system analysis.

Critical Component

Component, whose failure, in a given operating state of the system, results in the system failure.

Degradation Failure

A failure, which is both a gradual failure and a partial failure. In time, such a failure may develop into a complete failure.

Dependent Failures

Interdependent, simultaneous or concomitant failures of multiple entities.

Engineered Safety Features (ESFs)

The system or features specifically engineered, installed and commissioned in a nuclear power plant to mitigate the consequences of accident condition and help to restore normalcy, e.g., containment atmosphere clean-up system, containment depressurisation system etc.

Error of Commission

An error that amounts to an unintended action, excluding inaction. It includes selection error, error of sequence, time error and qualitative error.

Error of Omission

An error that amounts to omitting a part or entire task.

Event

Occurrence of an unplanned activity or deviations from normalcy. It may be an occurrence or a sequence of related occurrences. Depending on the severity in deviations and consequences, the event may be classified as an anomaly, incident or accident in ascending order.

Fail Safe Design

A concept in which, if a system or a component fails, then the plant/component/ system will pass into a safe state without the requirement to initiate any operator action.

Failure Mechanism

The physical, chemical or other process, which has led to a failure.

Failure Mode

The effect by which a failure is observed.

Failure Modes and Effects Analysis (FMEA)

A qualitative method of system analysis, which involves the study of the failure modes that can exist in every component of the system and the determination of the causes and effects of each failure mode.

Hazard

Situation or source, which is potentially dangerous for human, society and/or the environment.

Human Behaviour

The performance, i.e. action or response of human operator to occurrence of event(s).

Human Reliability

The probability that a human operator will perform a required mission under given conditions in a given time interval.

Human Reliability Assessment/Analysis

Assessment concentrating on the human errors liable to be committed by the operator having a mission to fulfill on a system.

Incident

Events that are distinguished from accidents in terms of being less severe. The incident, although not directly or immediately affecting plant safety, has the potential of leading to accident conditions with further failure of safety system(s).

Incipient

The component is in a condition that, if left unremedied, could manifest propagation of degradation or flaw ultimately leading to a failure or unavailable state.

Initiating Event/Initiator

An identified event that leads to anticipated operational occurrences or accident conditions and challenges safety functions.

In-service Inspection (ISI)

Inspection of structures, systems and components carried out at stipulated intervals during the service life of the plant.

Mean Time Between Failures (MTBF)

The expected operating time between two failures.

Mean Time to Failure (MTTF)

The expected operating time to first failure. The MTTF is also called MTTFF (mean time to first failure).

Mean Time to Repair (MTTR)

The expectation of the time for restoration (or to repair).

Mission Time

Duration/period for which the operation of the system must be ensured.

Nuclear Safety

The achievement of proper operating conditions, prevention of accident or mitigation of accident consequences, resulting in protection of site personnel, the public and the environment from undue radiation hazards.

Partial Failure

A failure which results in the inability of an entity to perform some, but not all, required functions.

Passive Component

A component which has no moving part and only experiences a change in process parameters such as pressure, temperature, or fluid flow in performing its functions. In addition, certain components, which function with very high reliability, based on irreversible action or change, may be assigned to this category (examples of passive components are heat exchangers, pipes, vessels, electrical cables, and structures. Certain components, such as rupture discs, check valves, injectors and some solid-state electronic devices have characteristics, which require special consideration before designation as an active or passive component).

Probabilistic Risk Assessment (PRA)/Probabilistic Safety Assessment (PSA)

A comprehensive structured approach to identifying failure scenarios constituting a conceptual and mathematical tool for deriving numerical estimates of risk. The term PRA and PSA are interchangeably used.

Quality

The totality of features and characteristics of an item or service that have ability to satisfy stated or implied needs.

Quality Assurance (QA)

Planned and systematic actions necessary to provide the confidence that an item or service will satisfy given requirements for quality.

Redundancy

Provision of alternative structures, systems, components of identical attributes, so that any one can perform the required function, regardless of the state of operation or failure of the other.

Reliability

The probability that a structure, system, component or facility will perform its intended (specified) function satisfactorily for a specified period under specified conditions.

Risk

A multi-attribute quantity expressing hazard, danger or chance of harmful or injurious consequences associated with an actual or potential event under consideration. It relates to quantities such as the probability that the specific event may occur and the magnitude and character of the consequences.

Risk Based Approach

Approach in which the decision making is solely based on the numerical result of the risk assessment judging against the probabilistic safety criteria set or established.

Risk Informed Approach

An approach to decision making that represents a philosophy whereby risk insights derived from risk assessment, by comparison of the results with the probabilistic safety goals, are considered together with other information obtained from deterministic safety analysis, engineering judgment and experience.

Root Cause

The fundamental cause of an event, which, if corrected, will prevent its recurrence, i.e. the failure to detect and correct the relevant latent weakness(es) (undetected degradation of an element of a safety layer) and the reasons for the failure.

Safety System

System important to safety and provided to assure that under anticipated operational occurrences and accident conditions, the safe shutdown of the reactor followed by heat removal from the core and containment of any radioactivity, is satisfactorily achieved. (Examples of such systems are shutdown systems, emergency core cooling system and containment isolation system).

Scheduled Maintenance

The preventive maintenance carried out in accordance with an established time schedule.

Significant Event

Any event, which degrades system performance function(s) without appreciable damage to either system or life or limb.

Unavailability

The inability of an entity to be in a state to perform a required function under given conditions at a given point of time. It is measured as the probability (relative frequency) that the entity is in an unavailable state at a point of time.

Uncertainty Analysis

An analysis to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.

SPECIAL DEFINITIONS
(Specific for the Present Technical Document)

Accident Sequence

Sequence of events leading to an accident.

Boundary

The physical or functional external interface of structure, system or a component.

Cognition

The capacity or mechanisms that lead to knowledge.

Common Cause Basic Event

In the context of system modelling, common cause events are a subset of dependent events in which two or more component fault states exist at the same time, or within a short time interval. A common cause basic event represents the unavailability of two or more components due to all shared causes that are not explicitly represented in the logic model as other basic events.

Common Cause Component Group

A group of (usually similar) components that are considered to have potential of failing due to the same cause.

Common Cause Event Model

A model, which is the basis for quantifying the frequency of common cause events. Examples include the beta factor, binomial failure rate, and basic parameter models.

Coupling Mechanism

An explanation of why and how a failure is systematically induced in several components.

Diagnosis

The capacity or mechanisms to understand what is perceived and realise the implications of a perceived situation.

Down Time

The time interval during which an entity is in a down state.

Failure Rate

The limit, if any, of the ratio of the conditional probability that the instant of time, T, of a failure of an entity falls within a given time interval, [t, t + Dt], to the length of this interval, Dt, when it tends to zero, given that the entity has not failed over [0, t]. It is also called as 'instantaneous failure rate'.

Gradual Failure

A failure due to gradual change of a given characteristics of an entity with respect to time.

Human Error

The departure of a human behaviour from what it should be.

Independent Basic Events

Two basic events, A and B, are statistically independent if, and only if P(A and B) = P(A) * P(B). Where P(x) is the probability of event x.

Knowledge Based Behaviour

When symptoms are ambiguous or complex, the state of plant is complicated by multiple failures or unusual events, or the instrument gives only an indirect reading of the state of the plant, the operator has to rely on his knowledge and his behaviour is determined by more complex cognitive processes.

Maintainability

The ability of an entity under given conditions of use, to be restored in or resulted to a state in which it can perform under given condition and using stated procedures and resources. The measure of maintainability is the probability that the above maintenance action can be carried out within a stated interval.

Maintenance Time

The time interval during which a maintenance action is performed on an entity either manually or automatically, including technical delays and logistic delays.

Performance Shaping Factor (PSF)

Any factor that shapes (influences) human performance to perform reliably or to make errors. It can be categorised into external PSFs (relating to situational characteristics, task and equipment characteristics), stressor PSFs (psychological and physiological)) and internal PSFs (characteristics of people resulting from internal and external influences).

Probability Density Function

The derivative, if any, of the cumulative distribution function of a random variable.

Repair

The part of corrective maintenance in which maintenance actions are performed on the entity.

Repair Time

That part of active corrective maintenance time during which repair actions are performed on an entity.

Rule Based Behaviour

A (hypothesized) mode of behaviour that amounts to following situation action plans.

Time Reliability Correlation

A relationship of probability of the (failure of) occurrence of an event to the time over which the event could occur.

Uncertainty Analysis

An analysis to estimate the uncertainties and error bounds of the quantities involved in, and the results from, the solution of a problem.

Wear-out Failure

A failure whose probability of occurrence increases with the passage of time, as a result of processes inherent in the entity. It is also called ‘ageing failure’.

CONTENTS

LIST OF ABBREVIATIONS

AERB	-	Atomic Energy Regulatory Board
AOV	-	Air Operated Valve
ASEP	-	Accident Sequence Evaluation Program
BFR	-	Base Failure Rate
BWR	-	Boiling Water Reactor
CCCG	-	Common Cause Component Group
CCF	-	Common Cause Failure
CRDM	-	Control Rod Drive Mechanism
/d	-	per demand
DAE	-	Department of Atomic Energy
DDP	-	Diesel Driven Pump
DG	-	Diesel Generator
ECCS	-	Emergency Core Cooling System
EDG	-	Emergency DG
EF	-	Error Factor
EPIX	-	Equipment Performance Information Exchange
EPROM	-	Erasable Programmable Read Only Memory
FTO /C	-	Fail to Open/Close
FTS /R	-	Fail to Start/Run
/h	-	per hour
HCR	-	Human Cognitive Reliability
HEP	-	Human Error Probability
HX	-	Heat Exchanger
I & C	-	Instrumentation & Control
ICDE	-	International CCF Data Exchange Program
IGCAR	-	Indira Gandhi Centre For Atomic Research
INPO	-	Institute of Nuclear Power Operation
LER	-	Licensee Event Report
LOFP	-	Loss Of Power
LOFW	-	Loss Of Flow
MDP	-	Motor Driven Pump
MGL	-	Multiple Greek Letter
MIL	-	HDBK - Military Handbook
MOS	-	Metal Oxide Semiconductor
MOV	-	Motor Operated Valve
NPPs	-	Nuclear Power Plants
PFBR	-	Prototype Fast Breeder Reactor
Pr.	-	Pressure
PROM	-	Programmable Read Only Memory
PSA/PRA	-	Probabilistic Safety/Risk Assessment
PSF	-	Performance Shaping Factor
PWR	-	Pressurised Water Reactor
ROM	-	Read Only Memory
SOV	-	Solenoid Operated Valve
TDP	-	Turbine Driven Pump
THERP	-	Technique for Human Error Reliability Prediction
UPS	-	Uninterupted Power Supply

EXECUTIVE SUMMARY

Reliability data based on the experience of operating plants is always desirable. However, relying on this source alone is usually not feasible, in view of inadequate data collection programs, small number of failures (particularly in safety related components), need for statistically significant data, etc. A generic reliability database is essential to standardise the PSA activities and also the PSA review process.

PSA activities in Indian nuclear reactors have been in progress for quite some time. So far, the persons engaged in PSA activities had to search for reliability data from a variety of diverse sources. They have also been estimating data when necessary, on the basis of expert judgment. In the process, different values may be used for failure rates or probabilities of the same component, resulting in different unavailability values for the given system. Thus, there is a definite need to have a standard data set for PSA studies. In order to facilitate the use of standard reliability data for PSA and to standardise the review process, AERB has initiated this study to compile a generic reliability database from various and diverse sources, for components being used in Indian nuclear reactors.

This report presents the results of efforts in compiling a database from a variety of international sources, e.g. WASH-1400, IEEE-500 and various NUREG sources. The components included in the database cover the large variety used in PSA studies. However, none of these sources include data for components used in computer based systems. Reliability models and data generally used and explained in US-MIL standard 217F, are briefly described in the report.

Reliability data, in terms of mean or median value and confidence limits representing upper and lower bounds (90% probability range), are included. The variability in failure rate/probability data is mostly represented by the log normal distribution, which is generally adequate, in view of the failure rates differing by factors.

It would be worthwhile comparing the failure data of components for a given failure and operating mode, from different sources, to establish a range of expected values. A large number of graphs, for components for which sufficient amount of data exists in the sources, have been obtained, and are included in the report. Such graphs will be quite useful in comparing the data based on our operating experience, with the data obtained from international experience.

It is possible to suggest the most likely value of the failure rate or probability of failure on demand for a component, or the range of values, based on such graphs. However, a proper standard value can be recommended, after obtaining some representative data from the operating experience.

It is seen that, the uncertainty in failure data for independent failures is not very large, and usually within an order or two of magnitude. However, in case of common cause failures, data obtained from operating experience is vital, in order to obtain an estimate of the parameters, since the uncertainty is high. An approach to quantification of CCFs is outlined.

The contribution of human errors to system unavailability, particularly, during the mitigating actions warranted in a potential accident sequence, could be significant. An approach to quantify human error probability (HEP), using human cognitive reliability models in detection and diagnosis of accident situations, and performing various stipulated actions for mitigation of consequences, is explained in the report. Relevant tables, from the Handbook NUREG/CR-1278, for HEP predictions, are also included.

Some generic failure rate data collected at IGCAR, for the reliability analysis of the safety systems of prototype fast breeder reactor (PFBR), have been obtained, and the same is included in the report for the purpose of making this compendium widely applicable.

It is recognised that the majority of PSA studies were performed worldwide during the eighties and the data collection efforts were made during the seventies and eighties. Thus, the data sources provide failure rate information about components designed and operated during this period. Some efforts have been made to collect data during nineties and early 2000. Reliability data is being collected by the Institute of Nuclear Power Operations, for the 100 US nuclear power plants since 1997, and processed in the equipment performance and information exchange (EPIX) database. Failure data for some critical components obtained from EPIX, is included, which depicts a general reduction in the failure rates, as expected due to modifications in design and maintenance.

1. INTRODUCTION

Component failure and maintenance data (i.e. reliability data) form an essential part of any probabilistic safety assessment (PSA) study. The quality of this data determines the quality of PSA to a large extent. Such data comprise:

- The failure rate of components operating continuously
- The probability of failure of components that are in standby mode
- The down time/repair time of failed components.

In view of the uncertainties associated with the data collection process, time to failure of components, failure models, etc., it is desirable to estimate the probability distribution and bounds for these parameters, for carrying out uncertainty analysis.

Component failure data based on the plant operating experience would be the most appropriate data for use in PSA. However, complete reliance on the experience of a plant is rarely possible since the operating experience is limited and also the number of failures recorded is too small for a meaningful statistical experience. The use of generic data is therefore unavoidable.

PSA activities for Indian nuclear reactors have been in progress for quite some time. So far, the persons engaged in PSA activities had to search for reliability data from a variety of diverse sources. They have also been estimating data whenever necessary, on the basis of expert judgment. In the process, different values may be used for failure rates or probabilities for the same component, resulting in different unavailability values for the given system. Thus, there is a definite need to have a standard data set for the PSA studies. In order to facilitate the use of standard reliability data for PSA and to standardise the review process, AERB has initiated this study to compile a generic reliability database from various and diverse sources, for components being used in Indian nuclear reactors. The objectives of this activity are as follows:

(i) To generate a standard reliability database which can be utilised, by various professionals in different units of DAE, for PSA studies, in the absence of plant specific data.

(ii) To facilitate AERB in the review of PSAs of various operating plants and projects.

(iii) To carry out comparative evaluations of plant specific data with international experience and to evaluate the trends in the generated data.

The details of the reliability database obtained from a variety of sources are explained in the following sections. Section 2 presents the format of the database, and various component groups and types included in the database. The applicable failure modes for all the components are covered. The section also includes a brief description of the various data sources from which the data has been extracted. The factors contributing to the uncertainty in interpreting the generic database are explained in section 3.

In a majority of the data sources, failure data on components used in computer-based systems is usually not available. A procedure for reliability analysis of components in computer-based systems is explained and relevant data for the same is included in section 4. The Reliability data of practically all the components used in PSA are included in section 5. There are more than 500 records in the database obtained from 22 diverse data sources. It would be worthwhile comparing failure data of a given component obtained from different sources and establishing the ranges. Graphs have been drawn in section 6 for a variety of components, wherever adequate data exists in the database for the purpose of comparative evaluation of the data. Data on common cause failures and human error are the integral parts of PSA. Approach towards analysis, and some models for CCF and human reliability analysis, are explained in section 7 and 8 respectively. The generic failure rate data collected at IGCAR being utilised for the reliability analysis of the safety systems of PFBR, is included in section 9.

It is recognised that practically all the generic data sources originated in the period seventies and eighties. Some data obtained from the most recent and up-to- date source, the equipment performance and information exchange (EPIX) database, for the period 1999-2001, is presented in section 10. The section also includes data on external leakage and rupture frequencies of some components, e.g piping, pumps, valves, flanges, etc. required for the risk analysis of the event ‘internal flooding’ in Nuclear Power Plants.

Based on the data, attempts have been made to suggest the likely value (median) of the failure rate/probability of the components in section 11. It is suggested that an estimate of the actual failure rate be obtained from operating experience so as to have an idea of its range compared with the generic data.

2. DATABASE FORMAT

Since the present database is derived from different data sources providing different types of information, it is necessary to consider a proper format, which would enable inclusion of information in a systematic and consistent manner. In addition, it would be desirable to have a system, which enables easy information overview and retrieval. The database covers the following categories of information [1].

(i) S. No.

(ii) Component group

(iii) Component type

(iv) Failure mode

(v) Failure rate/probability

(vi) Error factor

(vii) Confidence limits

(viii) Repair/down time

(ix) Comments including the data source

(x) Reference

2.1 Component Group

Components in the database may be divided in four major functional categories:

(i) Mechanical components

(ii) Electrical components

(iii) Instrumentation and control (I&C) including computer based systems

(iv) Civil structures

However, database on civil structures is not included in this report.

Component groups included in the mechanical components category are:

Air cooler	Orifice
Bellows	Penetration
Break	Piping
Clutch	Pump
Compressor	Rupture disk
Control Rod	Screen
Damper	Strainer
Diesel engine	Tank
Fan	Tubing
Filter	Turbine
Gasket	Valve
Heat exchanger	
Lifting and positioning devices	

DATABASE FORMAT (Contd.)

Component groups in electrical components category are:

Battery	Inverter
Battery charger	Isolator
Bus	Motor
Cable	Motor generator
Circuit breaker	Relay
Turbine driven generator	Transformer
Diesel generator	Wire
Fuse	UPS
Heater	

Component groups in Instrumentation and Control category including computer based systems are:

Annunciator	Sensors
Controller	Signal conditioning system
Indicating instruments	Switch
Instrumentation channel	Transmitter
Optical links	Microcircuits

2.2 Component Types

The database covers following component types within various component groups:

Component Type-Mechanical

Air cooler

Clutch
- Mechanical
- Electrical

Compressor
- Instrument air
- Annulus ventilation
- Containment air control
- Reciprocating

Shut off/control rod
- Boron carbide
- Cadmium
- KWU PWR
- BWR applications
- Dashpot
- Control rod drive
- Lead screw roller nut
- Magnetic jack latch

DATABASE FORMAT (Contd.)

Damper	- Shut off
	- Containment fan cooling system.
Fan	- Containment fan cooler
	- Reactor building cooler
Gasket	- Rubbers and elastomers
	- Metallic
Heat Exchanger	- U-Tube, horizontal
	- Shell and tubes
	- U-Tube, vertical
	- Plate
Lifting & Positioning Devices	- Crane
	- Hoist
Orifice	
Penetrations	- Cable
	- Piping
Piping	- < 1″
	- 1″ - 6″
	- < 3 ″
	- > 3 ″
	- Elbows 4″ - 6″
	- Expansion joint
	- Nozzle
	- Diaphragm 10″ - 16″
	- Reducer
	- Tees
	- Thermowell 10″ - 16″
	- Welds < 4″
Pump	- Motor driven
	- Turbine driven
	- Diesel driven
Screen	
Strainer/Filter	- Flow
	- Y- type
Tank	
Turbine	- Combustion
	- Steam

DATABASE FORMAT (Contd.)

Valve	-	Butterfly
	-	Condenser steam discharge
	-	Diaphragm
	-	Flow Control ½ ”
	-	Fluidic
	-	Gate
	-	Globe
	-	High pressure, steam dump
	-	Pressure relief system pilot valve
	-	Pressure relief
	-	Air operated
	-	Manual
	-	Motor operated
	-	Motor operated, regulating
	-	Power operated, relief
	-	Self operated, check, float
	-	Self operated, check, swing
	-	Solenoid operated
	-	Three way
	-	Safety

Component Type-Electrical

Battery	-	Nickel-cadmium
	-	Lead acid
	-	Power systems-wet cell
	-	125 V
Bus	-	230 kV
	-	6.6 kV
	-	415 V
	-	DC 250 V
	-	48 V
	-	12 V
Cable	-	Control
	-	Power
Circuit breaker	-	230 kV, 1250 A,
	-	6.6 kV 800 A
	-	6.6 kV 3000A

DATABASE FORMAT (Contd.)

	- 2000-3000A
	- 415 V
	- 250 DC
	- 48 V, 24 V, 12 V
	- Miniature
	- Reactor protection
Diesel Generator	
Fuse	- Fuse, all voltage levels
	- General
Heater	- Electrical
	- Steam
	- Feed water
	- Pressuriser
Inverter	- General
	- Solid state, 120V
	- Static single phase
	- Static three phase
Motor	- High pressure emergency injection
	- Low pressure emergency injection
	- Low pressure service water
	- Auxiliary boiler feed pump
	- Condensate extraction pump motor
	- Emergency service water
	- End shield tank cooling
	- Moderator pump
	- PHT feed pump
	- PHT pump
	- SDC pump
	- BFP
	- AC, general
	- AC, induction
	- AC, split synchronous
	- DC, general
	- Servo
	- Stepper

DATABASE FORMAT (Contd.)

Motor Generator	-	AC
	-	DC
Relay	-	General
	-	Power
	-	Protective
	-	Time delay
	-	Coil
	-	Contacts
Transformer	-	Auto, single phase, all voltage levels
	-	3 Phase
	-	General
	-	High voltage, outdoor
	-	Instrument current
	-	Instrument voltage
	-	Main power generator or unit, all voltage level, 1j
	-	Main power generator or unit, all voltage level, 3 j
	-	220/120V
	-	50/6kV
	-	6kV/380V
	-	8kV/6kV
	-	Dry, 4kV/600V
	-	Dry, 600V/208V
	-	Regulating 120V AC
UPS		
Component Type	**-**	**Instrumentation and Control**
Annunciator		
Controller	-	Flow
	-	General (Level, pressure, temperature)
Converter	-	Voltage to pneumatic
	-	Current to voltage
	-	Current to pneumatic
	-	Current to current
	-	Square root
Indicating instrument	-	Indicating alarm meter
Instrumentation channel		

DATABASE FORMAT (Contd.)

Micro circuits (e.g analog to digital, digital to analog converters, etc.)

Sensors	-	Core flux
	-	Flow
	-	Level
	-	Pressure
	-	Pressure differential
	-	Temperature
	-	Radiation

Signal Conditioning Unit

Switch	-	Flow
	-	Level
	-	Limit
	-	Manual
	-	Pressure
	-	Temperature
	-	Torque
Transmitter	-	Power
	-	Flow
	-	Level
	-	Pressure
	-	Pressure difference
	-	Temperature

2.3 Generic Failure Mode

The list of generic failure modes considered in the data is given below

(i) All Modes[1]

(ii) Degraded

(iii) Fail to change position

(iv) Fail to remain in position

(v) Fail to close

(vi) Fail to open

(vii) Fail to function

(viii) Short to ground

(ix) Short circuit

1 Failure mode "All Modes" signifies that the failure rate includes contribution from all applicable failure modes.

(x) Open circuit

(xi) Plug/Rupture

(xii) Spurious function

(xiii) Fail to start

(xiv) Fail to run

(xv) External leak

(xvi) Internal leak

(xvii) Fail to energise

(xviii) Fail to de-energise

It is important to clearly distinguish between the various failure modes of a component, since failure rate/probability is apportioned among various failure modes. The failure modes are based on component operation and the effects of failure. In case of operation, whether the component failure is a) demand related or b) time related or both is to be given. The effects of a failure to be considered are:

(a) Loss of function

(b) Failure to change state with demand

(c) Change of state without demand

2.4 Data Sources

The failure rate/probability data is derived from a variety of data sources and the selection of appropriate data necessitates the understanding of data collection procedures etc. followed in a given source. Each of the data sources could be put into one of three categories depending upon the nature of the ultimate origin of data.

The three categories are:

(a) Plant specific data

(b) Data extracted from reporting systems

(c) Data based on expert opinion, nuclear or non-nuclear experience.

(a) Plant specific data:

It is usually considered to be the best source of data for the plant being analysed, but not so when this data is considered for a dissimilar plant. A variation of this is plant specific data used for updating the generic data (using Bayesian methods). The Bayesian methodology has been adopted in many plant PSA studies e.g.- Oconee NPP PRA, Zion NPP PRA and in the source identified as 'Old PWR'.

(b) Data extracted from reporting systems:

A widely known system of reporting NPP events is the licensee event report (LER) system in US based on the reports for safety significant events. A number of sources, NUREG/CR- 1205, 1331,1363 and NUREG /CR- 1740 contain failure rate data derived from LERs. The Swedish reliability data is also based on the reports of Swedish LER system. The advantage in such systems is that a large component population is covered for deriving reliable statistics. However, in an event reporting system, identification of component failures is not straight forward. Similarly assessment of operating time or the number of demands is not precise. Also there is not much consideration of differences in component design, operational practices and environment.

DATABASE FORMAT (Contd.)

(c) Data based on expert opinion, nuclear or non-nuclear experience

The most widely known data source based on expert opinion and aggregation of data from nuclear and non-nuclear sources are WASH-1400, IEEE 500, NUREG/CR-2728 (interim reliability evaluation programme), NUREG/CR-2815 and the Sizewell-B assessment experience. Expert opinion is sometimes considered to be a low quality data source, but has several times proved to be in very good agreement with the actual operating experience.

The details of some important data sources are briefly discussed below:

(i) WASH-1400 Reactor Safety Study

WASH-1400 was the first and is the most widely used known PSA study performed. Considerable effort was made in the study to develop the data needed. Although the study is rather old, it is still used as a source of data or “prior” data for updating the plant data experience information. The data sources utilised in the study included the US Department of Defence data and industrial and nuclear power plant experience data. The vast variety was used to assess average and range statistics. Attempts were made to check the applicability of the log normal distribution in describing the data variability.

(ii) Swedish Reliability Data Book

The main aim of the compilation was to provide failure data for reliability calculations, as a part of the safety analysis of Swedish NPPs. Both failure rate applicable to components in continuous and intermittent operation, and failure per demand stating the probability that a component does not work when demanded, have been determined. The basic assumptions applicable to the statistical model for estimating parameters are as follows:

- Each individual component is assumed to have a constant failure rate within the interval studied. This leads to a Poisson distribution for time related failures and Binomial distribution for demand related failures.

- Failure rate and probability vary for the analysed population. The variation of parameters is described by a Gamma distribution for failure rates and Beta distribution for variation of failure probabilities.

The parameters, a and b, determining the distribution for each component are included in the data book. A great advantage of this source is that a component boundary is properly defined. Generally, the source is considered to be very good in the sense of the total population studied ,recorded failures and the definition of components and failure modes.

(iii) IEEE Standard-500

IEEE 500 is a very broad based source of failure data and is perhaps the richest source of information for reliability data on electrical, electronic and sensing instrumentation components, as well as mechanical devices. The database includes information from a variety of sources covering NUREG/CR-1205, 1331, 1363, 1740, 2886 and also NUREG/CR-2232 on nuclear plant reliability data systems. In addition, a number of non-nuclear data sources are also utilised. The raw data from which the values appearing in IEEE 500 were synthesised are found in the following forms:

(i) Statistical operating data from NPPs

(ii) Statistical operating data from fossil fired generating stations and other data from large industries e.g. chemical

DATABASE FORMAT (Contd.)

(iii) Statistical data from transmission grids and industrial plants with the use of expert judgment to estimate the failure rates

(iv) Data on failure and population estimated by individuals familiar with the operating and failure histories of specific generic devices[2].

(v) Data extracted from published sources for other industries, which was judged to have some level of applicability to components of NPPs. About 80% of data in IEEE 500 resulted from statistical data in one of the first three categories. About 180 records are provided in the IAEA database from the standard, which cover the whole spectrum of components found in NPPs. A special feature of IEEE 500 is an environmental factor matrix provided for the components. This is in the form of multipliers for high temperature, humidity and radiation effects. IEEE 500 values have been used as priors in other studies.

(iv) NUREG/CR - 4550 Volume-1

Generic database in NUREG/CR-4550 is the updated ASEP (accident sequence evaluation programme) database, which was used to calculate accident sequence frequencies for 100 LWRs. The ASEP database was formed from a broad information base. A number of PSA studies and other sources of information were reviewed and established. Some sources used are as follows:

- WASH-1400
- NUREG/CR-1659 reactor safety study methodology application programme
- Zion NPP PRA
- Limerick NPP PRA
- IEEE 500
- NUREG/CR-1032 evaluation of station blackouts accidents at NPPs.

The source provides mean value and log normal distribution error factors.

` (v) Old PWR

Under this name is a database compiled by updating generic data with plant specific operating experience. Extensive information is available on plant specific data. Support system failure rates are extensively covered.

(vi) Heavy Water Reactor (HWR) Assessment

- This source includes data compiled from accumulated operating experience.
- [3]The source provides a rather detailed division into component sizes (e.g. for valves) and functions (e.g. for pumps). The total amount of operating experience used to assess failure rates is substantial. About 70 component types in mechanical, electrical and I and C categories are covered.
- Mean values, 95% and 5% confidence limits and error factors are included in most of the records.

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2 In case where adequate data is not available, failure rates could be estimated, based on number of failures and the population information, by experts, familiar with the operational/failure history of the specific devices.

3 The source provides detailed data on components like valves with adequate sub-classification with respect to valve sizes e.g. 1-2″, 2-6″ etc. and pump classification with respect to safety systems e.g. auxiliary boiler feed pump, moderator pump etc.

- The mean time to repair (MTTR), which is the actual recorded time, is also included in most of the records.
- The information on all modes and the dominant failure modes is also provided. The population usually covered in the computations is generally included.

(vii) German Risk Study:

The principal objective of the German risk study was to assess one of the plants using WASH-1400 methodology. Following three sources were used to obtain the reliability data for the study:

- Review of the relevant literature
- Review of operating experience from NPPs Biblis and Stade
- Failure effects analysis for part of the I and C components.

Log normal distribution was used throughout the study. For the failure rates of the component, mean or median values, along with the error factors have been provided.

3. UNCERTAINTY FACTORS IN GENERIC DATABASE

In general, the major sources of uncertainty in PSA are as follows :

(i) Input parameter uncertainties

(ii) Modeling uncertainties

(iii) Completeness uncertainties

However, in this section only the uncertainties related to the failure data in various data sources are considered, since it is essential to understand the problem areas resulting in uncertainty, in interpreting a database. Following areas have been identified:

- Component boundary definition
- Failure mode definition
- Operating mode definition
- Operating environment definition

During the analysis of raw data for a plant such issues as the above can lead to significant errors.

3.1 Component Boundary

It is obvious that inadequate or improper definition of the component boundary could lead to misinterpretation of data and result in substantial differences in the failure rates among different sources. This has been adjudged as the prime source of data fluctuation.

Component boundary has been best defined in the Swedish reliability data source, wherein each component category has a sketch, exactly indicating component boundary and points of interface with other components or systems. Local control and protection components are included with the specific device.

Some of the NUREG documents also have adequately defined component boundaries, with precise definition of interface points. In some sources, components are defined as 'off the shelf items'. However, 'off the shelf' does not have the same meaning everywhere. (Generally, 'off the shelf' signifies that the component boundary is limited to the bare component itself and does not include the additional support components, whereas in the made-to-order devices it could be included.) Databases which are part of PSAs, usually do not provide an exact definition of the component boundary since such databases are compiled for specific use.

It is important to realise that while carrying out the updating, component boundary is important because of the need to match the "prior" data with the plant operating experience data. Such details of component boundaries are usually missing in case of compilations based on combining nuclear and non-nuclear experiences. Even the expert opinion derivations have the same problem. It would be worthwhile defining generic component boundaries, particularly in case of future data collection activities. Following major interface points need to be defined with the component boundary.

Mechanical interface, including the cooling system, lubricating system, etc. Power supply interface e.g. the circuit breaker connected to the supply bus. Control and protection system interface.

3.2 Failure Mode

The problem related to failure mode is to understand the exact and total failure modes applicable to the component under consideration, while comparing the failure data from different sources.

3.3 Operating Mode

The issues are related to understanding the various operating modes or states of particularly the active components e.g., pumps, diesel generators, etc. It is required to know all the operational and standby modes, and the durations associated with each state, or the mission time requirements. It is essential to derive and use the failure rate (standby and operational) in accordance with the specified conditions.

It is generally the case that the operational failure rate of a standby component is derived from the short term test runs conducted during test demands, and in the real situation, the requirements could be for a much longer operating period (e.g. for ECCS Pumps, DGs) during emergency conditions.

It is required to distinguish clearly between the failure rate as standby (time related) and failure on demand (demand related).

3.4 Operating Environment

In PSA, it is required to know the prevailing environmental conditions during

(a) normal operation, anticipated operational occurrences and accident conditions, since this could in certain cases change the component failure rate substantially,

(b) Generally the normal operating conditions are considered in a database.

WASH-1400 provides separate failure rates for post accident situations for pumps and motors. The IEEE-500 standard provides a list of environment multipliers (for most of the components included), for environmental effects like high radiation, humidity, temperature and pressure. For example, in case of a motor-driven pump, the median failure rate for the mode ’fail to run’ is 3E-5/h under normal operating conditions and 1E-3/h during extreme environmental conditions.

The number and types of components, which are affected by the accident conditions, have to be established. This is dependent upon the plant design and the type of accident. It would be worthwhile studying the component qualification procedures to check whether adequate testing under accident conditions has been carried out. In case of components not tested or qualified for use in accident conditions, the susceptibility to common cause failures increases significantly.

4. RELIABILITY DATA FOR COMPONENTS USED IN COMPUTER BASED SYSTEMS

Failure rate data in case of general electronic components and particularly digital gates, memory devices, microprocessors and other microcircuits, are not included in the data sources mostly compiled for nuclear system components.

US Military Standard MIL - HDBK - 217F [2] provides the necessary data and models for reliability analysis. The failure rate model used in the standard is as follows:

$$\lambda_c = \lambda_b * \prod_{i=1}^{n} \pi_i$$

where

λ_c is the component failure rate under actual field use /application conditions.

λ_b is the base failure rate (BFR) defined under ideal use conditions of low electrical stresses and controlled benign laboratory usage.

π_i are the application based multiplying factors to account for the actual thermal, use environment, manufacturing process, etc., n is the no. of multiplying factors associated with the component.

4.1 Failure Rate Model of Microcircuits like Digital Gates, Microprocessors, etc.

$\lambda_c = (c_1 \pi_T + c_2 \pi_E)\, \pi_Q\, \pi_L$ failures/ten lakh hours

where

c_1 = Die complexity failure rate depending upon the number of devices on the chip

c_2 = Packaging factor failure rate

π_T = Factor due to thermal stresses and activation energy

π_E = Factor due to environment

π_Q = Quality factor related to the manufacturing and reliability screening process

π_L = Learning factor related to the maturity of the process

c_1 and c_2 have the dimensions of "failures/ten lakh hours"

Application factors π_E, π_Q, π_L and π_T are as included in Tables 1, 2, 3 and 4 respectively and are reproduced from MIL-HDBF 217F. Package failure rate c_2 for various types of packages is shown in Table 5.

Complexity factor failure rate c_1 for microprocessor devices are shown in Table 6.

As an illustration, the failure rate of a microprocessor, at a junction temperature 40°C, based on MOS technology and being used in ground fixed environment and being manufactured in a stable and high quality process may be obtained as follows:

$$\begin{aligned}
\lambda &= (c_1 \pi_T + c_2 \pi_E)\, \pi_Q\, \pi_L \\
c_1 &= 0.56 \\
\pi_T &= 0.19 \\
c_2 &= < 0.1 \\
\pi_E &= 2, \pi_Q = 2 \\
&= (0.56 * 0.19 + 0.1 * 2)\, 2 * 1 \\
\lambda &= (0.1+0.2)2 \\
&= 0.6/\text{ten lakh hours}
\end{aligned}$$

4.2 Failure Rate Model for Memory Devices

The failure rate model for memory devices like ROM, PROM, EPROM, etc. is as follows:

$$\lambda_C = (c_1 \Pi_T + c_2 \Pi_E + \lambda_{CYC}) \Pi_Q \Pi_L \text{ failures/ten lakh hours}$$

The failure rate model is similar to microprocessor devices. An additional factor λ_{CYC} is incorporated to account for read/write cycling induced failures.

c_1 and c_2 are the usual complexity and package failure rate factors. c_1 for the given memory device is determined by the memory size. c_2 is determined from Table-5.

4.3 Software Reliability

The reliability analysis procedure described in the previous sections pertains to the reliability of hardware items used in the computer based systems. The software reliability aspects need also to be integrated to obtain the overall estimate of the system reliability. However, standard methods for quantification of software reliability are still in the development stage. Adequate verification and validation is usually carried out during the design and system integration phases. A model to estimate software reliability is described in AERB safety guide (Draft) on PSA (P.164, Appendix-VIII).

TABLE-1: ENVIRONMENT FACTOR-Π_E

Environment	Π_E
G_B- Ground Benign	0.5
G_F- Ground Fixed	2
G_M- Ground Mobile	4
N_S- Naval Sheltered	4
N_U- Naval Unsheltered	6
A_{IC}- Air Borne Inhabited Cargo	4
A_{IF}- Air Borne Inhabited Fighter	5
A_{UC}- Air Borne Uninhabited Cargo	5
A_{UF}- Air Borne Uninhabited Fighter	8
A_{RW}- Air Borne Rotary Winged	8
S_F- Space Flight	0.5
M_F- Missile Flight	5
M_L- Missile Launch	12
CL- Cannon Launch	220

TABLE-2 : QUALITY FACTORS = P_Q

Description	P_Q
Class S categories 1. Procured in full accordance with MIL-M-38510, Class S requirements. 2. Procured in full accordance with MIL-I- 38535(Class U) 3. Hybrids, procured to Class S requirements (quality level K) of MIL-H- 38534	0.25
Class B categories 1. Procured in full accordance with MIL-M- 38510, Class S requirements. 2. Procured in full accordance with MIL-I- 38535(Class Q) 3. Hybrids, procured to Class B requirements(quality level H) of MIL-H- 38534	1
Class B-1 categories Fully compliant with all the requirements of Para 1.2.1 of MIL-STD-883 and procured to government approved documentation.	2

The class S, B, B-1 etc. are the quality designators which have specified quality requirements as per the applicable MIL specifications. In case of microcircuits, the applicable MIL specifications are MIL-M 38510, MIL-I-38535 etc., which provide the detailed requirements for these levels.

TABLE-3 : LEARNING FACTOR = P_L

Years in Production (y)	P_L
< 0.1	2.0
0.5	1.8
1	1.5
1.5	1.2
>2	1.2
P_L = 0.01 exp (5.35 - 0.35y). y = Years generic device type has been in production.	

TABLE-4 : P_T VALUES FOR DIGITAL MOS, CMOS AND MEMORY DEVICES

Tj (junction temperature) ^{0}C	P_T	
	Digital MOS, CMOS	Memory Devices
25	0.1	0.10
30	0.13	0.15
35	0.16	0.21
40	0.19	0.31
45	0.24	0.43
50	0.29	0.61
55	0.35	0.85
60	0.4	1.2

TABLE-5 : PACKAGE FAILURE RATE FOR MICROCIRCUITS- C_2

Number of Functional Pins N_P	Hermetic: DIPs with the solder or weld seal etc..	DIPs with glass seal
3	0.00092	0.00047
4	0.0013	0.00073
6	0.0019	0.0013
8	0.0026	0.0021
10	0.0034	0.0029
12	0.0041	0.0038
14	0.0048	0.0048
16	0.0056	0.0059
18	0.0064	0.0071
22	0.0079	0.0096
24	0.0087	0.011
28	0.010	0.014
36	0.013	0.02
40	0.015	0.024
64	0.025	0.048
80	0.032	
128	0.053	
180	0.076	
224	0.097	

TABLE-6 : MICROPROCESSOR DIE COMPLEXITY FAILURE RATE C_1

No. Bits	Bipolar C_1	MOS C_1
Up to 8	0.06	0.14
Up to 16	0.12	0.28
Up to 32	0.24	0.56

5. GENERIC FAILURE RATES/PROBABILITY DATA

The generic failure rates/probability data for various component groups and types listed in the earlier sections is included in this section. The source associated with the respective specific data is indicated in the list. The reliability data is generally represented in the form of failure rate / h or per million h in case of normally operating components, and as probability of failure/demand in case of standby/demand related components. However, in case of standby failure rates, the demand failure probability is obtained by multiplying the failure rate and half the corresponding test interval (usually assumed as one month, if not specified). A large variety of sources (22) have been utilised in the database. However, the variability is usually within an order of magnitude.

The failure rate (failure probability) is described in terms of mean (or median)value and the confidence limits defining the upper and lower bounds (percentiles of the distribution, low and high or maximal and minimal values). In some cases, an error factor is also included in the database. In some data sources (Swedish reliability data book), the mean value and only the upper bound are included. In most of the data sources, log normal distribution has been used to describe the variability in failure data (Appendix: 2, WASH-1400 provides several justifications of the applicability of log normal distribution).

Generally, the variability is defined as 90% range, the lower end being the 5% bound and the upper end the 95% bound. This definition of range implies that there is a 90% probability that the data value would be within this range. The error factor for assumed log normal distribution is the upper limit of the range divided by the median, and since the median is geometric midpoint, it is also equal to the median divided by the lower limit.

Presently, in the failure rate/probability column of the database, the corresponding data is the mean value. However, data pertaining to the following sources represent the median:

(i) WASH -1400

(ii) German risk study

(iii) NUREG/CR-1205

(iv) NUREG/CR-4550 vol. 3

Also, the IEEE-500 database depicts the recommended values.

A comparative evaluation of the failure rate for a specific component among various data sources has been performed. Graphs depicting the comparison have been obtained and included in the next section. The column 'Reference' in the database indicates the figure number for the graph containing the information on the particular component.

TABLE-7: RELIABILITY DATABASE OF COMPONENTS

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
1.	Air Cooler		Fail to function	6E-6/h					NUREG 2815	
2.	Annunciator Module	Solid State	Fail to function	1.1E-6/h					IEEE 500	
3.	Annunciator Module	Solid State	Spurious function	1.7E-6/h					IEEE 500	
4.	Battery		Degraded output	3.2E-6/h		7.5 E-6	4.9 E-7	4 - 7 h	NUREG 3831	Fig. 1
5.	Battery		Fail to function	6.4E-7/h		3E-6	3E-8	4 - 7 h	NUREG 3831	Fig. 1
6.	Battery		Fail to function	1.3E-2/d		6.8 E-2	2 h		Swedish Rel Data	Fig. 1
7.	Battery		Fail to function	7.6E-8/h					Zion NPP PRA	Fig. 2
8.	Battery	125V	Fail to function	5.2E-7/h		1.2E-6/h	5E-8/h	5 h	Old PWR	Fig. 2
9.	Battery	Lead Acid	Fail to function	2E-8/h		3E-8	0.0		IEEE 500	Fig. 1
10.	Battery	Power Systems Wet Cell	Fail to function	2E-6/h		1E-5	8E-7/h		NUREG 2815	Fig. 1
11.	Battery	Power Systems Wet Cell	Fail to function	1E-6/h	3				IREP NUREG 2728	Fig. 1
12.	Battery	Power Systems Wet Cell	Fail to function	3E-6/h (med.)	3	1E-5	1E-6/h		WASH-1400	Fig. 1
13.	Battery Charger		Fail to function	6E-7/h		4E-6/h	3E-7		NUREG 2815	Fig. 3
14.	Battery Charger		Fail to function	1E-6/h	3				IREP NUREG 2728	Fig. 3
15.	Battery Charger		Fail to function	5.5E-7/h					Zion NPP PRA	Fig. 4
16.	Battery Charger	120 V	Fail to function	6.7E-6/h		1.3E-5	1.7E-6	5.6 h	Old PWR	Fig. 4
17.	Battery Charger	SCR Type	Fail to function	5E-6/h		1.3E-5	3E-7	10 h	Oconee NPP PRA	Fig. 4
18.	Battery Charger	Rectifier	Fail to function	4.9E-7/h		1.2E-5	6E-8		IEEE 500	Fig. 3

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
19.	Battery Charger	Solid State General	Fail to function	5.5E-6/h		1.8E-5	1.4E-6	5 - 10 h	NUREG 3831	Fig. 3
20.	Blower-Fan		All Modes	2.5E-6/h		2.8E-6	2.3E-6	1.5 h	IEEE 500	
21.	Bus	4 kV	Fail to function	6.2E-7/h		1.5E-6	3.1E-9		Oconee PRA	Fig. 6
22.	Bus	6.0 kV	Fail to function	4.1E-7/h		8.5E-7	6.6E-8	24 h	Old PWR	Fig. 6
23.	Bus	415 V	Fail to function	3.7E-7/h		7.5E-7	6.3E-8	24 h	Old PWR	Fig. 6
24.	Bus	DC 250 V	Fail to function	4.2E-7/h		8.3E-7	3E-10	10.8	Oconee NPP PRA	Fig. 6
25.	Bus		All Modes	3E-8/h		2E-7	6E-10		NUREG 2815	Fig. 5
26.	Bus		All Modes	1E-8/h	3				IREP NUREG 2728	Fig. 5
27.	Bus	120 V, 220 V AC	Fail to function	3.4E-7/h		6.8E-7	6.3E-8		Old PWR	Fig. 6
28.	Bus	120 V DC	Fail to function	4.2E-7/h		9.2E-7	6.9E-8		Old PWR	Fig. 6
29.	Bus	380 V	Fail to function	3.7E-7/h		7.5E-7	6.3E-8		Old PWR	Fig. 6
30.	Bus	Bare, Switch gear	Fail to function	2.3E-7/h		2E-6	4E-8		IEEE 500 (Failure Modes include open circuit, short line to line & short to ground	Fig. 5
31.	Bus	HV, Indoor	Fail to function	6.2E-7/h		1.5E-6	3.1E-9	10.8 h	Oconee NPP PRA	Fig. 6
32.	Bus	Low Voltage, Indoor	Fail to function	1.8E-7/h		8.3E-7	1.8E-9		Oconee NPP PRA	Fig. 6
33.	Bus	Metal, enclosed	Fail to function	8E-8/h		4E-7	0.0		IEEE 500	Fig. 5
34.	Cable	Control	Short to ground	2.4 E-6/h		4.4E-6	2.0E-8		IEEE 500	
35.	Cable	Control	Short Circuit	1.2 E-6/h		1.9E-6	1.0E-8		IEEE 500	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
36.	Cable	Power	Open Circuit	2.6 E-7/h		1.9E-6	0.0		IEEE 500	
37.	Cable	Power	Short to ground	1.2 E-6/h		8.8E-6	0.0		IEEE 500	
38.	Cable	Power	Short Circuit	7.1 E-7/h		5.3E-6	0.0		IEEE 500	
39.	Circuit Breaker	CB, 230 kV 1250 A	Fail to Change Position	1 E-3/d (Med)	3	3E-3/d	3 E-4/d	24 h	WASH-1400	
40.	Circuit Breaker	CB, 230 kV 1250 A	Fail to Remain in Position	1 E- 6/h	3	3E-6	3E-7	24 h	WASH-1400	
41.	Circuit Breaker	CB, 6-6 kV 800 A & 3000 A	Fail to Remain in Position	3.2 E-7/h		3.8E-7		6 h	Swedish Rel. Data a = 0.0145 b = 45200	
42.	Circuit Breaker	CB,6.6 kV 800A & 3000A	Fail to Change Position	2.9E-3/d		6.4E-3/d	1E-3d	6 h	Old PWR	
43.	Circuit Breaker	CB, 2000 - 3000A	Fail to Change Position	1.8E-3/d		7.3E-3/d		4h	Swedish Rel. Data a = 03, b = 16.3	
44.	Circuit Breaker	CB,2000 - 3000A	Fail to Remain in Position	4E-7/h		8.5E-7	4.5E-8	8 h	Oconee NPP PRA	
45.	Circuit Breaker	250 VDC, 630 A, 1000A, 2500A	Fail to Remain in Position	1.8E-7/h		4.2E-7	2E-10	6h	Oconee NPP PRA	
46.	Circuit Breaker	250 VDC, 630 A, 1000A, 2500A	Fail to Remain in Position	1 E-3/d	3	3E-3	3E-4	6h	WASH-1400	
47.	Circuit Breaker	Reactor Protection Breakers	Fail to open	9.8 E-3/d					Bayesian Estimate Zion NPP	
48.	Clutch	Clutch Mechanical	Fail to function	3E-4/d	3	1E-3	1E-4		WASH-1400	
49.	Clutch	Clutch Electrical	Fail to function	3E-4/d	3	1E-3	1E-4		WASH-1400	
50.	Clutch	Clutch Electrical	Fail to Remain	1E-6/h	10	1E-5	1E-7		WASH-1400	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
			in Position							
51.	Compressor	Compressed Instrument Air	Fail to start	2.4E-2/d		3.1E-2/d	1.6E-2/d		Old PWR Bayesian Estimate	
52.	Compressor	Compressed Instrument Air	Fail to run	3E-4/h		4.5E-4	2.8E-4	35 h	Old PWR	
53.	Compressor	Compressed Annulus Ventilation	Fail to run	2.9 E-5		7.3E-5	2.8E-6		Old PWR	
54.	Compressor	Compressed Annulus Ventilation	Fail to start	1.1E-2/d		1.5E-2	5.3E-3		Old PWR	
55.	Compressor	Compressed Containment Air Control	Fail to start	9.9 E-3/d		2E-2	2.3E-3		Old PWR	
56.	Compressor	Compressed Containment Air Control	Fail to run	2.5E-3/h		4.5E-3	8.2E-4/h	39.7 h	Old PWR	
57.	Compressor	Recipro-cating	All Modes	76E - 6/h		1890E-6	1.98E-6/h			
58.	Control Rod		Fail to insert	1E-4/d	3	3E-4	3E-5		WASH 1400	
59.	Control Rod	CR Cadmium	All Modes	2.3E-7/h		4E-7	1.1 E-7	120 h	IEEE-500	
60.	Control Rod	Boron Carbide	All Modes	2.3E-7/h		4E-7	1.1 E-7	120 h	IEEE-500	
61.	Control Rod	KWU PWR Type	Fail to insert	2E-7/h	4				German Risk Study	
62.	Control Rod	KWU PWR Type	Fail to insert	7E-5/d	4				German Risk Study	
63.	Control Rod	BWR Application	All Modes	2.8 E-5/d					Swedish Rel. Data	
64.	Control Rod	CR Drive	All Modes	1.6 E-6/h		4.3E E-6	1.1E-7		IEEE-500	
65.	Control Rod	Lead Screw Roller Nut drive	All Modes	3.5E-6		4.6E-6	2.1E-6		IEEE-500	
66.	Control Rod	MagneticJack Latch drive mechanism	All Modes	7.8E-7		1.7E-6	3.9E-7		IEEE-500	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
67.	Converter	Voltage to Pneumatic	All Modes	1.5 E-6/h		7.1E-6	5.7E-7		HWR Data	
68.	Converter	Current to Voltage	All Modes	2.3 E-5		2.9E-5	1.8 E-5	3 h	HWR Data	
69.	Converter	Current to Pneumatic	All Modes	7.3 E-6		3.1E-5	5.7E-7	3 h	HWR Data	
70.	Converter	Current to Current	All Modes	4.7 E-6		6.3 E-6	3.5 E-6	3 h	HWR Data	
71.	Converter	Square Root	All Modes	5.1 E-6/h		6.8 E-6	3.9E-6	3 h	HWR Data	
72.	Controller	Controller Flow	Fail to function	4.2 E-6/h				8h	Shoreham PRA	
73.	Controller	General (level, Pr, temp)	All Modes	4.9E-6		8.6E-6	3E-6	8h	HWR Data	
74.	Damper	Containment Fan Cooler System	Fail to function	1.9E-3/d					Zion NPP PSA	
75.	Diesel Engine	DE,6 Cylinder 4 Stroke	Fail to run	6.5 E-3/h	10	6.5E-2	6.5E-4	10 h	IEEE-500	
76.	Diesel Engine	DE,6 Cylinder 4 Stroke	Fail to start	3E-3/d				10 h	IEEE-500	
77.	Diesel Engine	DE,6 Cylinder 4 Stroke	Fail to run	3E-4/h	10	3E-3/h	3E-5/h		WASH-1400 (Data for emergency conditions)	
78.	Diesel Generator	Emergency, AC	Fail to run	3E-3/h	2,10			12 h	Large amount of data has been generated for emergency DGs	
79.	Diesel Generator	Emergency, AC	Fail to start	1E-2/d	3				Assessed	
80.	Diesel Generator	Emergency, AC	Fail to run	2.7E-3/h		3.7E-3	1.3E-3	6.8 h	Old PWR	Fig. 10
81.	Diesel Generator	Emergency, AC	Fail to run	1.4E-3/h		2.9E-3	5.4E-4		EPRI NP 2443	Fig. 9
82.	Diesel Generator	Emergency, AC	Fail to run	6E-3/h					Zion NPP PRA	Fig. 10

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
83.	Diesel Generator	Emergency, AC	Fail to start	7.1E-3/d	4.1				NUREG 4550 Vol.3	Fig. 8
84.	Diesel Generator	Emergency, AC	Fail to start	1.1E-2/d		1.5E-2/d	6.1E-3/d		Old PWR	Fig. 7
85.	Diesel Generator	Emergency, AC	Fail to start	1.2E-2/d				8 h	Swedish Rel. Data	Fig. 8
86.	Diesel Generator	Emergency, AC	Fail to start	1.8E-2/d					Zion NPP PRA	Fig. 7
87.	Fan	Containment Ventilation	Fail to run	6E-6/h		1.1E-5/h	1.9E-6/h		Old PWR	
88.	Fan	Containment Ventilation	Fail to start	3.3E-4/d		7.8E-4	5.0E-5		Old PWR	
89.	Fan	Containment Fan Cooler	Fail to run	3.5E-6/h					Sizewell-B	
90.	Fan	Containment Fan Cooler	Fail to start	2E-3/d					Sizewell-B	
91.	Fan	RB Cooling Unit	Fail to start	5.7E-3/d		1.2E-2	7.8E-4	40 h	Oconee NPP PRA	
92.	Fan	RB Cooling Unit	Fail to run	1.2 E-5/h		2.4E-5/h	1.3E-6	40 h	Oconee NPP PRA	
93.	Fuse		All Modes	1.1E-6/h				2 h	HWR Data	
94	Fuse		Spurious function	3E-6/h		2E-5/h	6E-8/h		NUREG-2815	
95.	Fuse		Spurious function	1E-6/h	10				German Risk Study	
96.	Fuse		Spurious function	1E-6/h	3	3E-6	3E-7		WASH-1400	
97.	Fuse		Fail to open	1E-5/d	3	3E-5/d	3E-6/d		WASH-1400	
98.	Gasket	Metallic	Leakage	4E-7/h	8				German Risk Study	
99.	Generator	AC, Gas Turbine Driven	All Modes	2.8E-3/y					IEEE-500	
100.	Generator	AC, Steam Turbine	Fail to run	7.2E-7/h		1.5 E-6	4E-8/h		IEEE-500	
101.	Generator	AC, Steam Turbine	Fail to start	4.5 E-7/h		9.5 E-7	2E-8/h		IEEE-500	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
102.	Generator	DC	Fail to run	2.4 E-7/h		2.4E-5/h	0		IEEE-500	
103.	Generator	DC	Fail to start	1.3 E-7/h		1.3 E-5	0		IEEE-500	
104.	Heat Exchanger	U-Tube Horizontal Shell& Tube	All Modes	4.8 E-6/h		7.6 E-6/h	2.9 E-6/h		IEEE-500	
105.	Heat Exchanger	U-Tube Horizontal Shell& Tube	All Modes	1.1E-5/h	1.6	1.90E-05	6.8 E-6	24 h	HWR Data All Modes include Plugged, External & Internal Leak, Inadequate Heat Transfer	
106.	Heat Exchanger	U-Tube Vertical Shell & Tube	All Modes	9.3E-6/h		1.4E-5/h	6.50E-6		IEEE-500	
107	Heat Exchanger	U-Tube Vertical Shell & Tube	All Modes	4E-5/h	1.3	5.2E-5/h	3.1E-5	24 h	HWR data	
108	Heat Exchanger	General	Leakage, Shell	3E-6/h	10				NUREG-2815, 2728 etc.	
109	Heat Exchanger	General	Leakage, Tube	3E-9/h		2E-8/h	8E-11/h		NUREG-2815, 2728 etc.	
110	Heat Exchanger	General	Plugged, Blockage	5.7E-6/h	10				NUREG-4550	
111.	Heat Exchanger	Plate	All Modes	40E-6/h					PSA 93 Conf.	
112.	Heater	Feed Water	All Modes	1.3E-5/h				54 h	IEEE-500	
113.	Heater	Pressuriser	Fail to function	2.2E-6/h					IEEE-500	
114.	Indicating Alarm Meter		Fail to function	7.7E-7/h		3.1E-6		2 h	Swedish Data a = 0.0315 b = 41100	
115.	Indicating Alarm Meter		Spurious function	5.6E-7/h		1.1E-5/h	2E-8	2 h	IEEE-500	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
116.	Instrumentation Channel	Transmitter, Amplifier Output Device	Degraded	1E-5/h	10	1E-4	1E-6		WASH-1400	
117.	Instrumentation Channel	Transmitter, Amplifier Output Device	Fail to function	1E-6/h	10	1E-5	1E-7		WASH-1400	
118.	Intake Screen	Service Water System	Plug	3.7E-6/h		9E-6	6.5E-7		Old PWR	
119.	Inverter	General	All Modes	4.2E-2/d	3				NUREG 4550 Vol.1	Fig. 11
120.	Inverter	General	Fail to function	6E-5/h		4E-4	3E-5		NUREG Sources	Fig. 11
121.	Inverter	Solid State 120 V AC	Fail to function	2.1E-5/h		1.9E-4	8.5E-6	4-8 h	NUREG-3831	Fig. 11
122.	Inverter	Static	Fail to function	1.2E-5/h				11 h	Swedish Rel. Data	Fig. 11
123.	Inverter	Static, 1 Phase	Fail to function	1E-6/h		1.2E-5	3E-7		IEEE-500	Fig. 11
124.	Inverter	Static, 3 Phase	Fail to function	3E-6/h		3E-5	1.9E-7		IEEE-500	Fig. 11
125.	Inverter	General	Fail to function	1E-4/h	3				NUREG 2728	Fig. 11
126.	Inverter	General	Fail to function	1.1E-5/h					Zion NPP PRA	Fig. 12
127.	Inverter	Instrument	Fail to function	4.3E-5/h		4.8E-5	4.9E-6		Oconee NPP PRA	Fig. 12
128.	Inverter	Static	Fail to function	5.2E-6/h		2.6E-5		13 h	Swedish Rel. Data	Fig. 12
129.	Iron Chamber		All Modes	3.87E-6/h		5.81E-6/h	2.32E-6/h		IEEE 500	
130.	Lifting & Positioning Equipment	Crane	All Modes	111.7E-6/h					IEEE 500	
131.	Lifting & Positioning Equipment	Hoist	All Modes	70.5E-6/h					IEEE 500	
132.	Motor	HP Emergency Injection Pump Motor	All Modes	1.7E-5/h	1.6	2.9E-5	1.1E-5	223 h	HWR Data	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
133.	Motor	LP Emergency Injection Pump Motor	All Modes	1E-5/h	1.8	2.1E-5	5.7E-6	210 h	HWR Data	
134.	Motor	LP Service Water Pump Motor	All Modes	9.8E-6/h	1.9	2.1E-5	5.1E-6	200 h	HWR Data	
135.	Motor	Aux BFP Motor	All Modes	1.1E-5/h	1.3	1.5E-5	8.6E-6	274 h	HWR Data	
136.	Motor	CEP Motor	All Modes	2.5E- 6/h	1.4	3.6E-6	1.7E-6	161 h	HWR Data	
137.	Motor	Emergency SW Pump Motor	All Modes	8E-6/h	1.4	1.2E-5	5.5E-6	150 h	HWR Data	
138.	Motor	End Shield Tank Cooling Pump Motor	All Modes	1.3E-5/h	1.9	2.7E-5	6E-6	211 h	HWR Data	
139.	Motor	Moderator Pump Motor	All Modes	1.5E-5/h	2	3.4E-5	7.3E-6	227 h	HWR Data	
140.	Motor	PHT Feed Pump Motor	All Modes	1.1E- 5/h	1.9	2.3E- 5	5.7E- 6	154 h	HWR Data	
141.	Motor	PHT Pump Motor	All Modes	1.5E- 5/h	1.7	2.9E- 5	8.7E- 6	170 h	HWR Data	
142.	Motor	SDC Pump Motor	All Modes	1.6E- 5/h	1.8	3.1E- 5	8.6E- 6	184 h	HWR Data	
143.	Motor	BFP Motor	All Modes	1.5E- 5/h	1.6	2.6E- 5	9.5E- 6	194 h	HWR Data	
144.	Motor	AC, General	Fail to run	3.2E-6/h.		3E- 3	0.0	1.8 h	IEEE-500	Fig. 14
145.	Motor	AC, Induction	Fail to run	1.2E- 6/h		1.6E- 3	1E- 8		IEEE-500	Fig. 14
146.	Motor	AC, Split Phase	Fail to run	1.6E- 6/h		1.5E-3/h	1E- 8		IEEE-500	Fig. 14
147.	Motor	AC, Synchronous	Fail to run	7E-7/h		8.4E- 7	5.6E-7		IEEE-500	Fig. 14
148.	Motor	DC General	All Modes	1.5E-5/h		3.7E-4	1.0E-8		IEEE-500	
149.	Motor	General	Fail to start	3E-4/d	3	1E-3	1E-4/d		WASH-1400	Fig. 13
150.	Motor	General	Fail to run	1E-3/h	10	1E-2	1E-4		WASH-1400	Fig. 14

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
151.	Motor	Servo	Fail to function	2.6E-7/h		5.5E-7	8E-8		IEEE-500	
152.	Motor	AC, Synchronous, Single Phase	Fail to start	5.5E-7/h		6.6E-7	4.4E-7		IEEE-500	Fig. 13
153.	Motor	General	Fail to run	2E-6/h	8				German Risk Study	Fig. 14
154.	Motor	General	Fail to run	1E-6/h					Shoreham PRA	Fig. 14
155.	Motor	General	Fail to run	1E-5/h	3	3E-5	3E-6		WASH-1400	Fig. 14
156.	Motor	General	Fail to start	1E-6/h (med)	8				German Risk Study	Fig. 13
157.	Motor Generator	AC, 220V	Fail to function	6.3E-6/h		1.4E-5/h	2.5E-6		Old PWR	
158.	Motor Generator	DC	Fail to function	3E-6/h		2E-5/h	6E-8		NUREG-2815	
159.	Orifice		Plug	3E-4/d	3	1E-3/d	1E-4/d		WASH-1400	
160.	Orifice		Rupture	1E-8/h	10	1E-7	1E-9		WASH-1400	
161.	Penetration	Cable	All Modes	1E-7/h					IEEE-500	
162.	Penetration	Piping	All Modes	8E-8/h					IEEE-500	
163.	Piping	Nuclear < 1″	Rupture	1.2E-9/h-m	1.6	2E-9	7E-10/h-m		HWR Data includes contribution from all Pr. boundary components, e.g- nozzles, fittings & valve body, etc.	
164.	Piping	Nuclear 1-6″	Rupture	7E-11/h-m	2.8	3E-10	2E-11/h-m		HWR Data includes contribution from all pressure boundary compo-	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
									nents, e.g- nozzles, fittings & valve body, etc.	
165.	Piping	Nuclear < 3″	Rupture/ Plug	1E-9/h section	30	3E-8	3E-11/ h		WASH-1400 (Section is defined as avg. length between two discontinuities)	
166.	Piping	Nuclear > 3″	Rupture/ Plug	1E-10/h	30	3E-9	3E-12/h		WASH-1400 (Section is defined as avg. length between two discontinuities)	
167.	Piping	Elbow 4-6″	All Modes	1.9E-5/h		1.9E-3/h	6.3E-7/h		IEEE-500	
168.	Piping	Expansion Joint	Rupture	5.9E-8/h		1.7E-7	1E-8		Old PWR	
169.	Piping	Nozzle	All Modes	1.8E-5/h		2.2E-3	1.8E-6/h		IEEE (The value is a composite of different sizes)	
170.	Piping	Spray Nozzle	Plug (50%)	2.4E-4/d		9E-4/d	9.5E-6/d		Oconee NPP PRA	
171.	Piping	Rupture Diaphragm 10-16"	All Modes	3.3E-6/h					IEEE-500	
172.	Piping	Tees	All Modes	1.9E-5/h		2.2E-3/h	1.7E-6/h		IEEE-500 (Composite of different sizes)	
173.	Piping	Thermowell 6-10"	All Modes	1.8E-5/h		7.3E-5/h	1.8E-6/h		IEEE-500	
174.	Piping	Welds < 4"	All Modes	2.2E-5/h		2.3E-3/h	7.6E-6/h		IEEE-500	
175.	Power Supply	General	Fail to function	1.4E-6/h		2E-6	3E-8/h		IEEE-500	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
176.	Pump	Aux BFP	All Modes	7.6E-5/h	1.6	1.3E-4/h	4.8E-5	11 h	HWR Data (All modes includes External leak, start, run failure, less than rated output)	
177.	Pump	Centrifugal	Fail to run	7.1E-6/h		5.8E-4	0.0		IEEE-500	
178.	Pump	Centrifugal	Fail to start	4.7E-3/y		2.5E-1/y	0.0		IEEE-500	
179.	Pump	CEP	All Modes	5.5E-5/h	1.2	6.8E-5	4.4E-5	16.3 h	HWR Data (based on large no. of failures)	
180.	Pump	Diesel Driven	Fail to start	1E-3/d	3				NUREG 4550	Fig. 15
181.	Pump	Diesel Driven	Fail to run	8E-4/h	30				IREP NUREG 2728	Fig. 16
182.	Pump	Diesel Driven	Fail to run	8E-4/h	10				NUREG 4550	Fig. 16
183.	Pump	Diesel Driven	Fail to start	2.1E-2/d		3E-1/d	4.4E-3/d		NUREG 2886	Fig. 15
184.	Pump	Diesel Driven	Fail to start	3E-3/d					NUREG 1205	Fig. 15
185.	Pump	Diesel Driven, Containment Spray	Fail to run	2.9E-2/h					Zion NPP PRA	Fig. 16
186.	Pump	Diesel Driven, Containment Spray	Fail to start	4.2E-3/d					Zion NPP PRA	Fig. 15
187.	Pump	General	Fail to start	1.8E-5/h	7				German Risk Study	
188.	Pump	General	Fail to run	2.9E-5/h	3.7				German Risk Study	
189.	Pump	Motor Driven	Fail to start	1E-3/d (med)	3	3E-3/d	3E-4/d		WASH - 1400 (Includes Motor)	Fig. 17

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
190.	Pump	Motor Driven	Fail to run	3E-5/h	10	3E-4/h	3E-6/h		WASH - 1400 (Include Motor, Extreme Environ- ment)	Fig. 20
191.	Pump	Motor Driven	Fail to run	1E-3/h	10	1E-2/h	1E-4/h		NUREG 2815 (Extreme Environ- ment)	Fig. 20
192.	Pump	Motor Driven	Fail to run	3E-3/h		2E-2/h	6E-5/h		NUREG 2815 (Normal Environ- ment)	Fig. 20
193.	Pump	Motor Driven	Fail to run	1E-4/h		5E-4	2E-6		NUREG 2815	Fig. 20
194.	Pump	Motor Driven	Fail to start	1E-5/h		5E-5/h	2E-7/h		NUREG 2815	Fig. 17
195.	Pump	Motor Driven	Fail to start	5.1E-4/d		7.1E-4/d	3.4E- 4/d		NUREG 1205	Fig. 19
196.	Pump	Motor Driven	Fail to start	3E-3/d	10				IREP NUREG 2728	Fig. 17
197.	Pump	Motor Driven, Centrifugal, Floor rate 30 kg/s	Fail to start	1.4E-3/d		8.3E-3/d		2 h	Swedish Rel. Data	Fig. 19
198.	Pump	Motor Driven, Centrifugal, Floor rate 120-240 kg/s	Fail to start	5.1E-3/d		2.1E-2/d		3 h	Swedish Rel. Data	Fig. 19
199.	Pump	Motor Driven	Fail to start	1.4E-3/d		3.2E-3/d	2E-4/d		Old PWR	Fig. 18
200.	Pump	Motor Driven, General	Fail to start	3E-3/d	10				NUREG 4550 Vol.1	Fig. 19
201.	Pump	Motor Driven, General	Fail to run	3E-5/h	10				NUREG 4550 Vol.1	Fig. 20

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
202.	Pump	Motor Driven, HP	Fail to start	4E-3/d					Sizewell B	Fig. 19
203.	Pump	Motor Driven, Containment Spray	Fail to start	5.5E-3/d		6E-4/d	5E-2/d		NUREG 2886	Fig. 19
204.	Pump	Motor Driven, LP	Fail to start	2E-3/d					Sizewell B	Fig. 17
205.	Pump	Motor Driven, Reciprocating	Fail to start	4E-3/d		2.1E-2/d		7 h	Swedish Rel. Data	Fig. 19
206.	Pump	Motor Driven, Recirculation	Fail to run	3.4E-5/h		8.1E-5/h	2.8E-6/h	4.2 h	Old PWR	Fig. 21
207.	Pump	Motor Driven, Recirculation	Fail to start	1.0E-3/d		2.5E-3/d	1.3E-4/d		Old PWR	Fig. 18
208.	Pump	Motor Driven, Rh	Fail to start	6.5E-3/d		1.7E-2/d	7.1E-4/d		Old PWR	Fig. 18
209.	Pump	Motor Driven, Well Water	Fail to run	3.4E-5/h		8.0E-5/h	2.8E-6/h		Old PWR	Fig. 21
210.	Pump	Motor Driven, Well Water	Fail to start	3.7E-3/d		8.4E-3/d	5.3E-4/d		Old PWR	Fig. 18
211.	Pump	Turbine Driven	Fail to start	1E-4/h		5E-4/h	2E-6		NUREG 2815	Fig. 23
212.	Pump	Turbine Driven	Fail to run	2E-5/h		1E-4/h	8E-6/h		NUREG 2815	
213.	Pump	Turbine Driven, Aux. FW	Fail to start	7.1E-3/d	4.6				NUREG 4550 Vol.3	
214.	Pump	Turbine Driven, Aux. FW	Fail to start	2.3E-2/d					Zion NPP PRA	Fig. 23
215.	Pump	Turbine Driven, Centrifugal	Fail to start	3.3E-2/d				8 h	Swedish Rel. Data	Fig. 23
216.	Pump	Turbine Driven, Emergency. FW	Fail to start	3.8E-2/d		5.8E-2/d	1.2E-2/d	24 h	Oconee NPP PRA	Fig. 23

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
217.	Pump	Diesel Driven	Fail to run	8.0E-4/h	10				NUREG 4550	Fig. 16
218.	Pump	Diesel Driven, Containment Spray	Fail to run	2.9E-2/h					Zion NPP PRA	Fig. 16
219.	Pump	Diesel Driven	Fail to run	8.0E-4/h	30				IREP NUREG 2728	Fig. 16
220.	Pump	Diesel Driven	Fail to run	8.0E-4/h					NUREG 4550 Vol 1	
221.	Pump	Diesel Driven	Fail to start	2.1E-2/d		3.0E-1/d	4.0E-3/d		NUREG 2886	Fig. 15
222.	Pump	Diesel Driven	Fail to start	1.0E-3/d	3				IREP NUREG 2728	Fig. 15
223.	Pump	Diesel Driven	Fail to start	3.0E-3/d					NUREG 1205	Fig. 15
224.	Pump	Diesel Driven, Containment Spray	Fail to start	4.2E-3/d					Zion NPP PRA	Fig. 15
225.	Pump	Diesel Driven	Fail to start	1.0E-3/d	3				NUREG 4550 Vol 1	Fig. 15
226.	Pump	Diesel Driven	Fail to start	3.6E-4/d		1.8E-3/d	7.2E-5/d		NUREG 2815	Fig. 15
227.	Rectifier	Excitation, > 600 V	Fail to function	1.3E-6/h		3.6E-6/h	3.2E-7/h		IEEE-500	Fig. 24
228.	Rectifier	Precipitator, > 600 V	Fail to function	1.4E-6/h		4.1E-6/h	3.6E-7/h		IEEE-500	Fig. 24
229.	Rectifier	Static	Fail to function	1.4E-6/h		5.8E-6/h		16 h	Swedish Rel. Data	Fig. 24
230.	Rectifier	General	Fail to function	1.0E-6/h		6.0E-6/h	6.0E-7/h		VVER Data	Fig. 24
231.	Relay	General	Fail to function (Fail to energise)	1.0E-4/d (med)	3	3E-4/d	3E-5/d		WASH - 1400	
232.	Relay	General	Fail to remain in position (failure	1.0E-7/h	3	3E-7/h	3E-8/h		WASH - 1400	Fig. 25

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
			of NC contacts by opening)							
233.	Relay	General	Fail to close (failure of NO cont-acts to close)	3E-7/h	3	1E-6/h	1E-7/h		WASH - 1400	
234.	Relay	Power	Fail to function	1E-6/h	15				German Risk Study	
235.	Relay	Protective	Fail to remain in position (spurious opera-tion)	3E-8/h		2.4E-4/h	0.0	55 h	IEEE-500	Fig. 25
236.	Relay	Protective	Fail to close	3E-6/y		6E-6/y	8.5E-7/y	55 h	IEEE-500	
237.	Relay	Protective	Fail to open	5.3E-7/y		1.1E-6	1.2E-7/y	55 h	IEEE-500	
238.	Relay	Time Delay	All Modes	1.9E-6/h		2.9E-6	1.4E-6	3 h	HWR Data	
239.	Relay	Time Delay	Fail to remain in position (prema-ture transfer)	1E-6/h		5E-6	2E-8/h		NUREG 2815	Fig. 25
240.	Relay	Coil	Short circuit (short to power)	1E-8/h	10	1E-7/h	1E-9/h	(3 h as per HWR)	WASH - 1400, HWR Data	
241.	Relay	Coil	Open Circuit	1E-7/h	10	1E-6/h	1E-8/h		WASH - 1400, HWR Data	
242.	Relay	Contacts	Short Circuit	1E-8/h		1E-7/h		3 h	HWR Data	
243.	Relay	Contacts	Short Circuit	1E-8/h	10	1E-7	1E-9		WASH - 1400	
244.	Relay	Core flux	Degraded	1.6E-7/h		2.1E-7/h	1.1E-7/h		NUREG - 1740 (PWR rate is 6 times	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
									of BWR rate)	
245.	Relay	Core flux	Fail to function	2.9E-7/h		3.5E-7/h	2.2E-7/h		PWR rate is order of magnitude higher	
246.	Relay	Control	Fail to remain in position	4.0E-8/h		2.5E-4/h	1.0E-8/h		IEEE 500	Fig. 25
247.	Sensor	Flow	Fail to function	3.3E-3/d (mean)		7.6E-3/d		2 h	Swedish Rel. Data	
248.	Sensor	Flow	Spurious function	4.3E-6/h		2.3E-5/h		2 h	Swedish Rel. Data	
249.	Sensor	Level	Fail to function	2.1E-4/d				3 h	Swedish Rel. Data	
250.	Sensor	Level	Spurious function	8.2E-7/h		4.6E-6/h		3 h	Swedish Rel. Data	
251.	Sensor	Pressure	Fail to function	7E-4/d				2 h	Swedish Rel. Data	
252.	Sensor	Pressure	Spurious function	8.7E-7/h		2.2E-6/h		2 h	Swedish Rel. Data	
253.	Sensor	Pressure, Differential	Fail to function	5.1E-3/d		2.6E-2/d		3 h	Swedish Rel. Data	
254.	Sensor	Pressure, Differential	Spurious function	3.2E-7/h				3 h	Swedish Rel. Data (2.5E-6 in case of PWR data)	
255.	Sensor	Temperature	Degraded	7.4E-7/h		1.2E-6/h	4.4E-7/h		NUREG - 1740 (Only PWR rate)	
256.	Sensor	Temperature	Fail to function	1.7E-6/h		2.4E-6	1.2E-6/h		NUREG - 1740 (Only PWR rate)	
257.	Sensor	Temperature	Fail to function	1.9E-3/d		1.1E-2/d		3 h	Swedish Rel. Data	
258.	Sensor	Temperature	Spurious function	7.1E-7/h		1.8E-6/h		3 h	Swedish Rel. Data	
259.	Sensor	General	Degraded	1.8E-6/h		2E-6/h	1.6E-6/h		NUREG - 1740	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
260.	Sensor	General	Fail to function	3.4E-6/h		3.7E-6/h	3.1E-6/h		The unit receives signal from the sensor & feeds the proper input to the com-parator	
261.	Signal Conditioning Unit	General	Plug	3E-5/h		2E-4/h	6E-7/h		NUREG 2185	
262.	Signal Conditioning Unit	General	Plug	3E-5/h	10				NUREG 2185	
263.	Strainer/ Filter	Flow	Degraded	3.4E-7/h				4h	HWR Data	
264.	Strainer/ Filter	Flow	Fail to function	1.7E-6/h				4h	HWR Data	
265.	Strainer/ Filter	Y-Type	All Modes	1.43E-6/h		4.3E-6/h	0.6E-6/h	0.5h	IEEE -500	
266.	Switch	Flow	Spurious function	1.6E-6/h				4h	HWR Data	
267.	Switch	Flow	Fail to function	9.8E-7/h		1.8E-6	8E-8/h	6h	IEEE-500	Fig. 26
268.	Switch	Flow	Spurious function	8.6E-7		1.6E-6	8E-8/h	6h	IEEE-500	
269.	Switch	Level	Degraded	7.2E-7				4h	HWR Data	
270.	Switch	Level	Fail to function	1.4E-6				4h	HWR Data	Fig. 26
271.	Switch	Level	Spurious function	3.2E-6				4h	HWR Data	
272.	Switch	Level	Spurious function	1.6E-6		3E-6	7.7E-7	1.5h	IEEE-500	
273.	Switch	Level	Fail to function	3E-8/y		6E-8/y	0.0	1.5h	IEEE-500	Fig. 26
274.	Switch	Limit	All Modes	3.3E-6/h	1.6	4E-6/h	2.9E-6/h	4h	HWR Data	
275.	Switch	Limit	Fail to function	3E-4/d	3	1E-3/d	1E-4/d		WASH-1400	Fig. 26
276.	Switch	Manual	Fail to change Position	1E-5/d	3	3E-5/d	3E-6/d		WASH-1400	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
277.	Switch	Manual	Fail to change Position	4.6E-7				3h	HWR Data	
278.	Switch	Manual	Spurious function	3.4E-7				3h	HWR Data	
279.	Switch	Pressure	All Modes	5.7E-6/h	1.4	8.1E-6	4.1E-6	4h	HWR Data (equal contributions from spurious & fail to operate modes)	
280.	Switch	Pressure	Fail to function	4.0E-7/h		1.9E-6	1E-8	6h	IEEE-500	Fig. 26
281.	Switch	Pressure	Spurious function	7E-8/h		3.1E-7/h	0	6h	IEEE-500	
282.	Switch	Pressure	Fail to function	1E-4/d	3	3E-4/d	3E-5/d		WASH-1400	Fig. 26
283.	Switch	Temperature	Degraded	1.8E-7/h					HWR Data	
284.	Switch	Temperature	Fail to function	5.3E-7/h					HWR Data	Fig. 26
285.	Switch	Temperature	Spurious function	5.5E-7/h					HWR Data	
286.	Switch	Temperature	Fail to function	2E-7/h		3.9E-7/h	5E-8/h	5 h	IEEE-500	Fig. 26
287.	Switch	Temperature	Spurious function	2.3E-7/h		4.5E-7/h	6E-8/h	5 h	IEEE-500	
288.	Switch	Torque	Fail to function	2E-7/h		1E-6/h	6E-8/h		NUREG 2815	Fig. 26
289.	Switch	Torque	Fail to function	1E-4/d	3	3E-4/d	3E-5/d		WASH - 1400	Fig. 26
290.	Switch	Flow	Fail to function	1.7E-6/h				4 h	HWR Data	Fig. 26
291.	Switch	Flow	Fail to function	2.6E-7/h					Shoreham PRA	Fig. 26
292.	Switch	Limit	Fail to function	6.0E-6/h		4.0E-5/h	8.0E-7/h		NUREG 2815	Fig. 26
293.	Switch	Limit	Fail to function	1.0E-4/d	3				IREP NUREG 2728	Fig. 26
294.	Switch	Pressure	Fail to function	3.1E-6/h	1.5	5.0E-6/h	2.0E-6/h		HWR Data	Fig. 26

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
295.	Switch	Pressure	Fail to function	1.0E-4/d	3				IREP NUREG 2728	Fig. 26
296.	Switch	Pressure	Fail to function	1.4E-7/y		3.0E-7/y	3.0E-8/y	0.6 h	IEEE-500	Fig. 26
297.	Switch	Temperature	Fail to function	2.3E-6/h					Shoreham PRA	Fig. 26
298.	Switch	Torque	Fail to function	1.0E-4/d	3				IREP NUREG 2728	Fig. 26
299.	Tank	FWST RWST	Rupture	2.7E-8/h		7.6E-8/h	7E-10/h		Old PWR	
300.	Transformer	Auto, 3phase All Voltage Levels	Fail to function	1.5E- 5/h		2.7E-6/h	4E-7		IEEE-500	Fig. 27
301.	Transformer	Auto, 1phase All Voltage Levels	Fail to function	4.5E-7/h		2E-6/h	1.3E-7/h		IEEE-500	Fig. 27
302.	Transformer	General	Fail to function	1.5E-6/h	5				German Risk Study	
303.	Transformer	General	Open/ Close	1E-6/h	3	3E-6/h	1E-7/h		WASH-1400	Fig. 27
304.	Transformer	High Voltage Outdoor	Fail to function	1.4E-6/h		3.5E-6/h	1.5E-7/h	10.8 h	IEEE-500	Fig. 27
305.	Transformer	Instrument, Current, All Levels	Fail to function	2.6E-7/h		4.9E-7/h	1.1E-7/h		IEEE-500	Fig. 27
306.	Transformer	Instrument, Voltage All Levels	Fail to function	4.2E-7/h		1.0E-6/h	2.7E-7/h		IEEE-500	Fig. 27
307.	Transformer	Main, Power Generator or Unit Trans-former, All Voltage Levels, 1phase	Fail to function	2.8E-7/h		1.8E-6/h	3E-8/h		IEEE-500 (failure mode includes: 1) Auto Removal 2) Manual Removal 3) Open Ckt. 1) is dominating	Fig. 27
308.	Transformer	Main, Power, Generator or Unit Trans-	Fail to function	5.8E-7/h		1.6E-6/h	1.0E-7		IEEE-500 (failure mode	Fig. 27

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
		former, All Voltage Levels, 3 Phase							includes: 1) Auto Removal 2) Manual Removal 3) Open Ckt; 1) is dominating	
309.	Transformer	Flow, level, Pr. (DP Cell)	All Modes	9.1E-6/h	1.2	4.8E-6/h	3.5E-6/h	3 h	HWR Data (includes equal contributions from degraded & fail to function modes)	
310.	Transformer	Pr. Difference	Fail to function	1.4E-6/h		8.3E-6/h		3 h	HWR Data (includes equal contributions from degraded & fail to function modes)	Fig. 28
311.	Transformer	220/120V	Fail to function	2.5E-6/h		5.2E-5/h	5.1E-7/h		Old PWR	Fig. 28
312.	Transformer	50/6 kV	Fail to function	1.3E-6/h		2.5E-6/h	2.8E-7/h		Old PWR	Fig. 28
313.	Transformer	6kV/380 V	Fail to function	4.9E-7/h		1.1E-6/h	8.6E-8/h		Old PWR	Fig. 28
314.	Transformer	8kV/6kV	Fail to function	1.3E-6/h		2.5E-6/h	2.8E-7/h		Old PWR	Fig. 28
315.	Transformer	Dry, 4kV/ 600V	Fail to function	4.8E-7/h		1.2E-6/h	2.1E-8/h	10.8 h	Oconee NPP PRA	Fig. 28
316.	Transformer	Dry, 600V/ 208V	Fail to function	3.1E-7/h		7.8E-7/h	5.7E-9/h	10.8 h	Oconee NPP PRA	Fig. 28
317.	Transformer	General	Fail to function	1.7E-6/h					Zion NPP PRA	Fig. 28
318.	Transformer	General, Voltage upto 6 kV	Fail to function	7.9E-7/h		3.5E-6/h		10 h	Swedish Rel. Data a = 0.0345, b = 43600	Fig. 27
319.	Transformer	Main/Unit, Single Phase, 2- 30 kV	Fail to function	2.2E-7/h		3.9E-7/h	9.5E-8/h		IEEE-500	Fig. 27

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
320.	Transformer	Main/Unit, Single Phase, 146-242kV	Fail to function	3.2E-7/h		6.2E-7/h	2.5E-7/h		IEEE-500	Fig. 27
321.	Transformer	Main/Unit, Single Phase, 347-550kV	Fail to function	1.2E-6/h		1.9E-6/h	5.3E-7/h		IEEE-500	Fig. 27
322.	Transformer	Main/Unit, Three Phase, 146-242kV	Fail to function	1.1E-6/h		1.5E-6/h	5.0E-7/h		IEEE-500	Fig. 27
323.	Transformer	Main/Unit, Three Phase, 347-550kV	Fail to function	7.4E-7/h		1.4E-6/h	4.3E-7/h		IEEE-500	Fig. 27
324.	Transformer	Main, 400kV /130 kV	Fail to function	3.5E-6/h		1.8E-5/h		38 h	Swedish Rel. Data a = 0.195, b = 56200	Fig. 27
325.	Transformer	Regulating, 120 V AC	Fail to function	2E-6/h		4.2E-6/h	4.4E-9/h		Oconee NPP PRA	Fig. 27
326.	Transformer	Station Service, Single Phase, All Voltage Levels	Fail to function	2.7E-7/h		2.3E-6/h	8E-8/h		IEEE-500	Fig. 27
327.	Transformer	Station Service, Thee Phase, All Voltage Levels	Fail to function	4E-7/h		1.4E-6/h	1.1E-7/h		IEEE-500	Fig. 27
328.	Transformer	Start up & Auxiliary, Voltage Levels 130/6kV, 70/6kV, 20/6kV	Fail to function	2.0E-6/h		1.1E-5/h		5 h	Swedish Rel. Data a = 0.101, b = 51800	Fig. 27
329.	Transformer	Substation Liquid Filled, Single Phase, All Voltage Levels	Fail to function	5.1E-7/h		2.6E-6/h	9.0E-8/h		IEEE-500	Fig. 27
330.	Transformer	Substation Liquid Filled, Three Phase, All Voltage Levels	Fail to function	8.0E-7/h		1.9E-6/h	3.1E-7/h		IEEE-500 (Failure Modes include 1) Automatic removal, 2) Manual	Fig. 27

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
									removal, 3) Open circuit. I) is dominating	
331.	Transmitter	Flow	Fail to function	1.5E-6/h		2.8E-6/h	6.2E-7/h		IEEE-500	Fig. 29
332.	Transmitter	Flow	Fail to function	3.4E-6/h		1.9E-9/h		3 h	Swedish Rel. Data a = 0.101, b = 30200	Fig. 29
333.	Transmitter	Flow, Level, Pr. (DP Cell)	Fail to function	1.2E-6/h	1.3	1.6E-6/h	9E-7/h		HWR Data	Fig. 29
334.	Transmitter	Flow, Level, Pr. General	Fail to function	1.9E-6/h		2.3E-3/h	1.6E-6/h		NUREG 1740 (PWR rate is two orders higher than BWR rate)	Fig. 29
335.	Transmitter	Level	Fail to function	1.4E-6/h		7.1E-7/h			IEEE-500	Fig. 29
336.	Transmitter	Level	Fail to function	3.8E-6/h		2.0E-5/h		2 h	Swedish Rel. Data a = 0.188, b = 49500	Fig. 29
337.	Transmitter	Pressure	Fail to function	8.8E-7/h		1.7E-6/h	2.0E-7/h		IEEE-500	Fig. 29
338.	Transmitter	Pressure	Fail to function	1.8E-6/h		1.0E-5/h		2 h	Swedish Rel. Data a = 0.056, b = 30500	Fig. 29
339.	Transmitter	Pressure Difference	Fail to function	1.4E-6/h		8.3E-6/h		3 h	Swedish Rel. Data a = 0.0942, b = 66200	Fig. 29
340.	Transmitter	Temperature	Fail to function	3.7E-7/h		3.3E-6/h	1.9E-7/h		IEEE-500 (Failure modes include 1) zero or maximum output 2) no change of output. 1) is domi-	Fig. 29

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
341.	Transmitter	Temperature	All Modes	4.9E-6/h	1.7	9.2E-6	2.7E-6	3 h	HWR Data	Fig. 29
342.	Transmitter	Temperature	All Modes	7.4E-7/h		6.5E-6	3.6E-7		IEEE-500 (Erratic or high out-put dominant)	Fig. 29
343.	Transmitter	Temperature	Fail to function	2.8E-6/h		1.5E-5		3 h	Swedish Rel.Data	Fig. 29
344.	Turbine	Combustion (Gas & Oil)	All Modes	5.7E-4/h		2E-3/h	2E-5		IEEE-500	
345.	Turbine	Steam Driven	All Modes	2.1E-4/h				81 h	IEEE-500	
346.	UPS	Single &Three Phase Static Invertors	All Modes	13.4E-6		100E-6/h	0.63E-6	2.5 h	IEEE-500	
347.	Valve	Butterfly	All Modes	1.2E-6/h		3.5E-4	3E-8/h	19 h	IEEE-500	
348.	Valve	Condenser Steam Discharge	All Modes	2.3E-5/h	1.3	3.1E-5/h	1.7E-5/h	12 h	HWR Data	
349.	Valve	CSDV	Fail to close	3.2E-6/h	2	7.3E-6/h	1.6E-6	5 h	HWR Data	
350.	Valve	CSDV	Fail to open	6.3E-6/h	1.7	1.1E-5/h	3.7E-6	5 h	HWR Data	
351.	Valve	CSDV	External Leak	4.8E-6/h	1.8	9.4E-6	2.6E-6	42 h	HWR Data	
352.	Valve	Diaphragm	All Modes	2.8E-6/h		6.2E-5	1.2E-6/h	9 h	IEEE-500	
353.	Valve	Flow Control 1/2″	All Modes	5.5E-6/h		1.0E-5	2E-6	I h	IEEE-500	
354.	Valve	Gate	All Modes	1.9E-6/h		4.6E-5	1.7E-7	3.3 h	IEEE-500	
355.	Valve	Globe	All Modes	3.5E-6/h		1.7E-4	9E-8	8 h	IEEE-500	
356.	Valve	High Pressure Steam Dump	Fail to change position	4E-2/d	10				German Risk Study	
357.	Valve	Pressure Relief System Pilot Valve	Fail to close	1.2E-3/d		6.8E-3/d			Swedish Rel. Data	

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
358.	Valve	Pressure Relief System Pilot Valve	Fail to open	8.3E-3/d		4.7E-2/d			Swedish Rel Data	
359.	Valve	Pressure Regulating	All Modes	1.3E-6/h	1.2	1.6E-6	1.1E-6	10 h	HWR Data (All modes include: 1) External leak 2) Fail to operate 3) Fail to open 4)Fail closed 5) Out of calibration 6) Unspecified. Dominant 3 & 4 and Negligible 1)	
360.	Valve	Relief	Fail to remain in position (Premature opening)	1E-5/h	3	3E-6/h	3E-6/h		WASH - 1400	
361.	Valve	Relief	Fail to open	1E-5/d	3	3E-5/d	3E-6/d		WASH - 1400	
362.	Valve	Relief	Fail to close, given open	2E-2/d	3				IREP NUREG 2728	
363.	Valve	Relief	Fail to remain in position (Premature opening)	3E-6/h					IEEE-500	
364.	Valve	Air Operated	Fail to change position	3E-4/d	3	1E-3/d	1E-4/d		WASH-1400	Fig. 30
365.	Valve	Air Operated	Fail to remain in position	1E-4/d	3	3E-4/d	3E-5/d		WASH-1400	Fig. 33
366.	Valve	Air Operated	Rupture	1E-8/h	10	1E-7/h	1E-9/h		WASH-1400	
367.	Valve	Air Operated	Fail to change position	4.3E-5/h	23				German Risk Study	Fig. 30

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
368.	Valve	Air Operated, Butterfly> 24"	Fail to change position	2.6E-3/d	1.3	3.4E-3/d	2E-3/d	6 h	HWR Data	Fig. 31
369.	Valve	Air Operated	Fail to change position	1.6E-3/d		3.1E-3/d	3.2E-4/d		Oconee NPP PRA	Fig. 31
370.	Valve	Air Operated	Fail to change position	1.4E-3/d					Zion NPP PRA	Fig. 31
371.	Valve	Air Operated, Globe 2-6"	Fail to change position	5.4E-4/d	1.3	7.0E-4/d	4.0E-4/d		HWR Data	Fig. 31
372.	Valve	Air Operated, Globe < 2"	Fail to change position	3.6E-4/d	1.3	5.0E-4/d	2.8E-4/d		HWR Data	Fig. 31
373.	Valve	Air Operated	Fail to change position	6.5E-3/d					Swedish Rel. Data	Fig. 30
374.	Valve	Air Operated, Purge Isolation	Fail to open	1.3E-3/d		2.4E-3/d	4.6E-4/d		Old PWR	Fig. 32
375.	Valve	Air Operated, Vent Isolation	Fail to open	1.1E-2/d		2.0E-2/d	4.0E-3/d		Old PWR	Fig. 32
376.	Valve	Air Operated	Fail to open	8.4E-4/d		1.4E-3/d	3.5E-4/d		Old PWR	Fig. 32
377.	Valve	Air Operated	Fail to open	1.5E-4/d		3.6E-4/d			Swedish Rel. Data	Fig. 32
378.	Valve	Air Operated	Fail to remain in position	1.2E-7/h		2.7E-7/h	1.4E-8/h		Old PWR	Fig. 33
379.	Valve	Air Operated, Purge Isolation	Fail to remain in position	2.0E-7/h		5.0E-7/h	1.5E-8/h		Old PWR	Fig. 33
380.	Valve	Air Operated	Fail to remain in position	5.5E-6/h		1.2E-5/h	7.7E-7/h		Old PWR	Fig. 33
381.	Valve	Air Operated, Vent Isolation	Fail to remain in position	2.2E-7/h		5.5E-7/h	1.6E-8/h		Old PWR	Fig. 33
382.	Valve	Air Operated, Butterfly> 24"	Fail to remain in position	7.2E-6/h	1.3	9.3E-6/h	5.7E-6/h		HWR Data	Fig. 33

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
383.	Valve	Air Operated	Fail to remain in position	3.0E-7/h	3	1.0E-6/h	1.0E-7/h		WASH - 1400	Fig. 33
384.	Valve	Air Operated	Fail to remain in position	8.0E-7/h		2.3E-6/h	3.9E-8/h		Oconee NPP PRA	Fig. 33
385.	Valve	Air Operated	Fail to remain in position	1.1E-7/h					Zion NPP PRA	Fig. 33
386.	Valve	Hydraulic, General	Fail to change position	1E-3/d	3				NUREG 4550, Vol. 1	
387.	Valve	Hydraulic, General	External Leak (Plugged)	4E-5/d	3				NUREG 4550, Vol. 1	
388.	Valve	Manual	Fail to change position (fail to operate)	6.3E-5/d		1.6E-4/d	2.1E-5/d		NUREG 1363	Fig. 38
389.	Valve	Manual	Fail to change position	7.2E-5/d		3.6E-4/d	2.8E-5/d		NUREG 2815	Fig. 38
390.	Valve	Manual	Fail to change position	1E-4/d	3				IREP NUREG 2728	Fig. 38
391.	Valve	Manual	Fail to change position	1.0E-4/d (med.)	3	3E-4/d	3E-5/d		WASH-1400	Fig. 38
392.	Valve	Manual	Fail to change position	7E-5/y					IEEE-500	Fig. 38
393.	Valve	Manual	Fail to remain in position	1.7E-8/h		4.3E-8/h	1.4E-9/h		Old PWR	Fig. 39
394.	Valve	Manual	Fail to remain in position	3.1E-8/h		9.8E-8/h	1.5E-9/h		Old PWR	Fig. 39
395.	Valve	Manual	Fail to remain in position	2.8E-7/h (med.)	3	8E-7/h	8E-8/h		WASH-1400	Fig. 39
396.	Valve	Manual	Fail to remain in position	1E-7/h		5E-7/h	2E-8/h		VVER Data	Fig. 39

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
397.	Valve	Manual	Fail to remain in position	1E-4/d	3	3E-4/d	3E-5/d		WASH-1400, IREP NUREG 2728	Fig. 39
398.	Valve	Manual	Fail to remain in position	8.9E-8/h		2.4E-7	4.8E-9		Oconee NPP PRA	Fig. 39
399.	Valve	Manual	Fail to change position	2E-7/h		1E-6/h	8E-8/h		NUREG - 2815	Fig. 38
400.	Valve	Manual	Fail to change position	4.7E-6/h	12				German Risk Study	Fig. 38
401.	Valve	Manual	Fail to change position	6E-5/y					IEEE-500	Fig. 38
402.	Valve	Manual	Leakage, External Leak (fails from plugging)	4E-5/d	3				NUREG - 4550	
403.	Valve	Manual	Leakage, External Leak (fails from plugging)	3E-8/h					IEEE-500	
404.	Valve	Motor Operated	Fail to change position	1E-3/d	3	3E-3/d	3E-4/d		WASH - 1400	Fig. 40
405.	Valve	Motor Operated	Fail to change position	1.7E-5/h (5.4E-3/d)	3				German Risk Study	Fig. 40
406.	Valve	Motor Operated	Fail to change position	3E-3/d	10				NUREG 4550	Fig. 40
407.	Valve	Motor Operated	Fail to change position	4E-3/y					IEEE-500	Fig. 40
408.	Valve	Motor Operated MSIV, Gate	Fail to change position	6.8E-3/d	4				German Risk Study	Fig. 40

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
409	Valve	Motor Operated PWR	Fail to change position	4.1E-3/d		4.9E-3/d	3.4E-3/d		NUREG 1363	Fig. 40
410	Valve	Motor Operated, Control	Fail to change position	2.5E-3/d		1.6E-1/d		4 h	Swedish Rel. Data	Fig. 40
411	Valve	Motor Operated, BWR	Fail to change position	8E-3/y					IEEE 500	Fig. 40
412	Valve	Motor Operated, PWR	Fail to change position	4E-3/y					IEEE 500	Fig. 40
413	Valve	Motor Operated, Isolation, 100-200 mm	Fail to change position	6.3E-3/d		3.7E-2/d		4 h	Swedish Rel. Data	Fig. 40
414	Valve	Motor Operated, Isolation, > 200 mm	Fail to change position	7.2E-3/d		4.2E-2/d		5 h	Swedish Rel. Data	Fig. 40
415	Valve	Motor Operated, Isolation, < 100 mm	Fail to change position	7.9E-3/d		3.6E-2/d		4 h	Swedish Rel. Data	Fig. 40
416	Valve	Motor Operated, Regulating	Fail to change position	3.6E-3/d	7				German Risk Study	Fig. 40
417	Valve	Motor Operated	Fail to change position	1.4E-3/d					Sizewell B	Fig. 40
418	Valve	Motor Operated	Fail to change position	6E-4/d		3E-3/d	1E-2/d		VVER Data	Fig. 40
419	Valve	Motor Operated, Chemical Volume Control System	Fail to change position	3.7E-3/d					Zion NPP PRA	Fig. 41
420	Valve	Motor Operated	Fail to change position	6.4E-3/d		7.7E-3/d	4.5E-3/d		Oconee NPP PRA	Fig. 41
421	Valve	Motor Operated	Fail to change position	1.6E-3/d					Zion NPP PRA	Fig. 41
422	Valve	Motor Operated, Condensate Cooling	Fail to change position	1E-1/d		1.6E-1/d	2.7E-2/d		Oconee NPP PRA	Fig. 41

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
		Water System								
423.	Valve	Motor Operated, Containment Spray	Fail to change position	5.7E-3/d					Zion NPP PRA	Fig. 41
424.	Valve	Motor Operated, Butterfly, 12-24"	Fail to change position	1E-3/d	1.4	1.4E-3/d	7E-4/d	10 h	HWR Data	Fig. 41
425.	Valve	Motor Operated, Butterfly, 2-6"	Fail to change position	3.2E-5/d	2.7	1E-4/d	1.2E-5/d	1 h	HWR Data	Fig. 41
426.	Valve	Motor Operated, Butterfly, 6-12"	Fail to change position	1.3E-3/d	1.3	1.7E-3/d	1E-3/d	3 h	HWR Data	Fig. 41
427.	Valve	Motor Operated, Gate, 12-24"	Fail to change position	7E-4/d	1.2	8E-4/d	5.8E-4/d	21 h	HWR Data	Fig. 41
428.	Valve	Motor Operated, Globe, 2-6"	Fail to change position	3.5E-4/d	1.1	4E-4/d	3.2E-4/d	5 h	HWR Data	Fig. 41
429.	Valve	Motor Operated, Isolation, 100-200 mm	Fail to change position	1.7E-3/d					Swedish Rel. Data	Fig. 41
430.	Valve	Motor Operated, Isolation, > 200 mm	Fail to change position	3.3E-3/d				8 h	Swedish Rel. Data	Fig. 41
431.	Valve	Motor Operated, Isolation, < 100 mm	Fail to change position	5.3E-3/d				3 h	Swedish Rel. Data	Fig. 41
432.	Valve	Motor Operated	Fail to remain in position	2E-7/h		1E-6/h	8E-8/h		NUREG 2815	Fig. 42
433.	Valve	Motor Operated	Fail to remain in position	7.3E-8/h		1.6E-7/h	9.1E-9/h		Old PWR	Fig. 43
434.	Valve	Motor Operated	Fail to remain in position	1.2E-7/h		3.6E-7/h	5.8E-9/h		Oconee NPP PRA	Fig. 43

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
435.	Valve	Motor Operated	Fail to remain in position	5.3E-8/h					Zion NPP PRA	Fig. 43
436.	Valve	Motor Operated	Fail to remain in position (Exce-ssive Leakage though the Valve)	3.1E-8/h					Zion NPP PRA	Fig. 43
437.	Valve	Motor Operated	Fail to remain in position (Failed Closed)	1.5E-7/h					Shoreham PRA	Fig. 42
438.	Valve	Motor Operated	Fail to remain in position (Failed Closed)	1.6E-7/h					Shoreham PRA	Fig. 42
439.	Valve	Motor Operated	Fail to remain in position	2E-7/h		4E-7/h	5E-8/h		VVER Data	Fig. 42
440.	Valve	Motor Operated	Fail to remain in position	3E-7/h	3	1E-6/h	1E-7/h		WASH - 1400	Fig. 42
441.	Valve	Motor Operated	Rupture (External Leakage)	2E-6/h					Sizewell-B	
442.	Valve	Motor Operated	Rupture (External Leakage)	1E-8/h	10	1E-7	1E-9		WASH - 1400	
443.	Valve	Motor Operated	External Leakage (Plugging)	4E-5/d	3				NUREG 4550	
444.	Valve	Motor Operated	External Leakage (Plugging)	1E-7/h					IEEE-500	
445.	Valve	Motor Operated, Regulating	Fails to Change position	1E-5/h	7				German Risk Study	Fig. 40
446.	Valve	Primary Relief	Fail to Close	3.1E-3/d		4.7E-3/d	2.1E-3/d		NUREG 1363	Fig. 45

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
			(Given Open)							
447.	Valve	Power Operated Relief (PORV)	Fail to open	2.8E-6/h					Sizewell-B	Fig. 44
448.	Valve	Power Operated Relief (PORV)	Fail to close	3.3E-2/d		6.7E-2/d	1E-2/d		Old PWR	Fig. 45
449.	Valve	Power Operated Relief (PORV)	Fail to close	1.1E-2/d		3E-2/d	6.9E-4/d		Oconee NPP PRA	Fig. 45
450.	Valve	Power Operated Relief (PORV)	Fail to open	4.2E-3/d		8.6E-3/d	1.4E-3/d		Old PWR	Fig. 44
451.	Valve	Power Operated Relief (PORV)	Fail to open	4.9E-3/d		1.1E-2/d	2.1E-4/d		Oconee NPP PRA	Fig. 44
452.	Valve	Power Operated Relief (PORV)	Fail to close	3E-2/d	10				NUREG 4550, Vol.1	Fig. 45
453.	Valve	Power Operated Relief (PORV)	Fail to close	2E-2/d					Sizewell B, Yearly Test Interval	Fig. 45
454.	Valve	Power Operated Relief (PORV)	Fail to close	2E-2/d		6E-2/d	2.5E-3/d		VVER Data	Fig. 45
455.	Valve	Power Operated Relief (PORV)	Fail to open	5E-3/d					Sizewell B, YearlyTest Interval	Fig. 44
456.	Valve	Relief	Fail to open	3E-4/d	10				IREP NUREG 2728	Fig. 44
457.	Valve	Relief, Main steam Atmos-pheric Relief	Fail to open	3E-3/d		7E-3/d	3.6E-4/d		Old PWR	Fig. 44
458.	Valve	Relief, Primary	Fail to open	8.9E-3/d		1.1E-2/d	6.8E-3/d		NUREG 1363	Fig. 44

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
459.	Valve	Relief	Fail to open	1E-3/d		1E-2/d	1E-4/d		VVER	Fig. 44
460.	Valve	Check	Internal Leak (Severe)	3E-7/h	3	1E-6/h	1E-7/h		WASH - 1400	
461.	Valve	Check	Internal Leak (Severe)	1E-7/h		7E-7	1E-10		NUREG 2815	
462.	Valve	Check	Internal Leak (Severe)	3.9E-5/h	10				German Risk Study	
463.	Valve	Check	All Modes	2.1E-6/h		3.3E-4/h	8E-8/h	1.8 h	IEEE-500	
464.	Valve	Check	Fail to open	1E-4/d	3	3E-4/d	3E-5/d		WASH-1400 and other NUREG Sources	Fig. 34
465.	Valve	Check	Fail to open	2E-7/h		1E-6/h	8E-8		NUREG - 2815	Fig. 34
466.	Valve	Check	Fail to open	26E-4/d	4				German Risk Study (ECCS and RHR Systems)	Fig. 34
467.	Valve	Check	Fail to open	1E-7/h					Sizewell-B (In Safe-guard Systems)	Fig. 34
468.	Valve	Check	Fail to open	1E-4/d	3				IREP NUREG 2728 (Hourly rate is 3E-7/h (EF 10), based on 1 Actuation per month)	Fig. 34
469.	Valve	Check	Fail to open	1E-4/d	3				NUREG 4550 Vol.1	Fig. 34
470.	Valve	Check	Fail to open	5.4E-5/d					Shoreham PRA	Fig. 34
471.	Valve	Check, ESF Systems	Fail to open	6.4E-5/d		1.7E-4/d	1.7E-5/d		NUREG 1363	Fig. 34

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
472.	Valve	Check > 100 mm	Fail to open	6.5E-4/d				9 h	Swedish Rel. Data a = 0.071 b = 11.2	Fig. 34
473.	Valve	Check, Testable	Fail to open	8E-5/d					Shoreham PRA	Fig. 34
474.	Valve	Check	Fail to open	1.8E-4/d		2.8E-4/d	6.9E-5/d		Old PWR	Fig. 35
475.	Valve	Check	Fail to open	4E-5/d					Zion NPP PRA	Fig. 35
476.	Valve	Check, 2-6"	Fail to open	7E-6/d	2.8	3E-5/d	2E-6/d	6 h	HWR Data	Fig. 35
477.	Valve	Check < 2"	Fail to open	2E-6/d	3	1.2E-5/d	8E-7/d	4 h	HWR Data	Fig. 35
478.	Valve	Stop Check	Fail to open	9.9E-5/d		2.2E-4/d	2.1E-5/d		Oconee NPP PRA	Fig. 35
479.	Valve	Check, Swing	Fail to open	9.8E-5/d		2.1E-4/d	2E-5/d		Oconee NPP PRA	Fig. 35
480.	Valve	Self Operated Check	Fail to close	2.8E-4/d		4.5E-4/d	1.4E-4/d		Old PWR	Fig. 37
481.	Valve	Self Operated Check	Fail to close	8.4E-7/d					Zion NPP PRA	Fig. 37
482.	Valve	Check, 12-24"	Fail to close	1.2E-7/h	2.1	3.2E-7/h	5.7E-8/h	19 h	HWR Data	Fig. 37
483.	Valve	Check, 2-6"	Fail to close	1.1E-7/h	1.8	2.2E-7/h	6.8E-8/h	6 h	HWR Data	Fig. 37
484.	Valve	Check, 6-12"	Fail to close	1.4E-7/h	2	3.2E-7/h	6.8E-8/h	6 h	HWR Data	Fig. 37
485.	Valve	Check < 2"	Fail to close	3.4E-8/h	2	6.8E-8/h	1.1E-8/h	4 h	HWR Data	Fig. 37
486.	Valve	Check, Main Steam	Fail to close	2.4E-4/d		4.7E-4/d	5.2E-5/d		Old PWR	Fig. 37
487.	Valve	Stop Check	Fail to close	1.6E-4/d		3.4E-4/d	3.3E-5/d		Oconee NPP PRA	Fig. 37
488.	Valve	Swing Check	Fail to close	9.8E-5/d		2.1E-4/d	2E-5/d		Oconee NPP PRA	Fig. 37
489.	Valve	Check	Fail to close	7.2E-4/d		3.6E-3/d	2E-4/d		NUREG 2815	Fig. 36
490.	Valve	Check	Fail to close	1.1E-3/d	3				German Risk Study	Fig. 36

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
491	Valve	Check	Fail to close	1E-3/d	3				IREP NUREG 2728	Fig. 36
492	Valve	Check	Fail to close	1E-3/d	3				NUREG 4550 Vol 1	Fig. 36
493	Valve	Check	Fail to close	5.8E-4/d					Shoreham PRA	Fig. 36
494	Valve	Check	Fail to close	1.4E-3/d					Sizewell B	Fig. 36
495	Valve	Check	Fail to close	3.4E-4/d		1.9E-2/d		9 h	Swedish Rel. Data	Fig. 36
496	Valve	Check	Fail to close	5.5E-4/d					Swedish Rel. Data	Fig. 36
497	Valve	Check, Testable	Fail to close	8E-4/d					Shoreham PRA	Fig. 36
498	Valve	Check	Fail to close	1E-3/d		3E-3/d	2E-4/d		VVER Data	Fig. 36
499	Valve	Safety	Fail to close	1.6E-2/d		4E-2/d	4E-3/d		NUREG 2815	Fig. 47
500	Valve	Safety	Fail to close	3E-2/d					IREP NUREG 2728	Fig. 47
501	Valve	Safety	Fail to close	7E-3/d					German Risk Study	Fig. 47
502	Valve	Safety	Fail to close	1.6E-3/d					Sizewell B	Fig. 47
503	Valve	Safety	Fail to close	2E-3/d		6E-3/d			Swedish Rel. Data	Fig. 47
504	Valve	Safety	Fail to close	2E-3/d		1E-4/d	6E-3/d		Old PWR	Fig. 47
505	Valve	Safety	Fail to close	4E-3/d		1E-2/d	1E-3/d		Oconee NPP PRA	Fig. 47
506	Valve	Safety	Fail to close	1E-2/d	3				IREP NUREG 2728	Fig. 47
507	Valve	Safety	Fail to open	4E-3/y					IEEE 500	Fig. 46
508	Valve	Self Operated Code Safety	Fail to open	6E-3/d		8E-2/d	1.4E-3/d		NUREG 2815	Fig. 46
509	Valve	Pilot	Fail to	7.8E-4/d		1.4E-3/d		9 h	Swedish	Fig. 46

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
		Operated Safety, 125, 150, 300 mm	open						Rel. Data a = 0.0167 b = 21.4	
510.	Valve	Safety, Pressuriser or Main Steam Line	Fail to open	4E-3/d	6				German Risk Study	Fig. 46
511.	Valve	Self Operated Pressuriser Safety	Fail to open	2.7E-4/d		8E-4/d	7.4E-6/d		Oconee NPP PRA	Fig. 46
512.	Valve	Self Operated Code Safety	Fail to open	1E-5/d	3				IREP NUREG 2728	Fig. 46
513.	Valve	Self Operated Primary Safety	Fail to open	4.5E-2/d		4E-1/d	1.8E-2/d		NUREG 2815	Fig. 46
514.	Valve	Self Operated Primary Safety	Fail to open	1E-5/d	3				IREP NUREG 2728, BWR only	Fig. 46
515.	Valve	Self Operated Main Steam	Fail to open	3.3E-4/d		1.1E-3/d	1.3E-5/d		Old PWR	Fig. 46
516.	Valve	Self Operated Main Steam	Fail to open							Fig. 46
517.	Valve	Self Operated Safety Valve, PWR	Fail to open	3.9E-3/d		7.4E-3/d	1.8E-3/d		NUREG 1363	Fig. 46
518.	Valve	Self Operated Safety Valve, BWR	Fail to open	1E-5/d	3				NUREG 4550	Fig. 46
519.	Valve	Solenoid Operated	All Modes	2.7E-7/h	1.3	3.5E-7/h	2.1E-7/h	5 h	HWR Data	
520.	Valve	Solenoid Operated	Fail to change position	2E-6/h		1E-5/h	8E-7/h		NUREG 2815	Fig. 48
521.	Valve	Solenoid Operated	Fail to change position	3.7E-5/h	20				German Risk Study	Fig. 48
522.	Valve	Solenoid Operated	Fail to change position	1.0E-3/d	3	3E-3/d	3E-4/d		WASH - 1400	Fig. 48
523.	Valve	Solenoid Operated	Fail to change position	7.1E-7/h		3.7E-6/h		3 h	Swedish Rel. Data	Fig. 48

TABLE-7: RELIABILITY DATABASE OF COMPONENTS (Contd.)

S. No.	Component Group	Component Type	Failure Mode	Failure Rate/ Probability	Error Factor	Confidence Limits		Repair/ Down Time	Remarks (Source)	Reference
524.	Valve	Solenoid Operated	Fail to remain in position	1E-4/d	3	3E-4/d	3E-5/d		WASH - 1400	
525.	Valve	Solenoid Operated	Fail to change position	1 E-3/d	3				IREP NUREG 2728	Fig. 48
526.	Valve	Solenoid Operated	Fail to change position	1E-3/d	3				NUREG 4550	Fig. 48
527.	WIRE		Short to ground	3E-7/h	10	3E-6	3E-8		WASH - 1400	
528.	WIRE		Short to ground	3E-8/h		2E-7	6E-10		NUREG 2815	
529.	WIRE		Short Circuit	1.0E-8/h	10	1E-7	1E-9		WASH - 1400	
530.	WIRE		Open Circuit	3E-6/h	3	1E-5	1E-6		WASH - 1400	

6. COMPARISON OF RELIABILITY DATA FROM DIFFERENT SOURCES

A large number of sources (22) have been used in setting up the reliability database for various components used in PSA studies. It would be worthwhile comparing the data sources and establishing the ranges for the components for which adequate data exists in the databases. [3]

Following component types have been selected for the comparative study:

- Diesel driven pump
- Motor driven pump
- Turbine driven pump
- Air operated valve
- Motor operated valve
- Solenoid operated valve
- Manual valve
- Relief valve
- Safety valve
- Diesel generator
- Battery
- Battery charger
- Bus
- Motor
- Inverter
- Rectifier
- Transformer
- Relay
- Switch
- Transmitter

For meaningful comparisons, separate graphs with data from different sources would be required for each component type, failure mode, operating mode (where applicable) or type of environment. Apart from comparison of data for similar component types from different sources, the graphs are also useful in comparing reliability data from a particular source, or data based on our operating experience, with data obtained from literature. Another purpose of these graphs is to facilitate the assessment of the ‘centre points’ as well as the higher and lower values of the data found in the literature. On comparing a data set with the ranges of data presented in the graphs, tendencies towards lower or higher values can be easily identified. Whenever a plant model is available, sensitivity analysis using the extreme values depicted in the graphs can also be performed. To some extent, the graphs can be used to establish acceptable ranges for component failure rates/probabilities.

Graphs for a given component type, failure mode, etc., have been plotted for different data sources and are included in this section. The various sources and their respective codes, which are on the graphs’ X-axis, are given in Appendix A. The sources have been categorised as follows:

(a) Generic Sources

(b) Plant Specific Sources[4]

(c) Updated Source.

Sources (b) and (c) have been generally plotted together. The details of the data sources in each category, together with examples, have been given in section 2.4.

4 Abbreviation ‘PS’ has been used for ‘Plant Specific’ in a number of graphs.

GRAPHS FOR COMPARATIVE EVALUATION

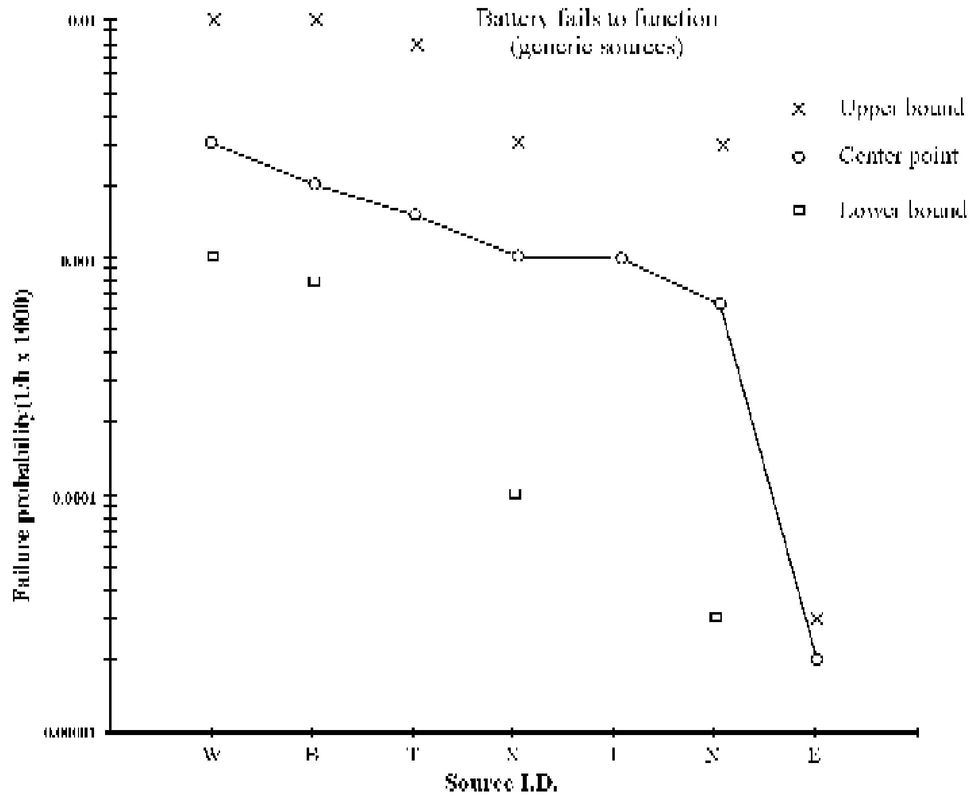


FIG. 1: BATTERY FAILS TO FUNCTION (GENERIC SOURCES)

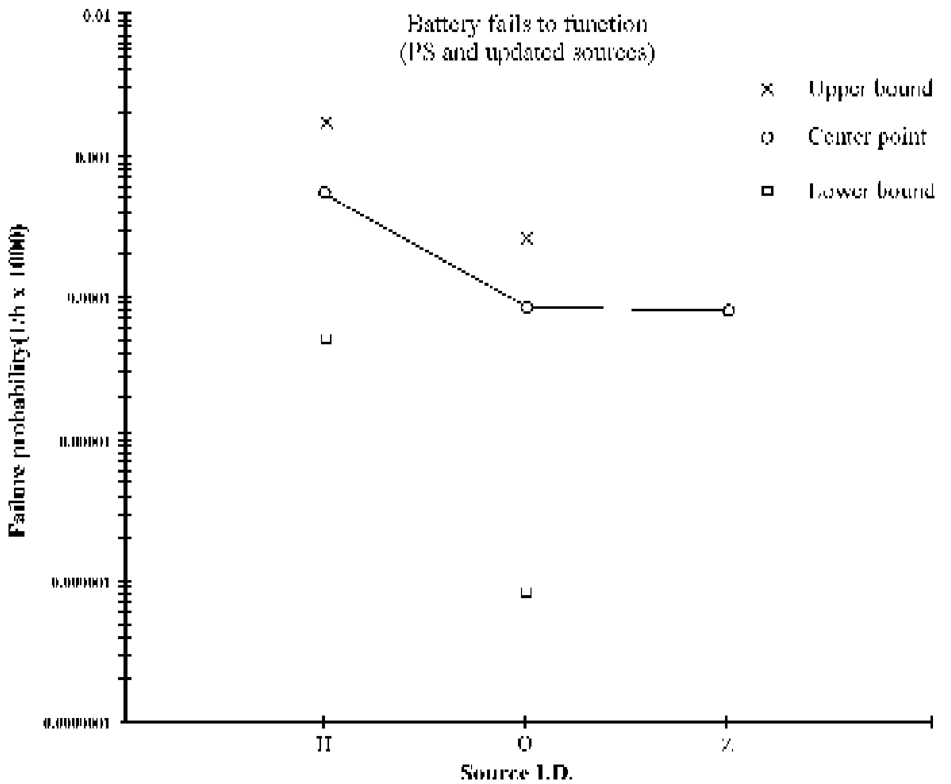


FIG. 2: BATTERY FAILS TO FUNCTION (PS AND UPDATED SOURCES)

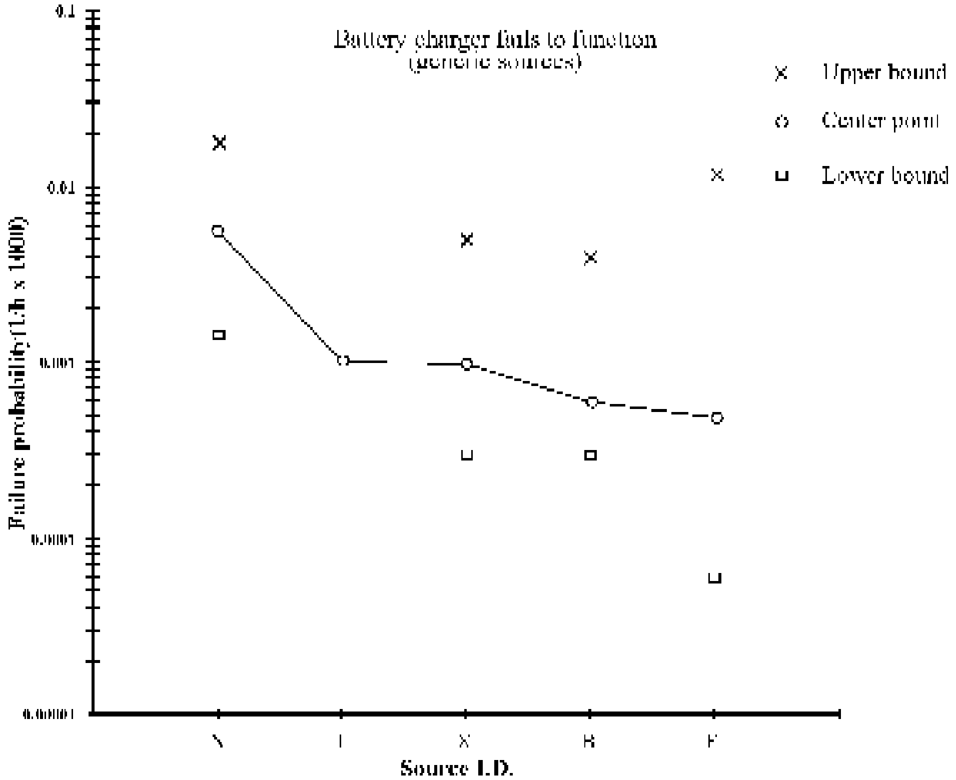


FIG. 3: BATTERY CHARGER FAILS TO FUNCTION (GENERIC SOURCES)

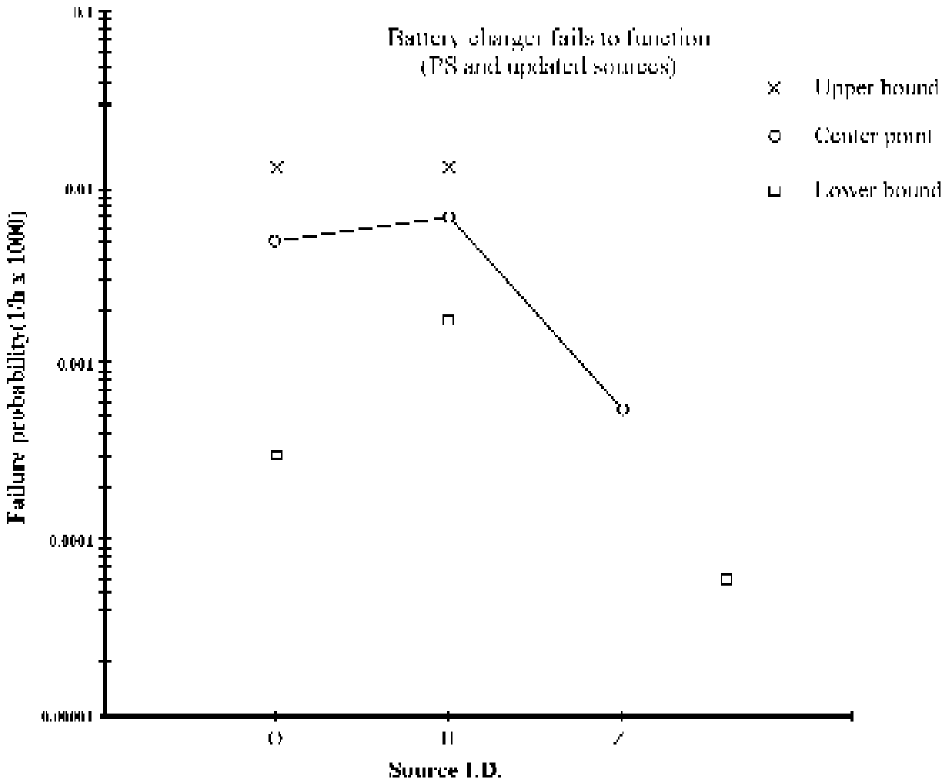


FIG. 4: BATTERY CHARGER FAILS TO FUNCTION (PS AND UPDATED SOURCES)

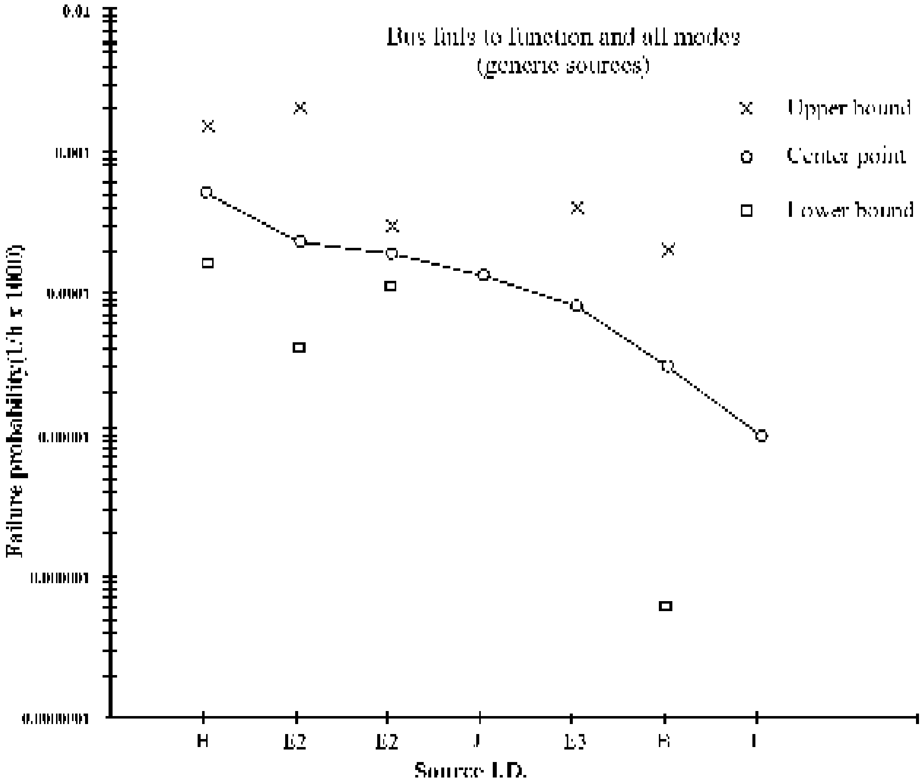


FIG.5: BUS FAIL TO FUNCTION IN ALL MODES (GENERIC SOURCES)

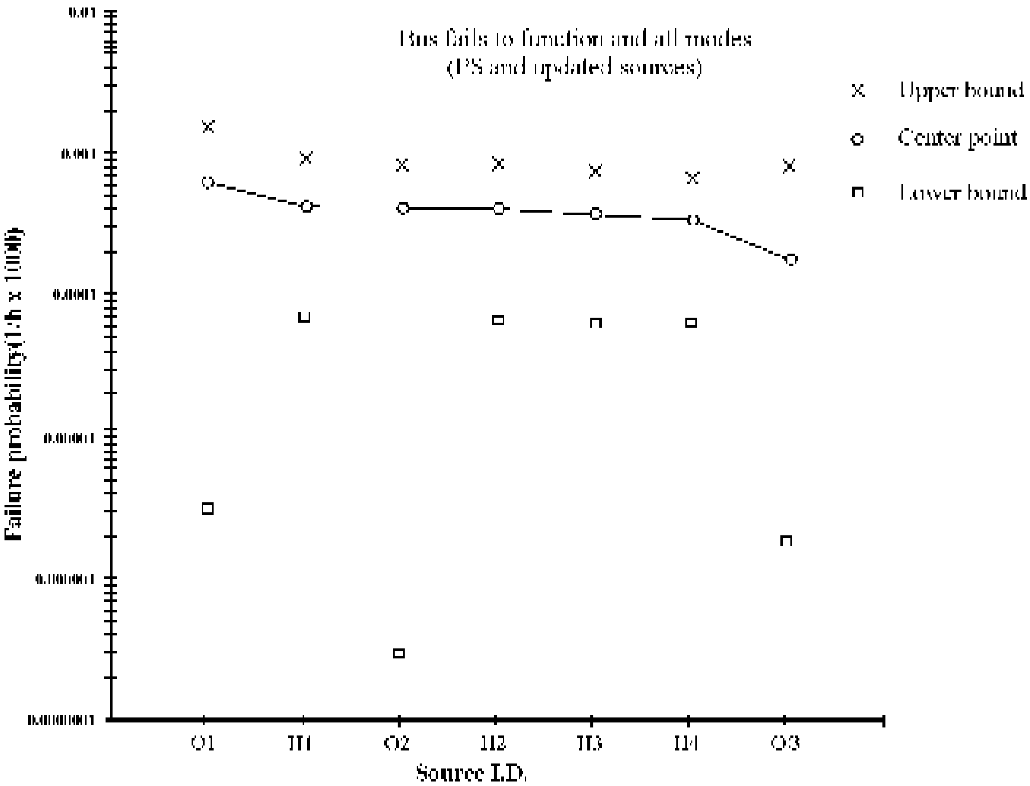


FIG. 6: BUS FAILS TO FUNCTION AND ALL MODES (PS AND UPDATED SOURCES)

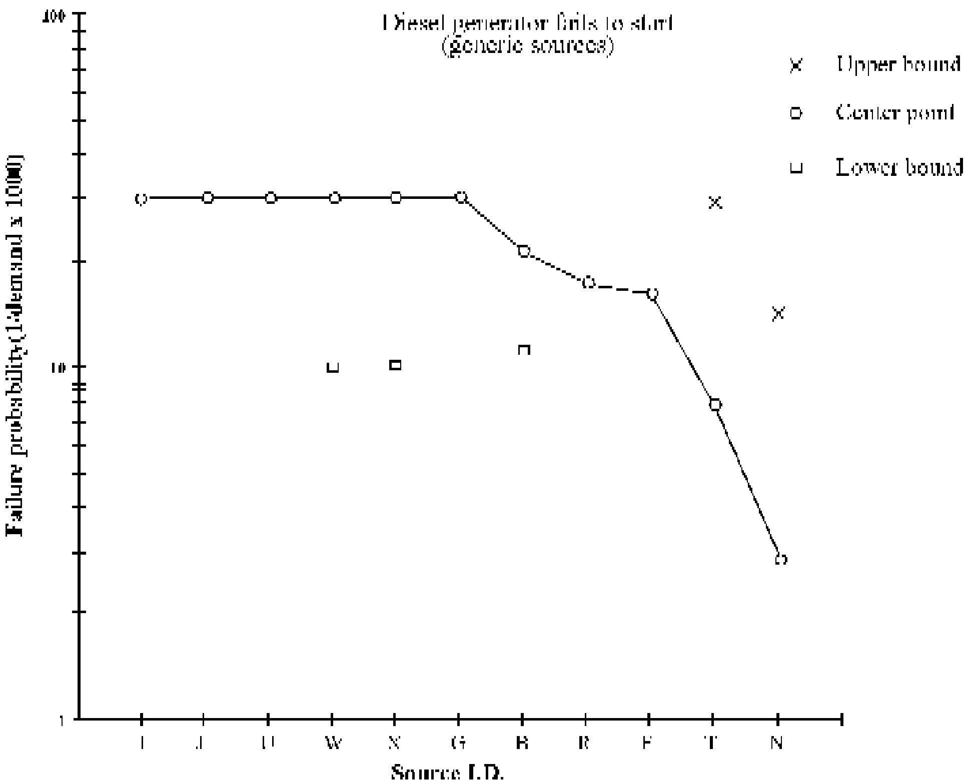


FIG. 7: DIESEL GENERATOR FAILS TO START (GENERIC SOURCES)

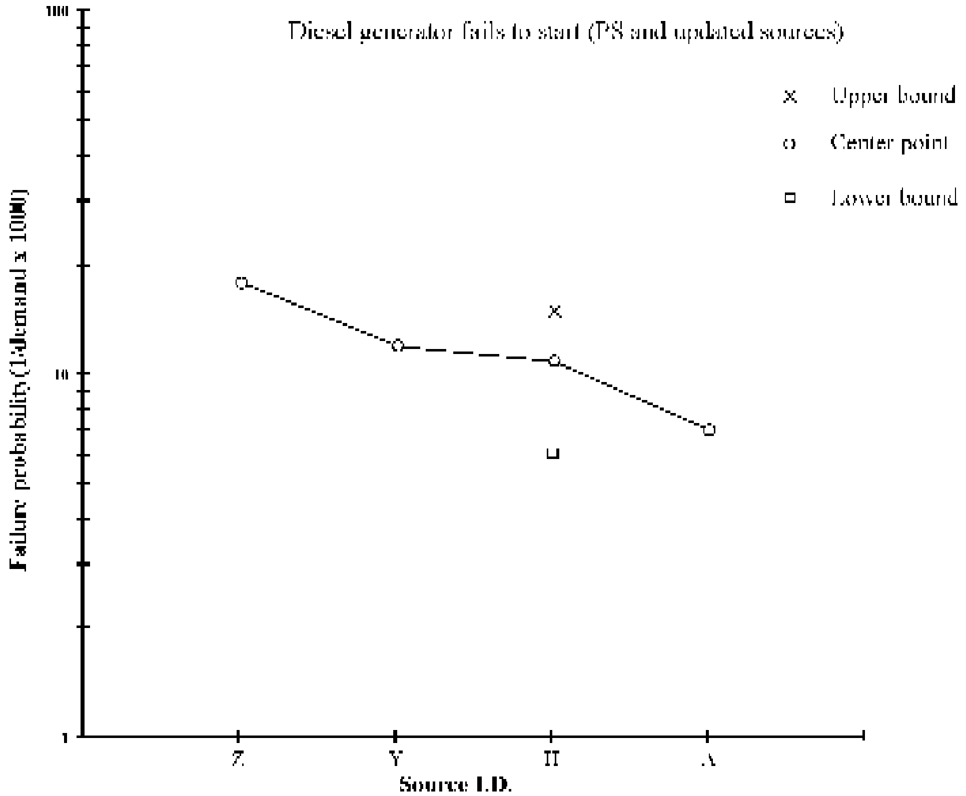


FIG. 8: DIESEL GENERATOR FAILS TO START (PS AND UPDATED SOURCES)

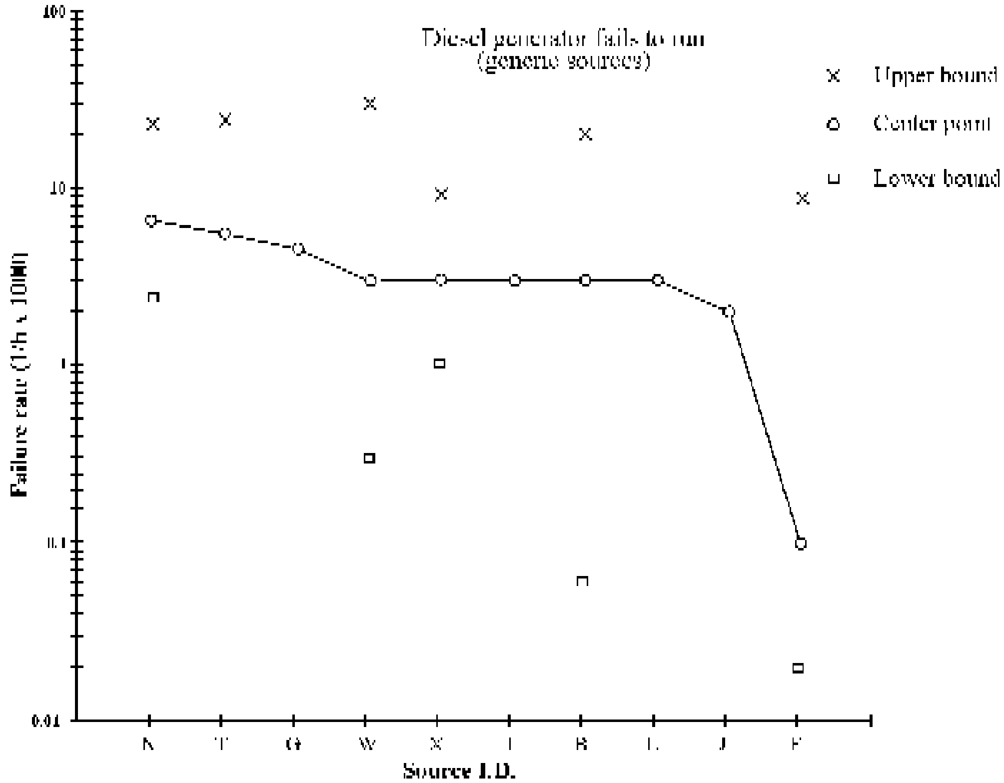


FIG. 9: DIESEL GENERATOR FAILS TO RUN (GENERIC SOURCES)

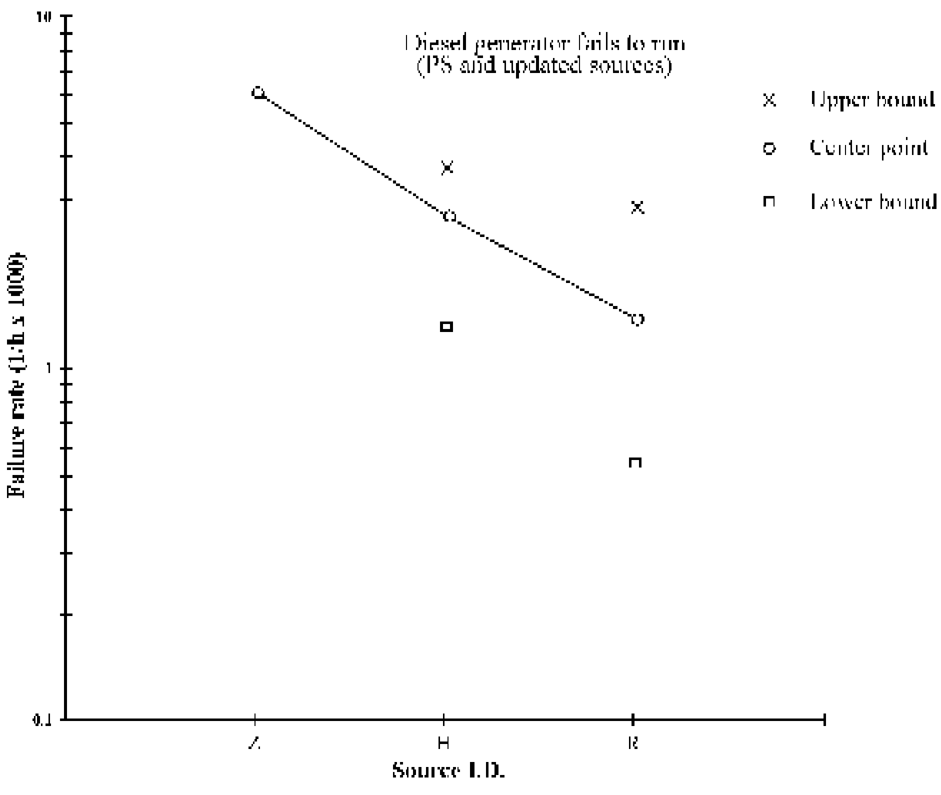


FIG. 10: DIESEL GENERATOR FAILS TO START (PS AND UPDATED SOURCES)

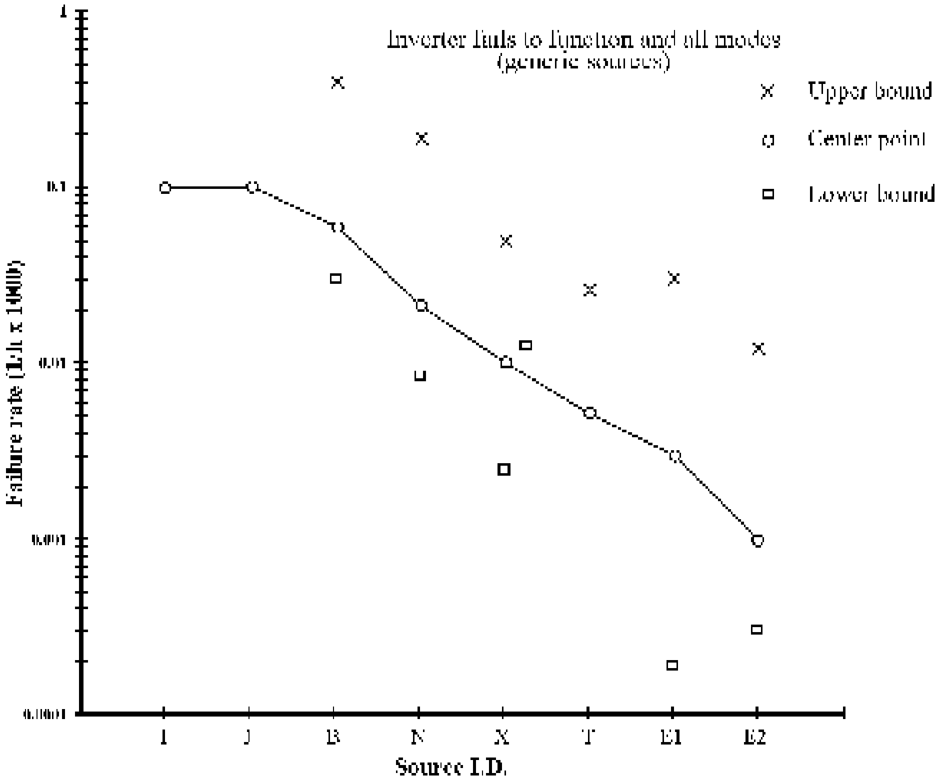


FIG. 11: INVERTER FAILS TO FUNCTION AND ALL MODES (GENERIC SOURCES)

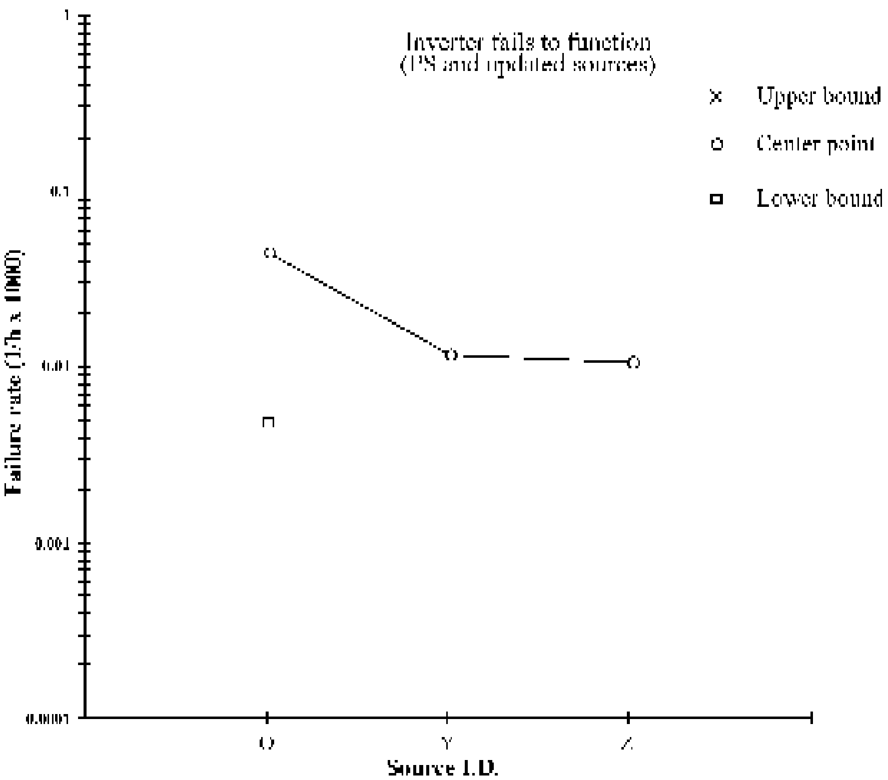


FIG. 12: INVERTER FAILS TO FUNCTION (PS AND UPDATED SOURCES)

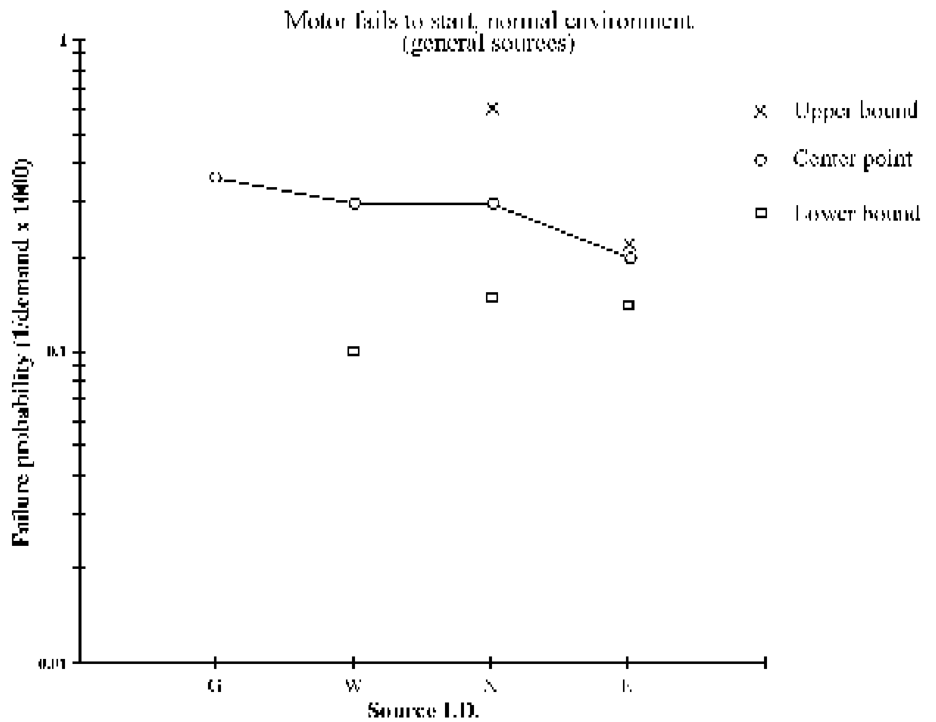


FIG. 13: MOTOR FAILS TO START, NORMAL ENVIRONMENT (GENERIC SOURCES)

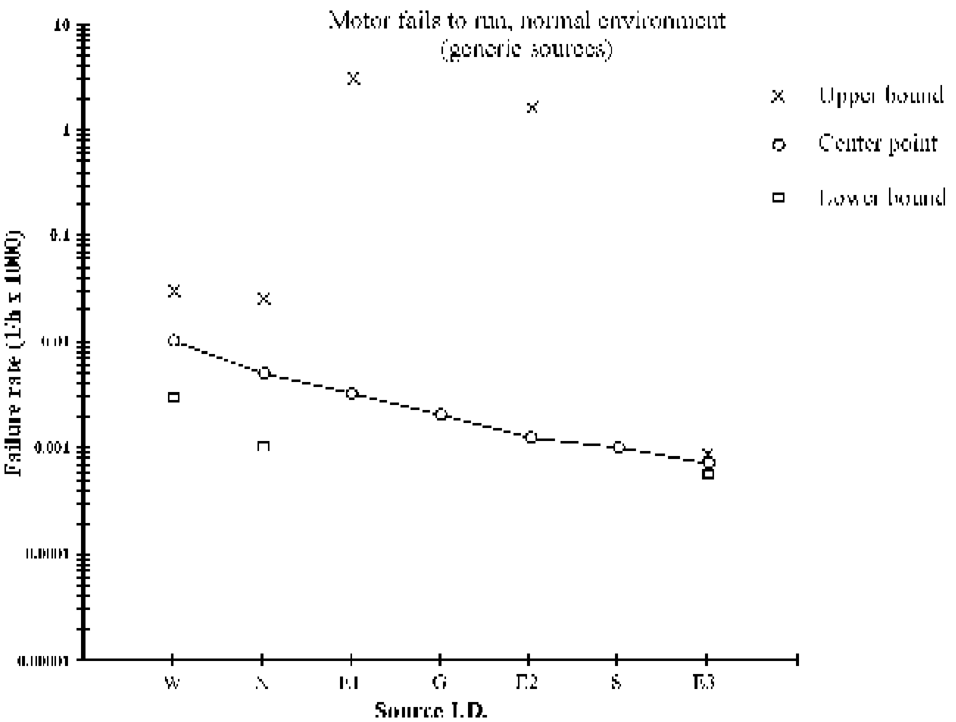


FIG. 14: MOTOR FAILS TO RUN, NORMAL ENVIRONMENT (GENERIC SOURCES)

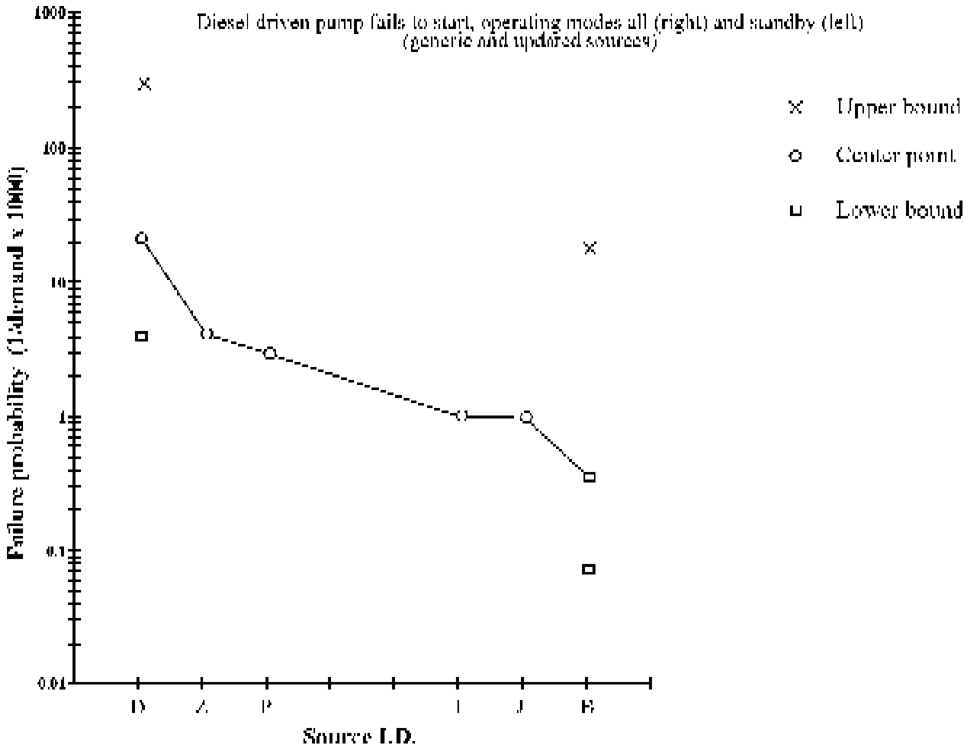


FIG. 15: DIESEL DRIVEN PUMP FAILS TO START, OPERATING MODES ALL (RIGHT) AND STANDBY (LEFT) (GENERIC AND UPDATED SOURCES)

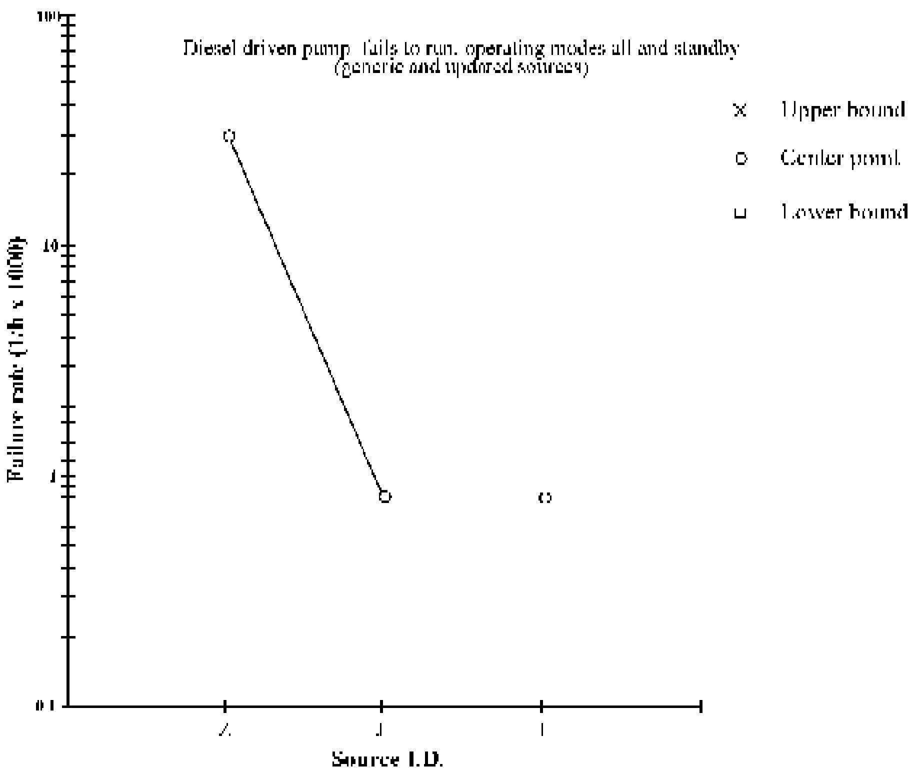


FIG. 16: DIESEL DRIVEN PUMP FAILS TO RUN, OPERATING MODES ALL AND STANDBY (GENERIC AND UPDATED SOURCES)

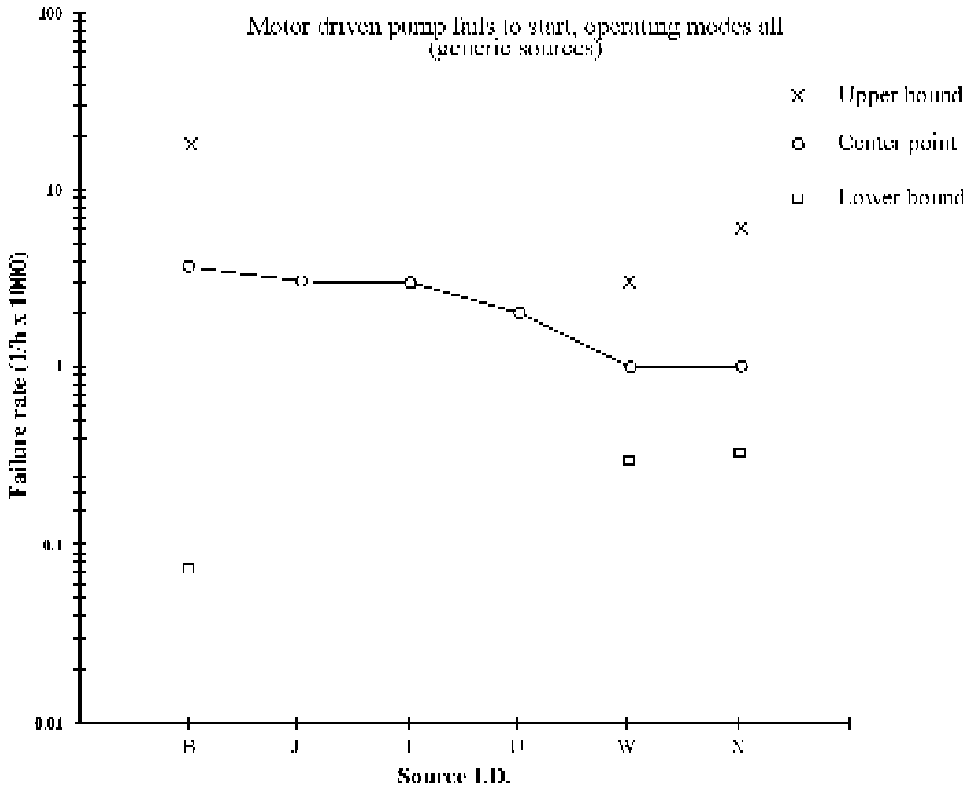


FIG. 17: MOTOR DRIVEN PUMP FAILS TO START, OPERATING MODES ALL (GENERIC SOURCES)

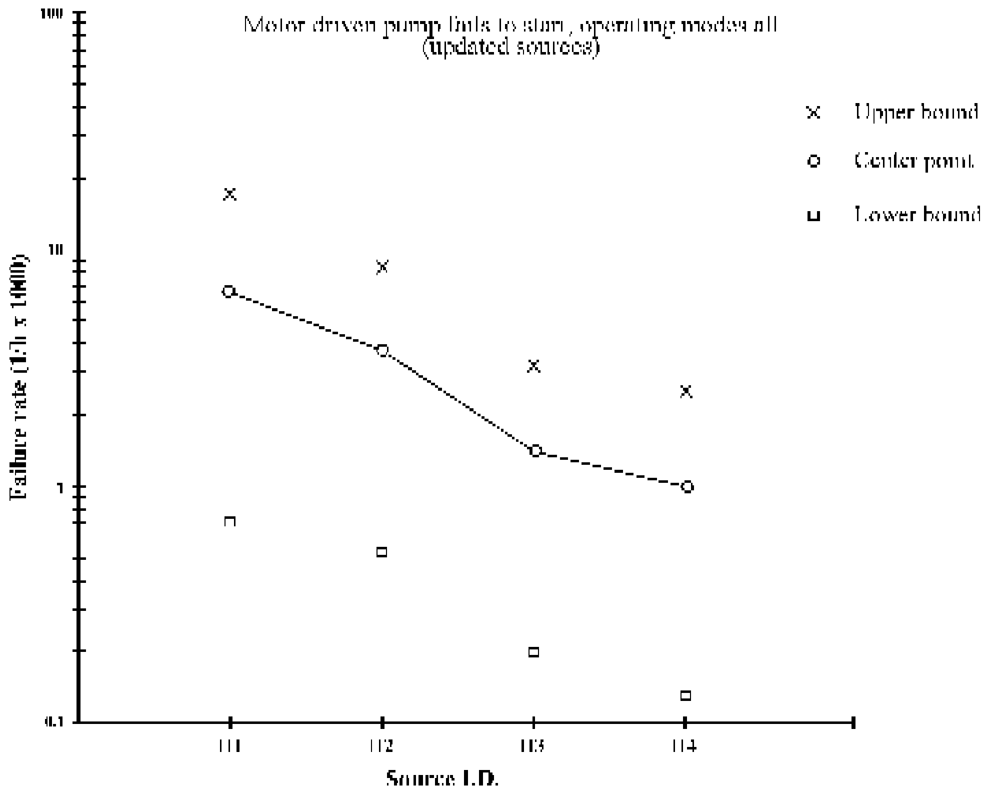


FIG. 18: MOTOR DRIVEN PUMP FAILS TO START, OPERATING MODES ALL (UPDATED SOURCES)

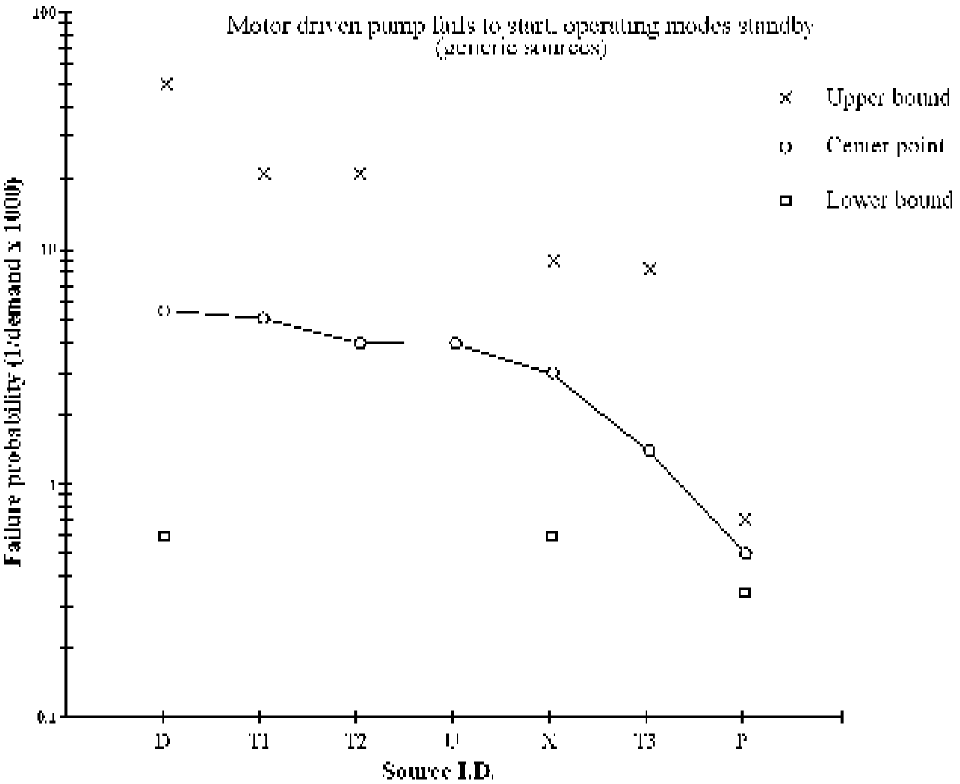


FIG. 19: MOTOR DRIVEN PUMP FAILS TO START, OPERATING MODES STANDBY (GENERIC SOURCES)

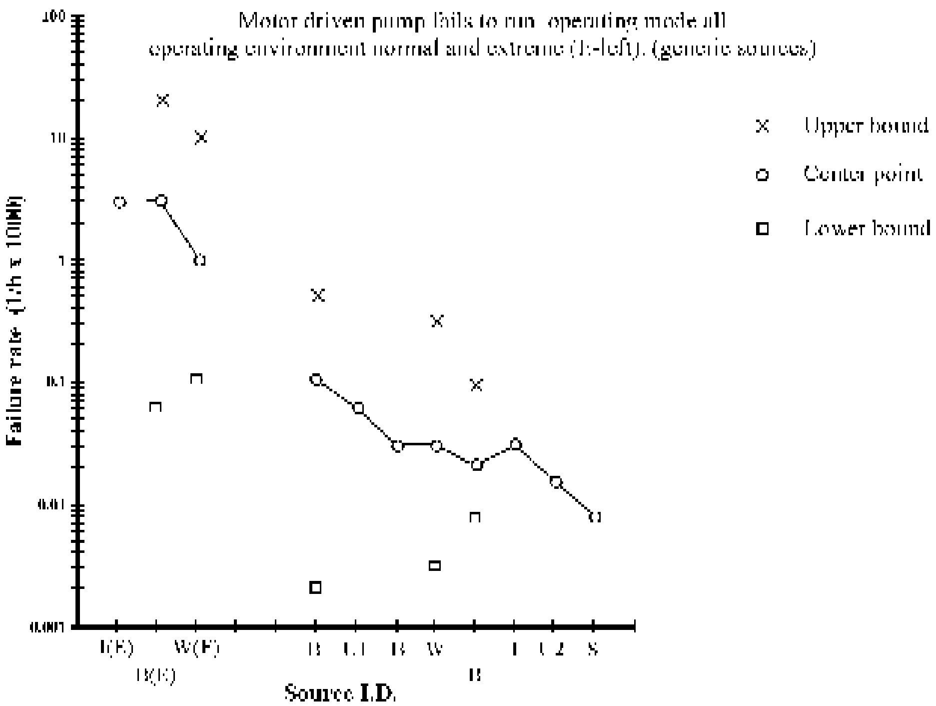


FIG. 20: MOTOR DRIVEN PUMP FAILS TO RUN, OPERATING MODES ALL OPERAING ENVIRONMENT NORMAL AND EXTREME (E-LEFT) (GENERIC SOURCES)

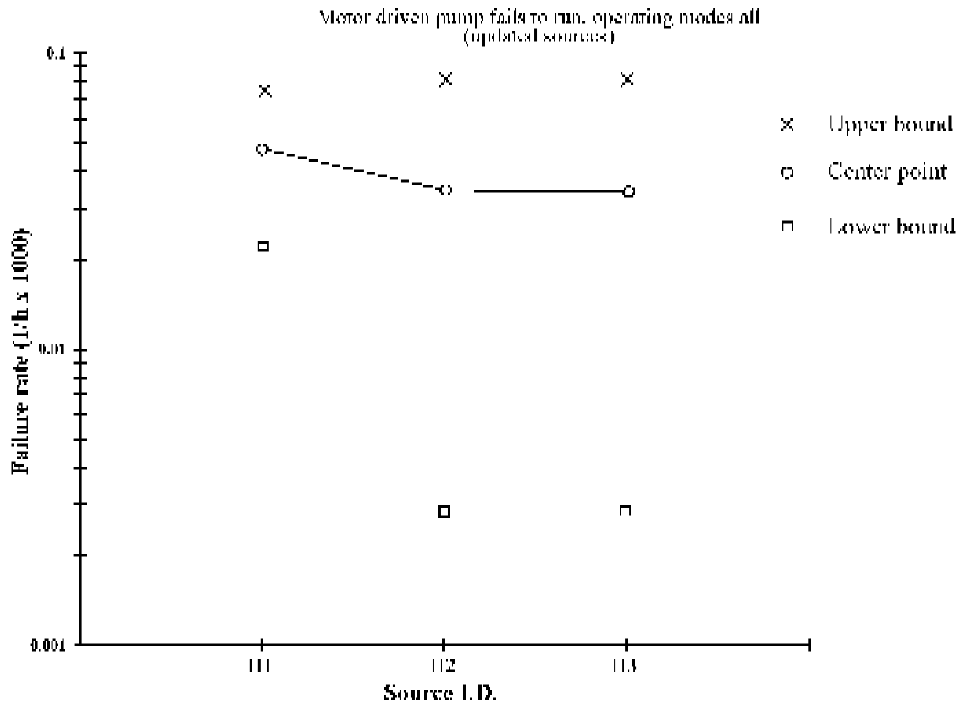


FIG. 21: MOTOR DRIVEN PUMP FAILS TO RUN, OPERATING MODES ALL (UPDATED SOURCES)

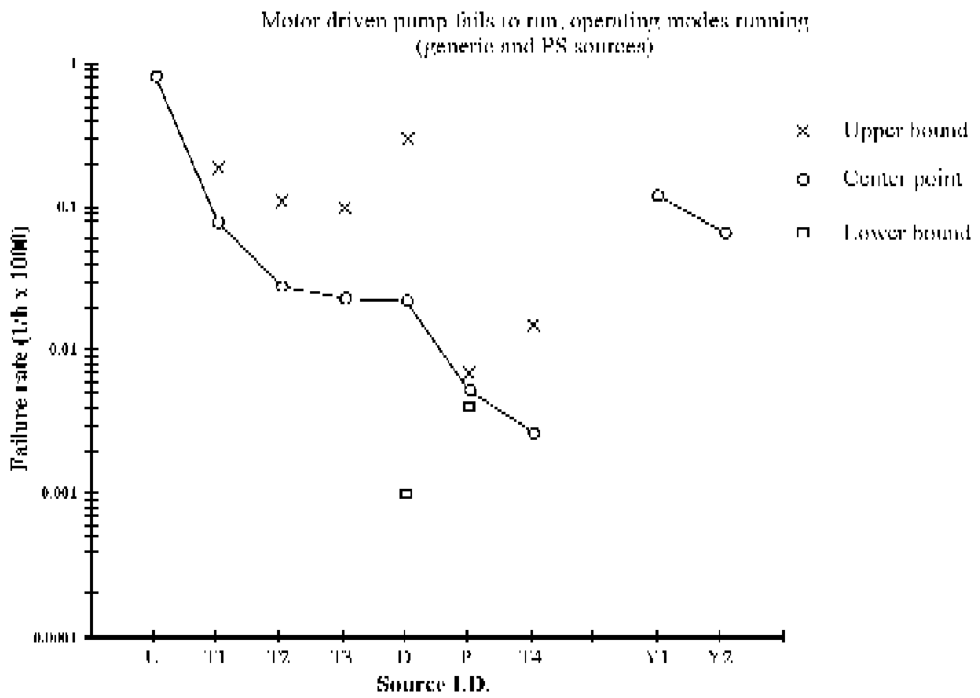


FIG. 22: MOTOR DRIVEN PUMP FAILS TO RUN, OPERATING MODES ALL (GENERIC AND PS SOURCES)

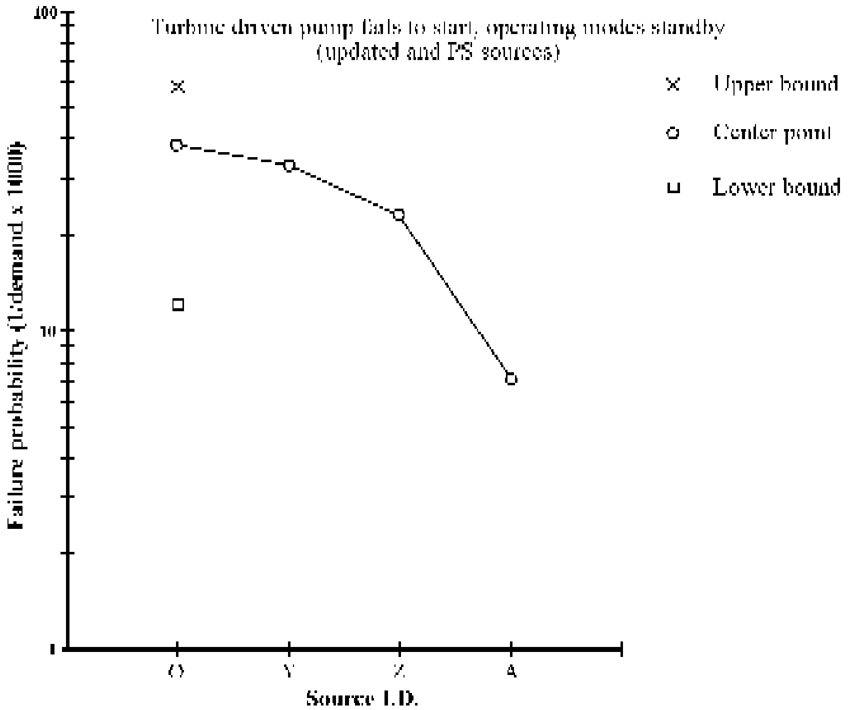


FIG. 23: TURBINE DRIVEN PUMP FAILS TO START, OPERATING MODES STANDBY (UPDATED AND PS SOURCES)

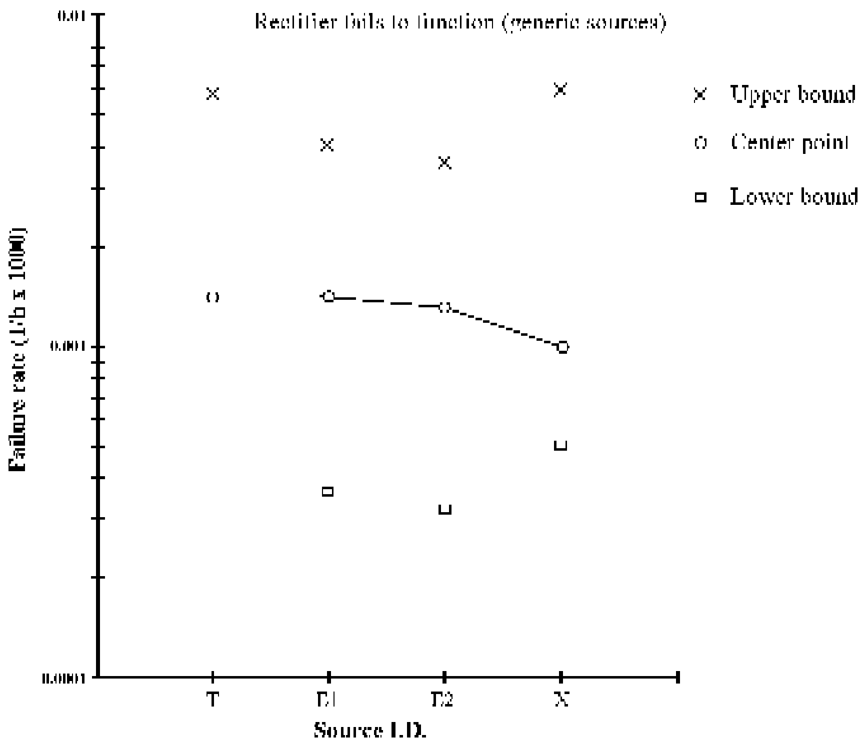


FIG. 24: RECTIFIER FAILS TO FUNCTION (GENERIC SOURCES)

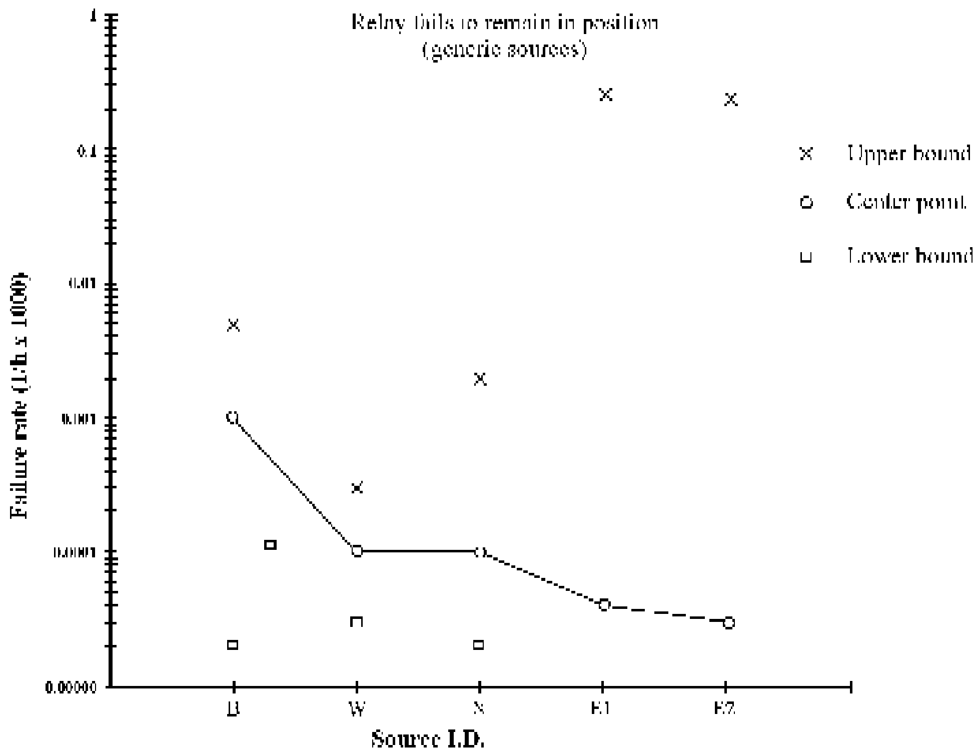


FIG. 25: RELAY FAILS TO REMAIN IN POSITION (GENERIC SOURCES)

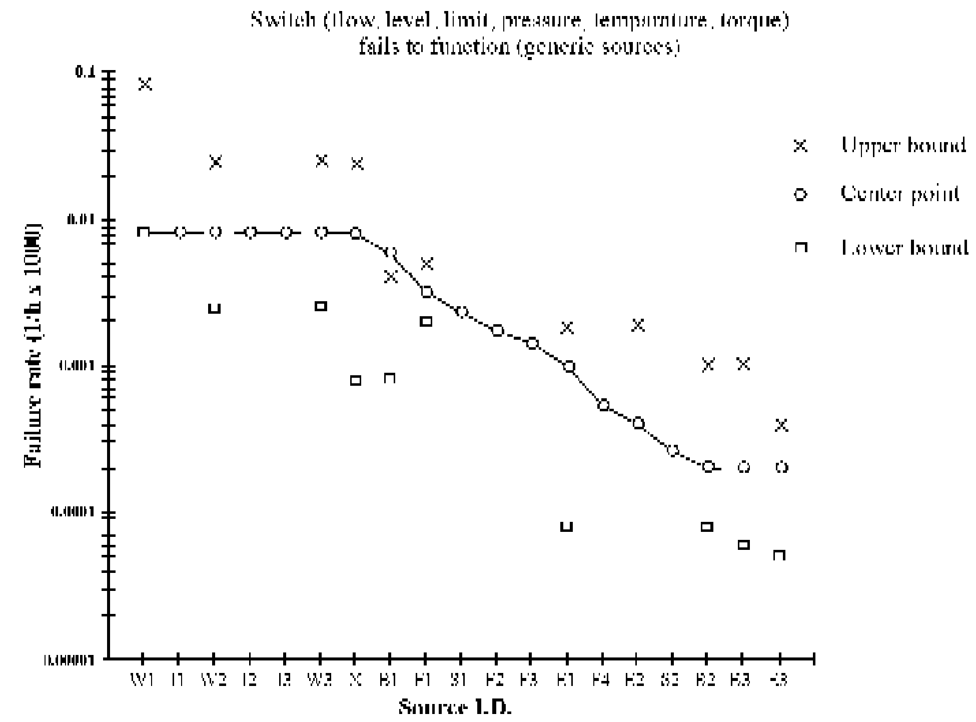


FIG. 26: SWITCH (FLOW, LEVEL, LIMIT, PRESSURE, TEMPERATURE, TORQUE) FAILS TO FUNCTION (GENERIC SOURCES)

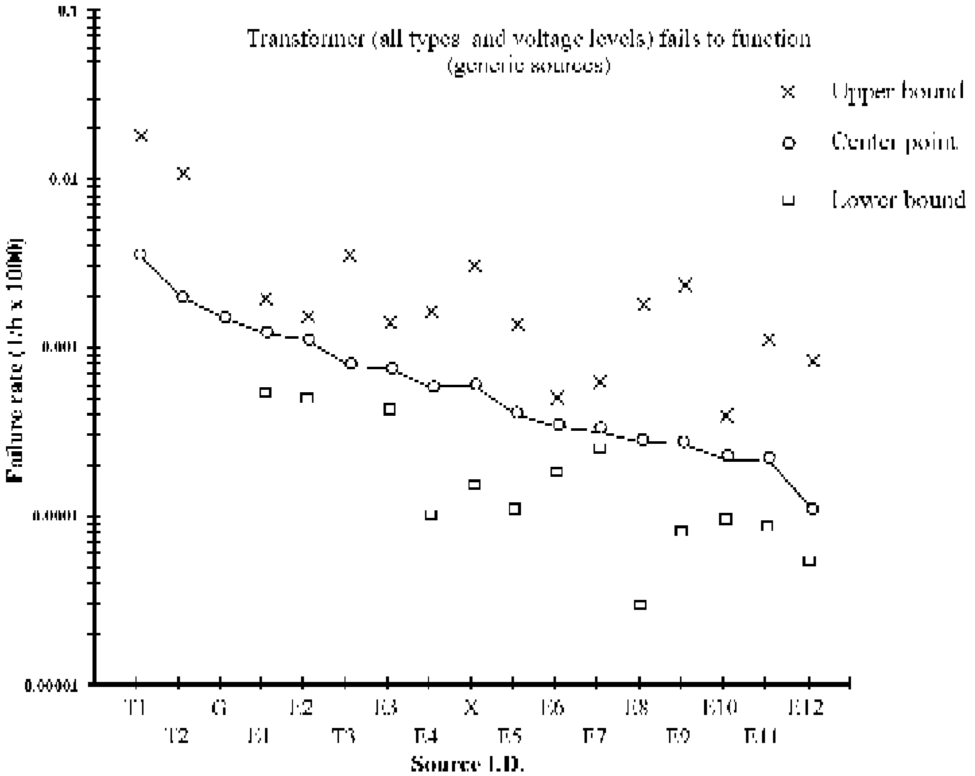


FIG. 27: TRANSFORMER (ALL TYPES AND VOLTAGE LEVELS) FAILS TO FUNCTION (GENERIC SOURCES)

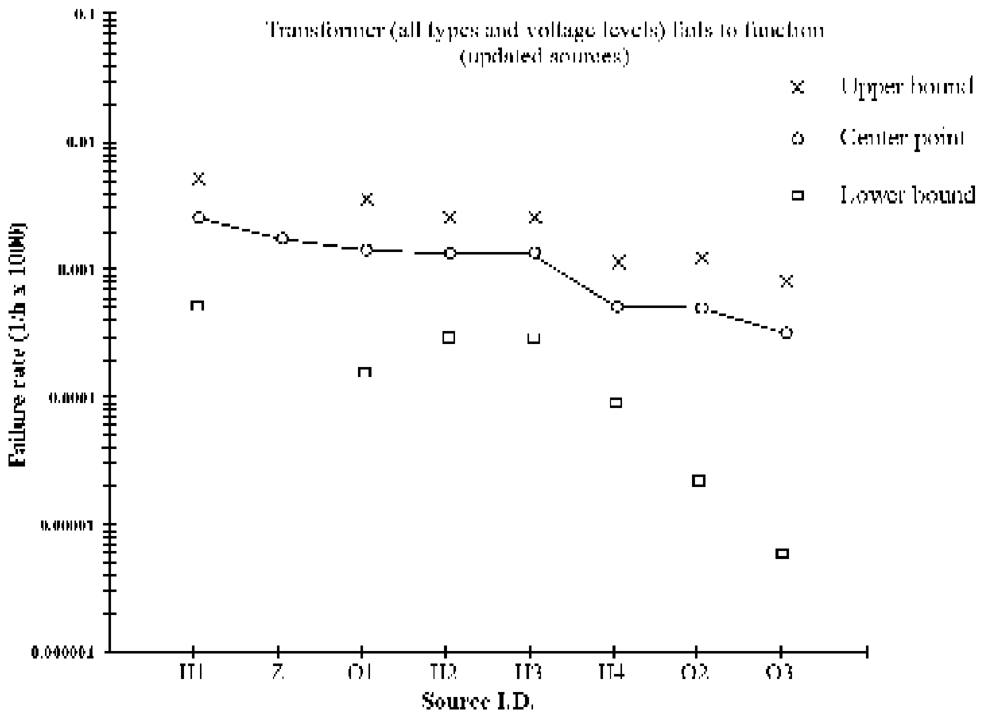


FIG. 28: TRANSFORMER (ALL TYPES AND VOLTAGE LEVELS) FAILS TO FUNCTION (UPDATED SOURCES)

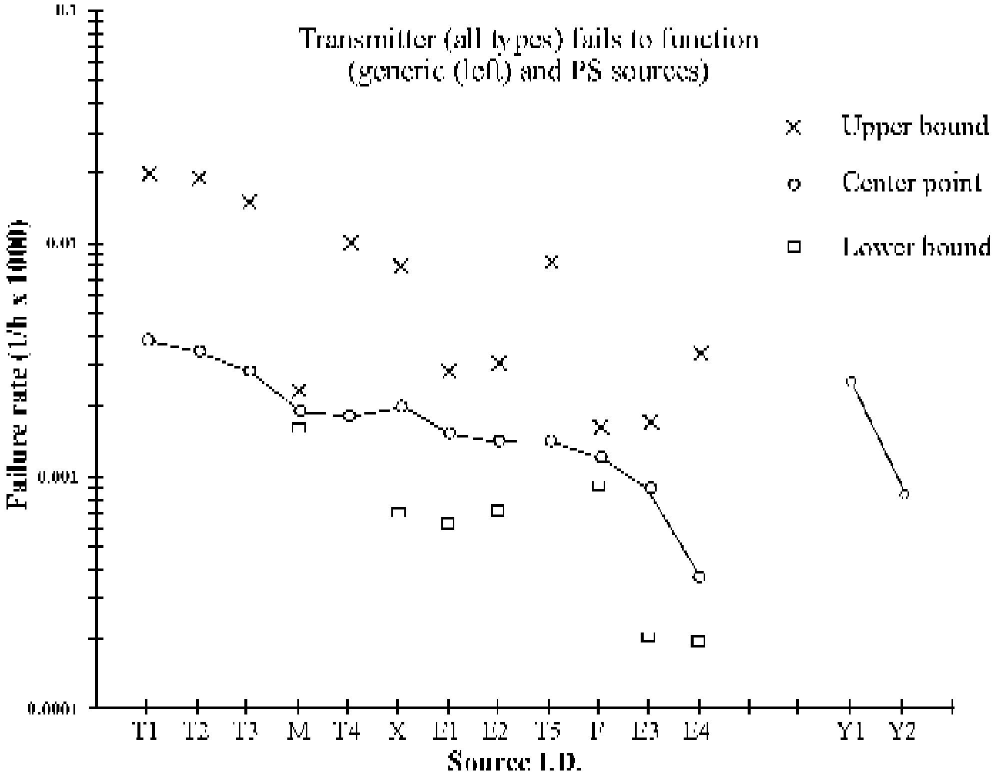


FIG. 29: TRANSMITTER (ALL TYPES) FAILS TO FUNCTION GENERIC (LEFT) AND PS SOURCES

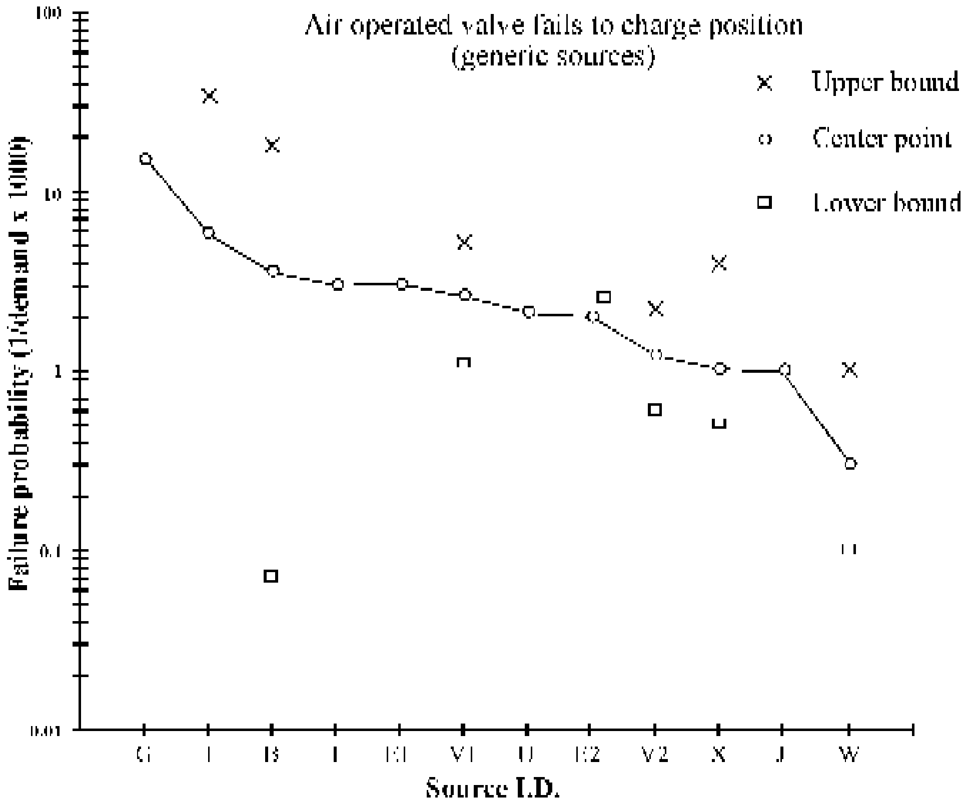


FIG. 30: AIR OPERATED VALVE FAILS TO CHANGE POSITION (GENERIC SOURCES)

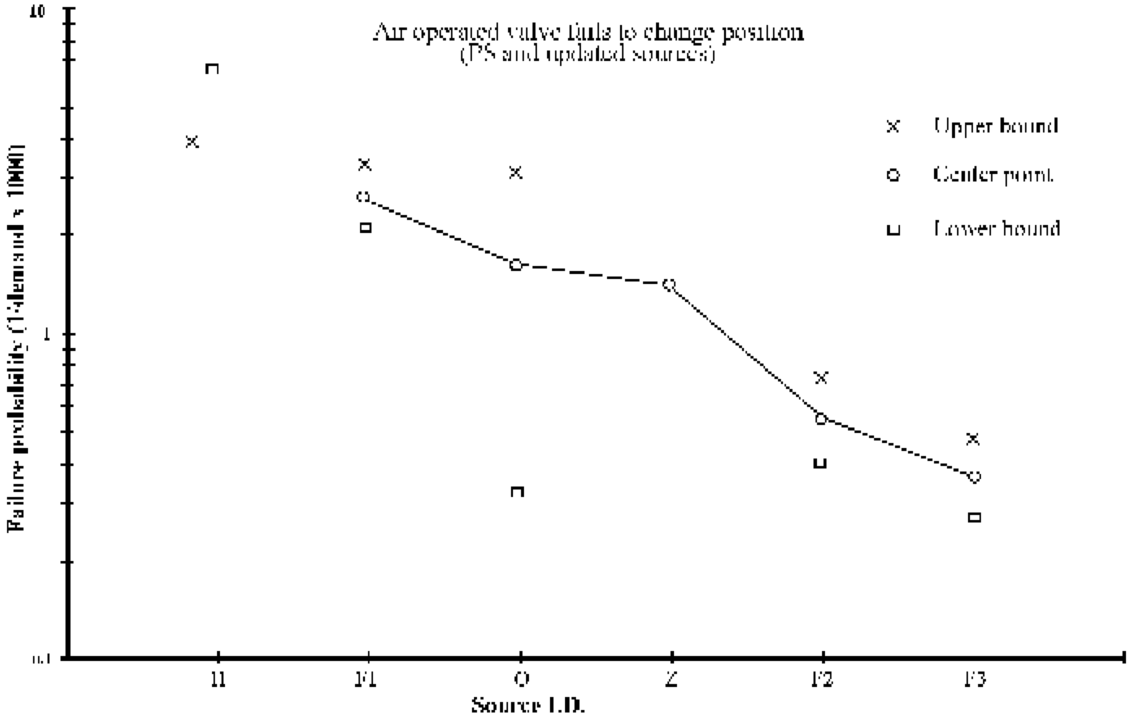


FIG. 31: AIR OPERATED VALVE FAILS TO CHANGE POSITION (PS AND UPDATED SOURCE)

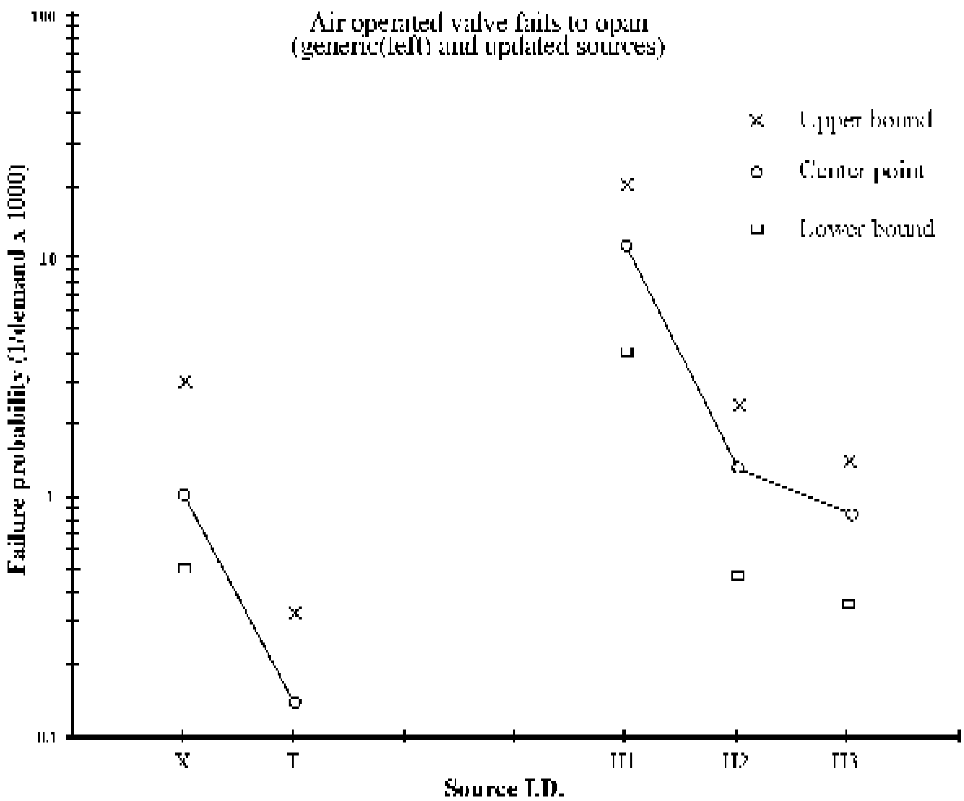


FIG. 32: AIR OPERATED VALVE FAILS TO OPEN (GENERIC (LEFT) UPDATED SOURCES)

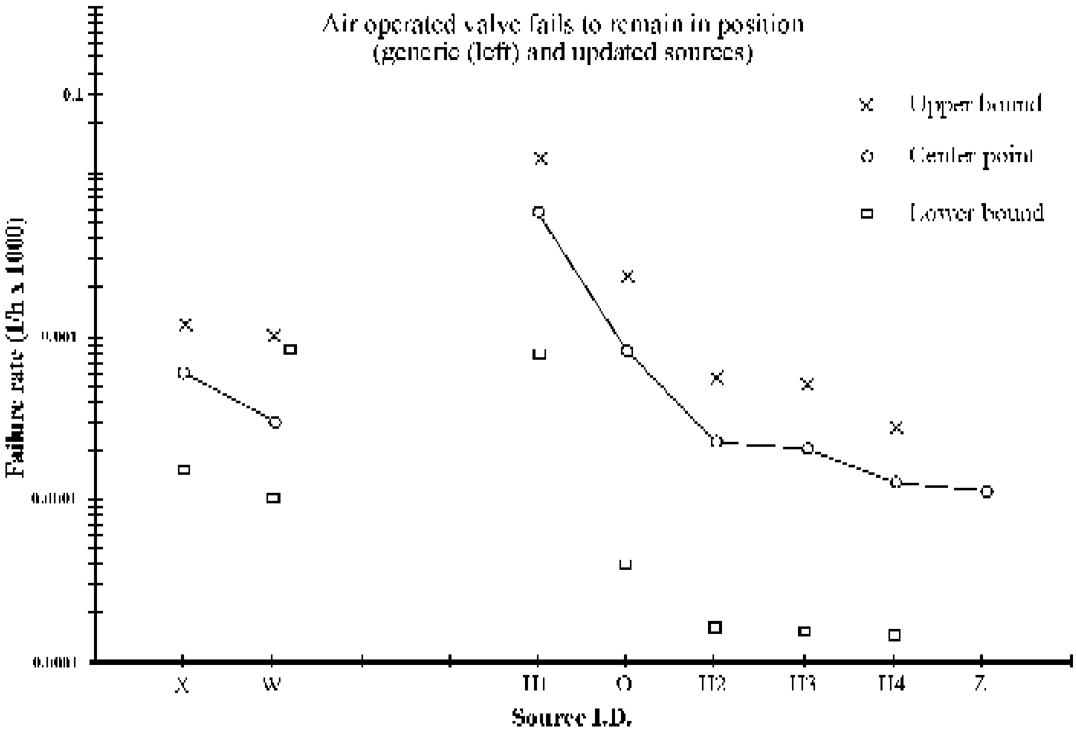


FIG. 33: AIR OPERATED VALVE FAILS TO REMAIN IN POSITION (GENERIC (LEFT) AND UPDATED SOURCES)

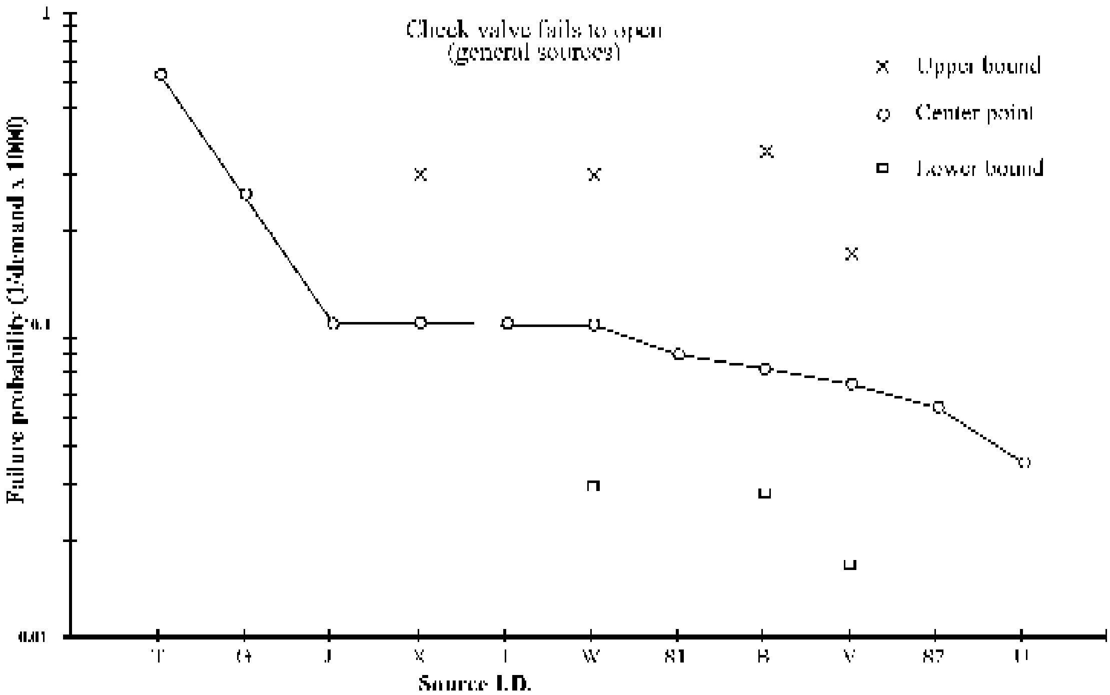


FIG. 34: CHECK VALVE FAILS TO OPEN (GENERIC SOURCES)

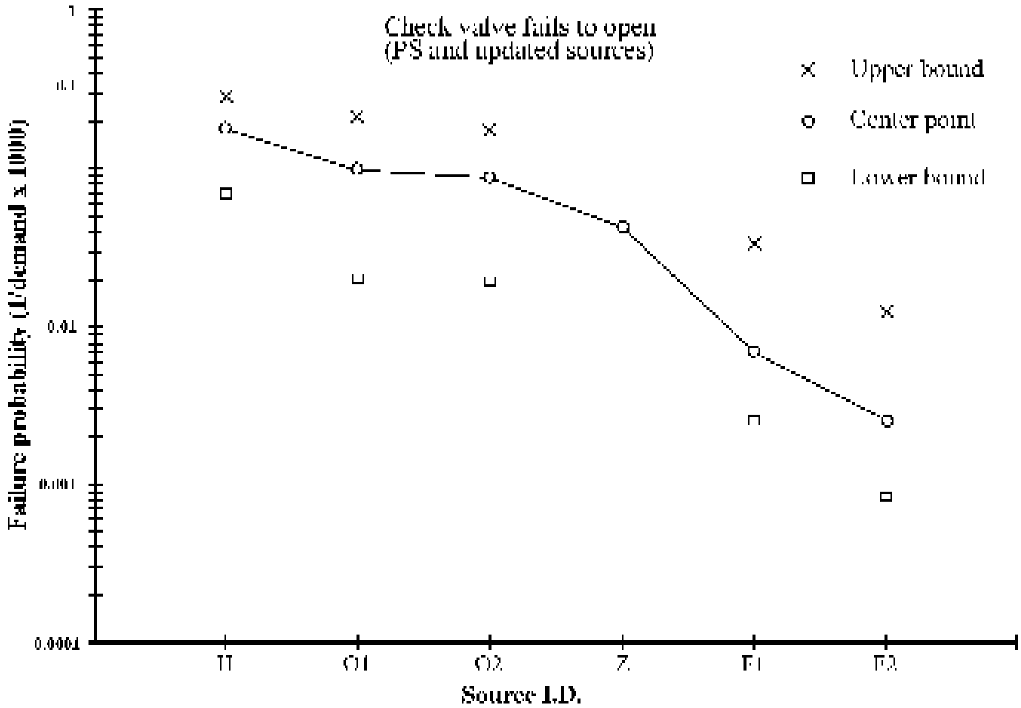


FIG. 35: CHECK VALVE FAILS TO OPEN (PS AND UPDATED SOURCES)

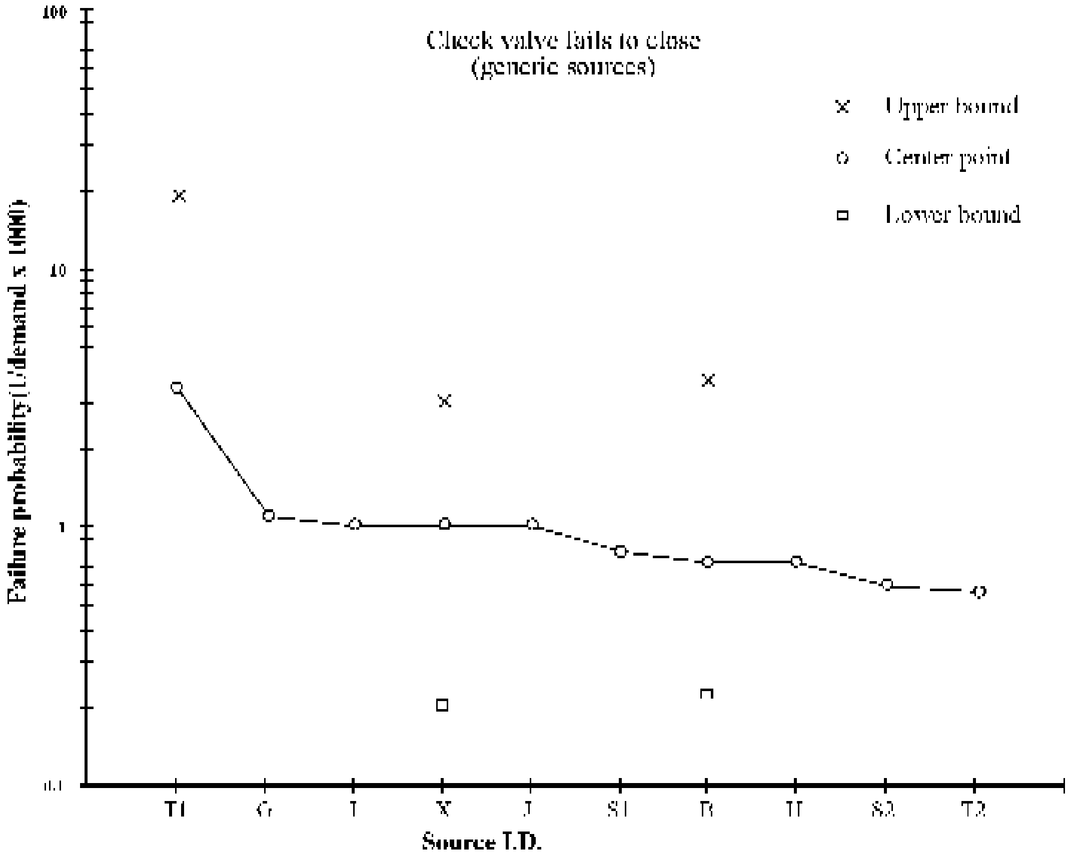


FIG. 36: CHECK VALVE FAILS TO CLOSE (GENERIC SOURCES)

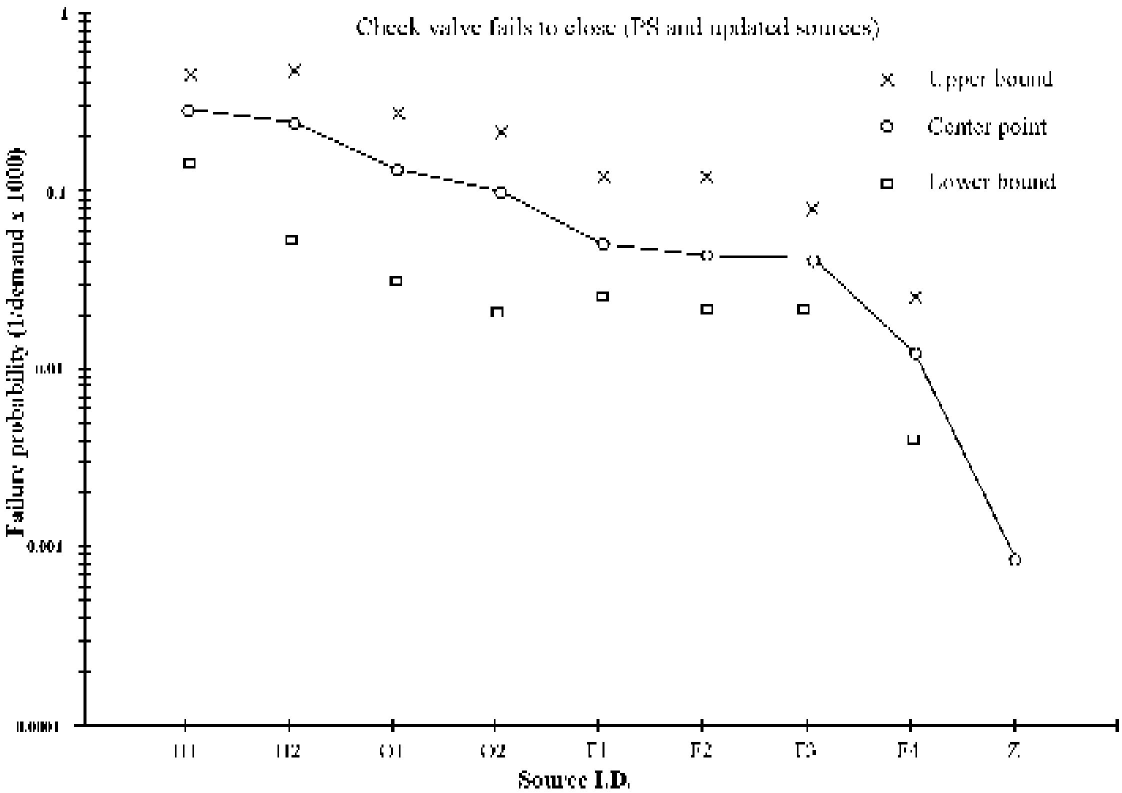


FIG. 37: CHECK VALVE FAILS TO CLOSE (PS AND GENERIC SOURCES)

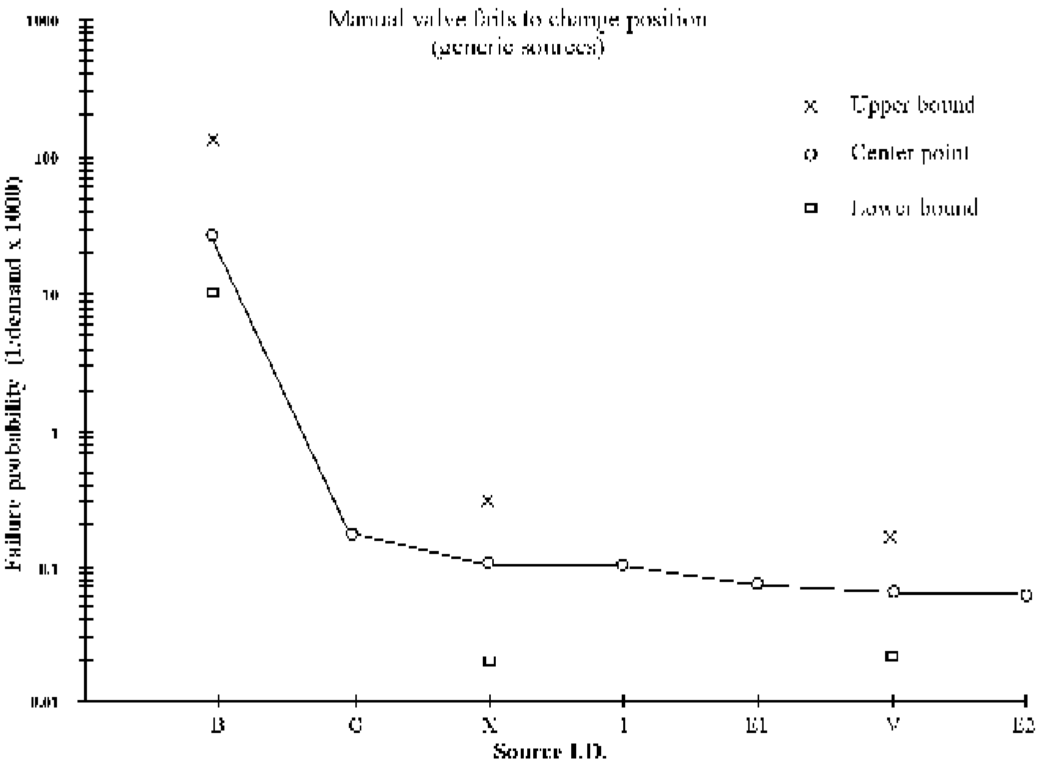


FIG. 38: MANUAL VALVE FAILS TO CHANGE POSITION (GENERIC SOURCES)

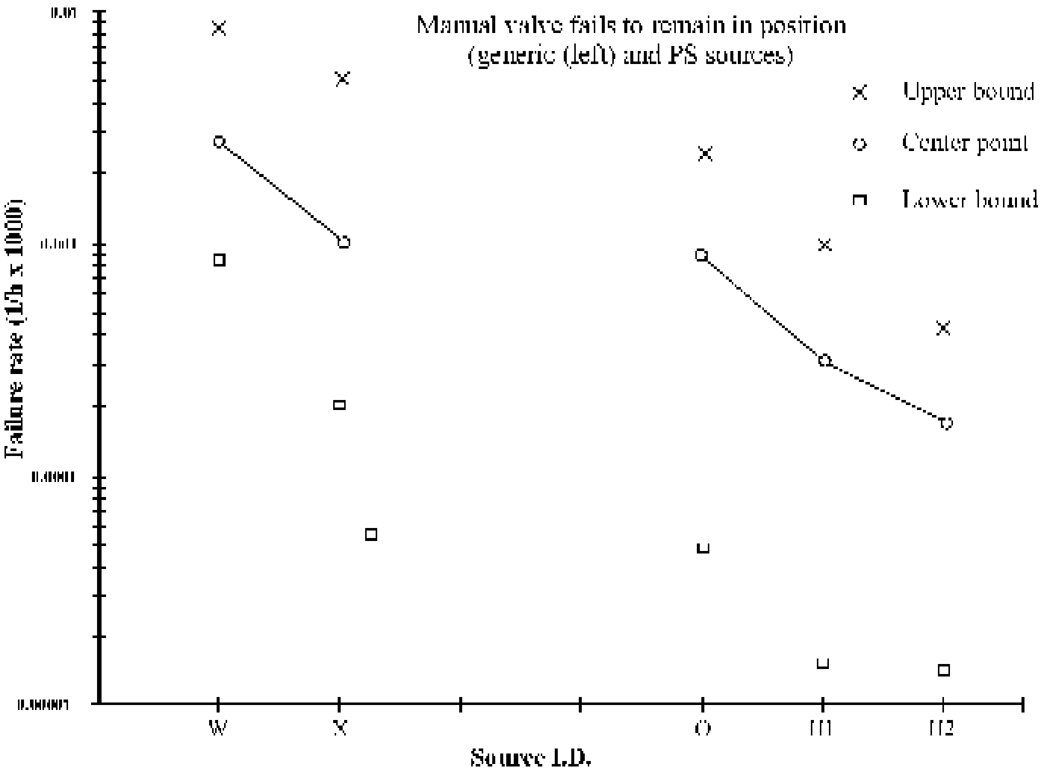


FIG. 39: MANUAL VALVE FAILS TO REMAIN IN POSITION (GENERIC (LEFT) AND PS SOURCES)

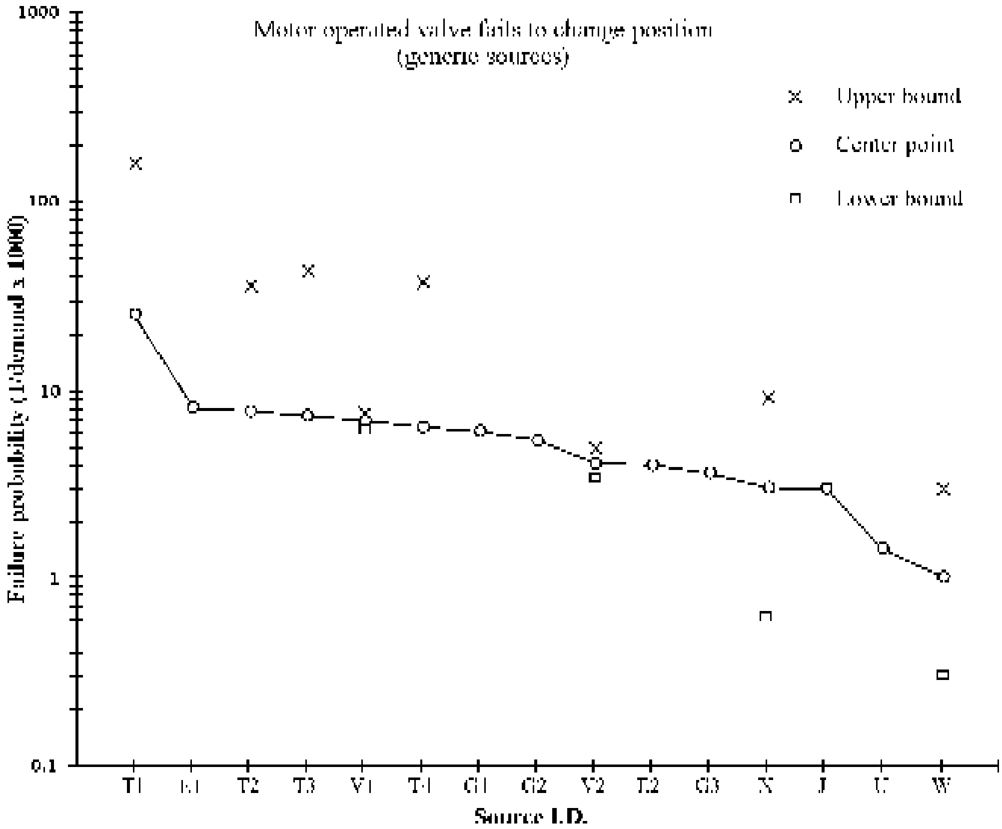


FIG. 40: MOTOR OPERATED VALVE FAILS TO CHANGE POSITION (GENERIC SOURCES)

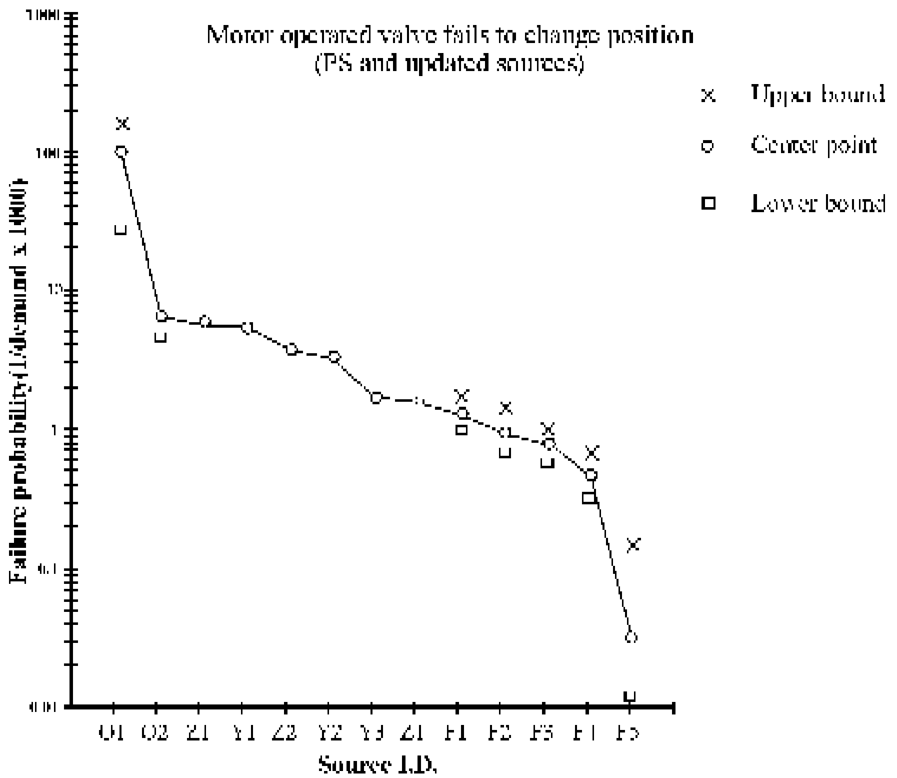


FIG. 41: MOTOR OPERATED VALVE FAILS TO CHANGE POSITION (GENERIC SOURCES)

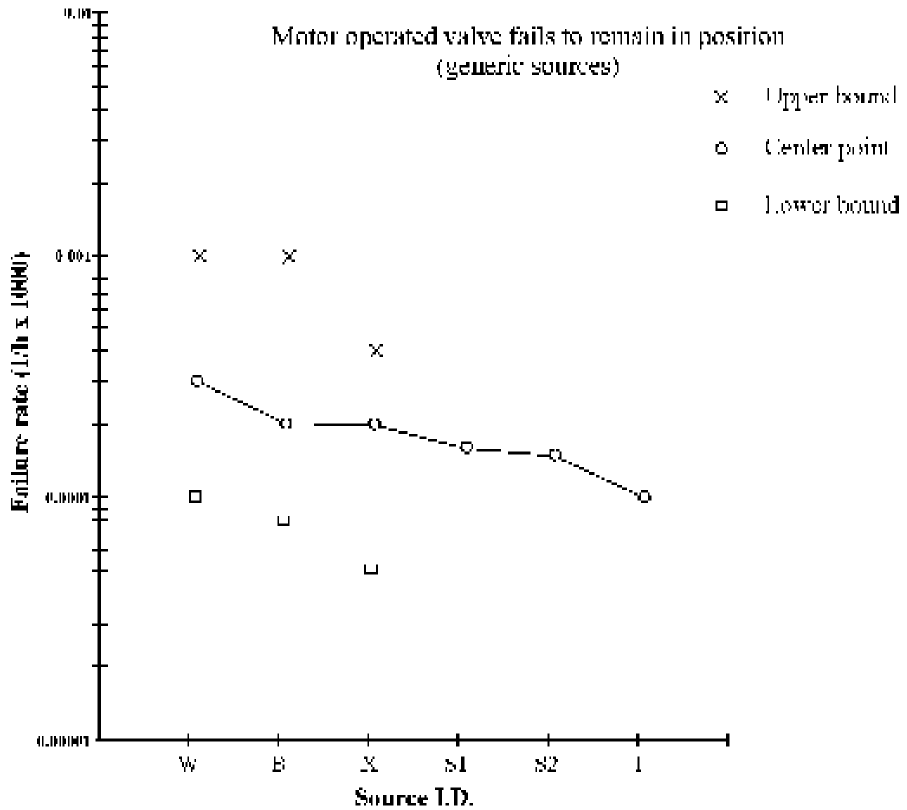


FIG. 42: MOTOR OPERATED VALVE FAILS TO REMAIN POSITION
(GENERIC SOURCES)

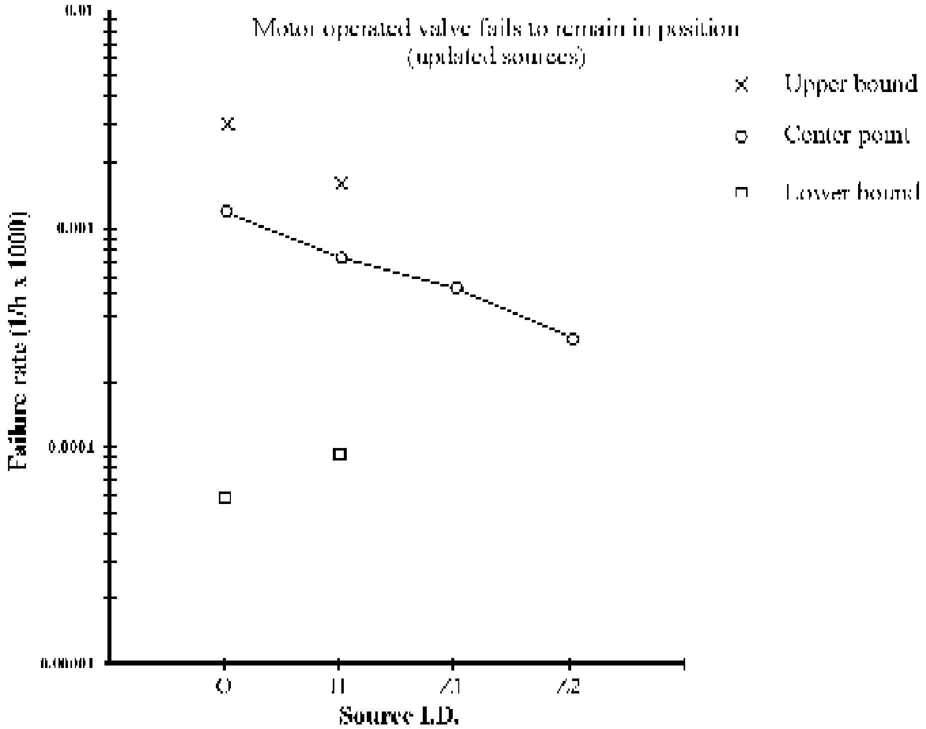


FIG. 43: MOTOR OPERATED VALVE FAILS TO REMAIN IN POSITION (GENERIC SOURCES)

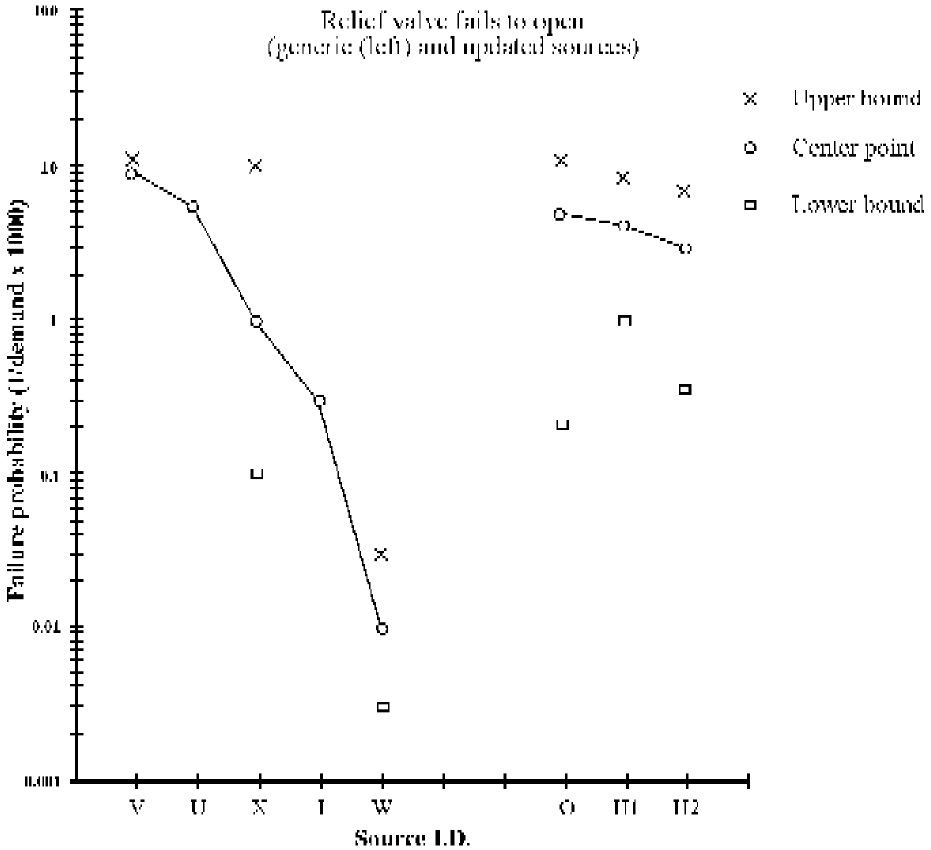


FIG. 44: RELIEF VALVE FAILS TO OPEN (GENERIC (LEFT) AND UPDATED SOURCES)

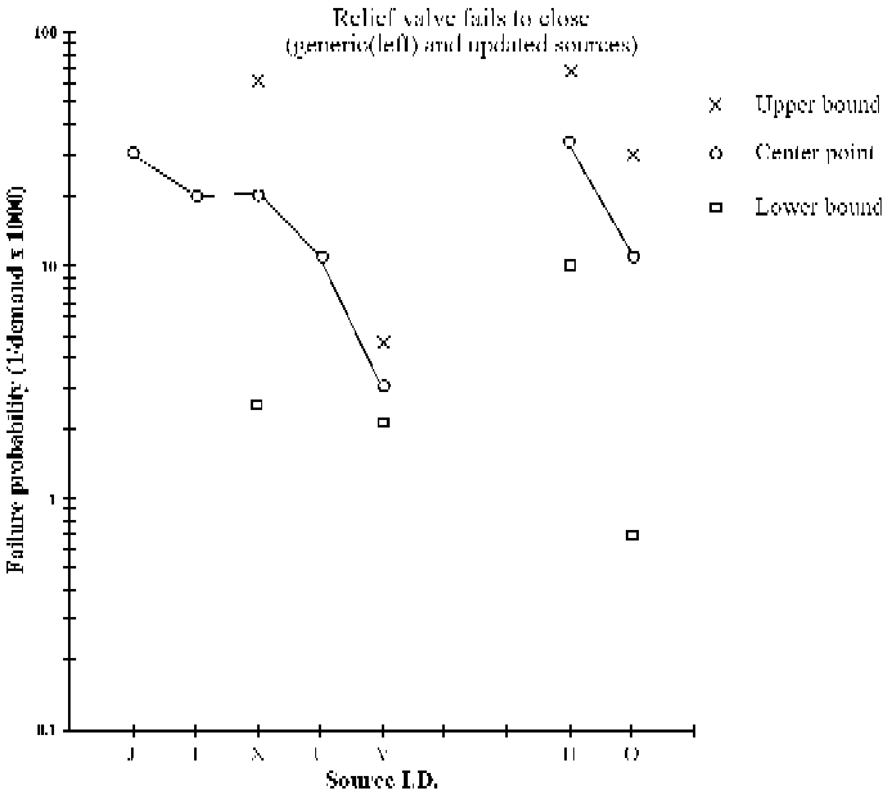


FIG. 45: RELIEF VALVE FAILS TO CLOSE (GENERIC (LEFT) AND UPDATED SOURCE)

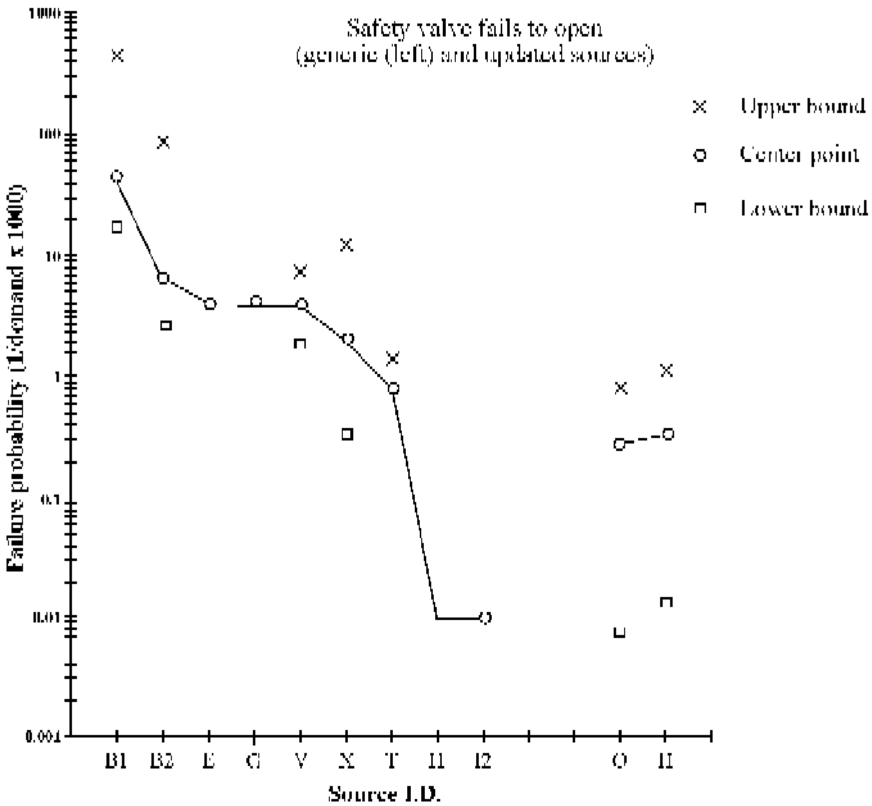


FIG. 46: SAFETY VALVE FAILS TO OPEN (GENERIC (LEFT) AND UPDATED SOURCES)

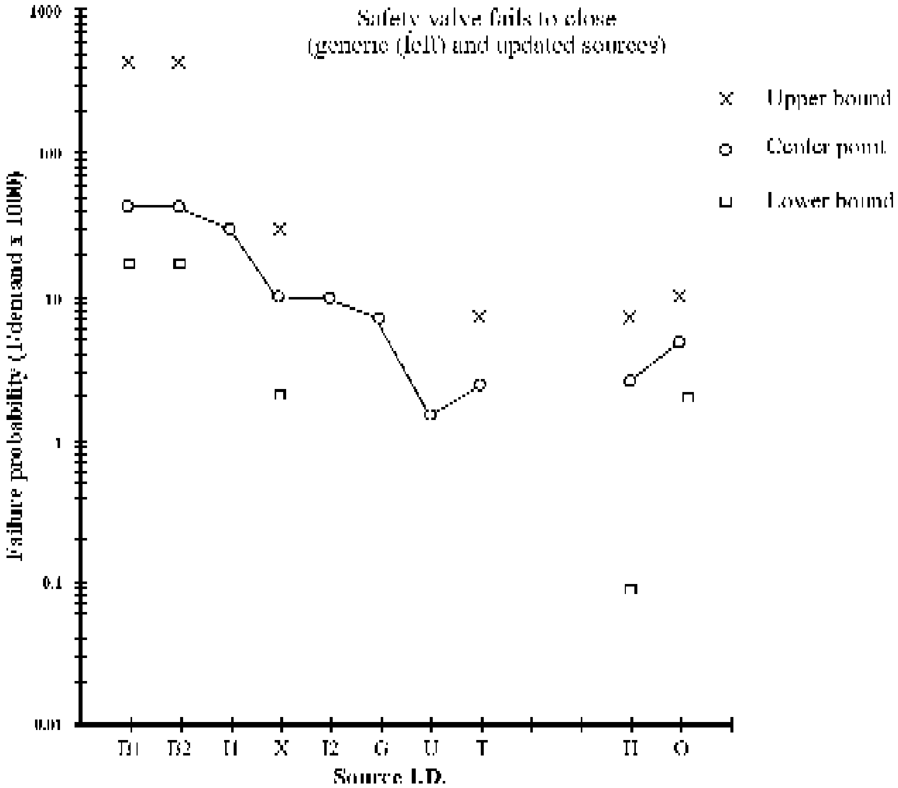


FIG. 47: SAFETY VALVE FAILS TO CLOSE (GENERIC (LEFT) AND UPDATED SOURCES)

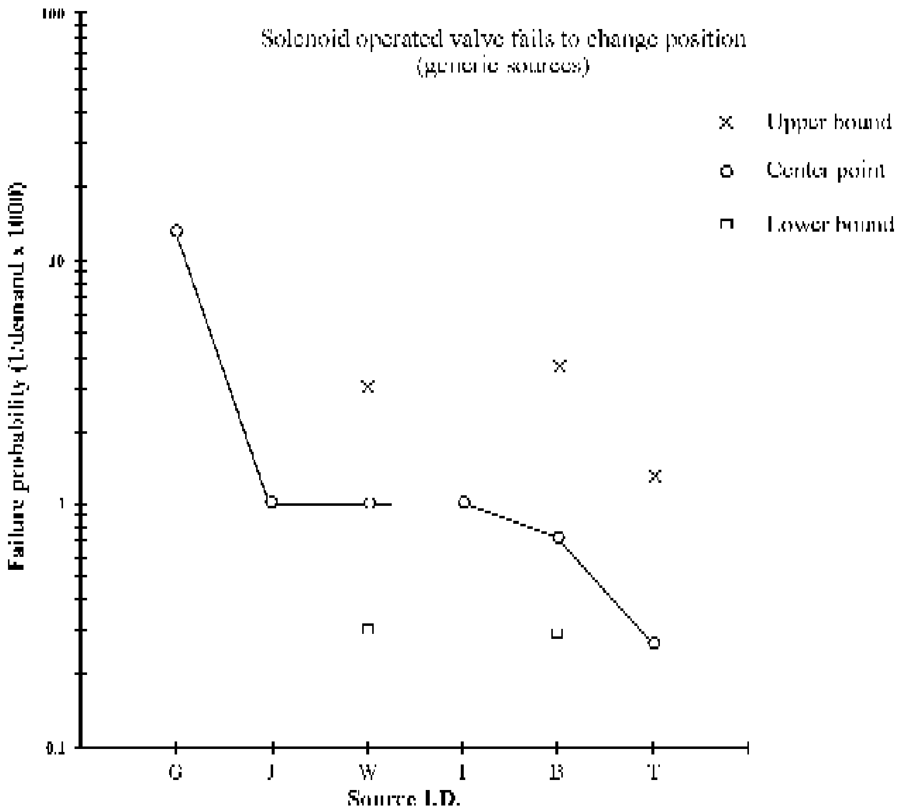


FIG. 48: SOLENOID OPERATED VALVE FAILS TO CHANGE POSITION (GENERIC SOURCES)

7. COMMON CAUSE FAILURE DATA AND ANALYSIS

Common cause failures (CCFs) are multiple, dependent failures arising due to a common initiating cause. It is not the intent here to discuss the technicalities of CCF analysis but to briefly outline the approach to be considered, in view of the limitations in the CCF data.

Dependencies may be classified as functional (relating to shared systems or components) and non-functional (relating to design, manufacture, operation, test and maintenance, human related, environmental failures, etc.) Functional dependencies can be explicitly modeled in the system fault trees. In case of non-functional dependencies, following approach may be followed, as recommended in NUREG/CR-5801. [4]

Phase - I:

Screening analysis involving qualitative and quantitative analysis to 1) identify all the potential vulnerabilities of the systems to CCFs, 2) identify common cause component groups (CCCGs) within the system whose common cause failures can contribute significantly to system unavailability.

Phase - II:

This phase covers a detailed qualitative analysis, involving an understanding of plant specific vulnerabilities to CCFs, by examining the susceptibility of the systems and components to causes and coupling mechanisms of CCFs. This requires identification of plant specific defense mechanisms and qualitative evaluation of their effectiveness to identify dominant CCCGs. The usual technique used in this phase is the cause - defense matrix technique.

Phase - III:

This phase uses the results of phases I and II, and requires detailed logic modeling, parametric representation and data analysis, to obtain quantitative estimates for system unavailability due to CCFs.

Approach to Quantitative CCF Analysis

The analysis of dominant CCCGs depends upon the availability of CCF data. In case independent failures, particularly component failures, have been observed, the variability or uncertainty in failure data is not very significant. However, incase of CCF, uncertainty prevails both in respect of data (small number of observed failures) and also the models. CCF analysis, using the conservative global parametric model- b- factor model has been widely used in PSA studies. The b factor model is simple to use but is generally suitable in the case of two component systems. The basic assumption in this model is that a common cause affects all the components in the redundant system. This model is too conservative.

It may be argued that an appropriate model, e.g. multiple greek letter (MGL) model and a-factor model, may be used in case of higher order redundant systems (involving 3 or more components in the CCCG) like the emergency power supply system. However the paucity of plant specific data to estimate the parameters of say a-factor model, may necessitate the use of generic a-factors. This could introduce larger uncertainties.

The conservatism in b- factor model may be taken care of by applying the partial b- factor model wherein, the b- factor is apportioned into various factors contributing to the non-functional dependencies. SRD-146 (Safety and Reliability Directorate of UKAEA) provided an insight into the estimates of partial b- factors. Recently, studies have been carried out in the international common cause failure data exchange (ICDE) Programme (Table 8 and Table 9) to determine the CCF root cause distributions for emergency diesel generators, motor operated valves, etc.

Comparative contributions of various root causes have been estimated to minimise the same during the design stage. The following table indicates the results of such studies, which provide an idea of the potential b- factors. It is important to note that this data is based on large population of components and systems.

INTERNATIONAL COMMON CAUSE FAILURE DATA EXCHANGE (ICDE) PROGRAMME

TABLE-8: CCF ROOT CAUSE DISTRIBUTION FOR EMERGENCY DIESEL GENERATORS

Root Cause	No. of Events	Percent
Abnormal Environmental Stress	13	12.3
Design, Manufacture or Construction Inadequacy	46	43.4
Human Actions	16	15.1
Internal To Component	12	11.3
Maintenance	7	6.6
Procedural Inadequacy	10	9.4
Others	2	1.9
Total	**106**	**100**

TABLE-9: CCF DATA OF MOTOR OPERATED VALVES

Root Cause	No. of Events	Percent
Abnormal Stress	3	3.75
Design	25	31.75
Human Action	10	12.5
Internal Parts	24	30.0
Maintenance	1	1.25
Procedure Inadequacy	11	13.75
Others	6	7.5
Total	**80**	**100**

8. HUMAN RELIABILITY ANALYSIS

Human interactions associated with safety systems and control room operations are recognised as important contributors to the safe operation of nuclear power plants. It is essential to identify the key human interactions to be considered in safety assessment. A classification scheme as below helps the analysts to consider the possible interactions in the different stages of accident sequences and provides completeness to a large extent.

Type 1: Testing and maintenance actions prior to an initiating event.

Type 2: Human errors that directly initiate accidents.

Type 3: Amelioration of an accident by correctly responding to an event.

Type 4: Exacerbation of an accident by taking incorrect actions.

Type 5: Amelioration of an accident sequence in progress by improvisations, which were not specifically included in the procedures.

By defining the above types of action categories, the selection of the most appropriate analysis and quantification techniques can be made to account for differences in the mechanisms leading to significant human errors. For example, miscalibration events and failure to restore equipment following maintenance (Type 1) occur under controlled conditions (e.g. no accident, little or no time pressure). Type 3 and Type 5 actions would depend upon the cognitive behaviour of the operator in detection and diagnosis of the situation, before the decision making process to carry out specific actions, in a limited time under high stress. Cognitive actions are usually represented by the human cognitive reliability (HCR) model, which is essentially time dependent and validated with data from training simulator exercises. Human error probability (HEP) data associated with manual actions (error of omission, error of commission, etc.) during test and maintenance (Type 1) or post accident (Types 3, 4, 5) and also the various performance shaping and recovery factors are indicated in various tables of Appendix B [5] taken from NUREG/CR - 1278 handbook. [6]

8.1 Human Cognitive Reliability (HCR) Models

The HCR model is a normalised time -reliability curve (with HEP being represented by non-response probability) depicting the human cognitive processing associated with the task being performed. The model essentially applies to cases of short time duration wherein the thinking and decision times available subsequent to the annunciation of an incident are important for diagnosis. The normalised curves in the figure correspond to 3 categories of cognitive behaviour, namely, skill, rule and knowledge based. The normalised time in the abscissa is the ratio of time available to the crew for completing a set of actions before the onset of damage, to the median time taken by the crew to complete the actions or the tasks. The time available for diagnosis and action is usually obtained from the thermal hydraulic behaviour of the systems during the abnormal situations. The effects of performance shaping factors (PSFs), e.g. operationally induced stresses, the arrangement of control room equipment, i.e. the man machine interface design, skill of the operating crew, etc. are accounted for by modifying the median time to perform the tasks. It is assumed that while the type of cognitive processing is unaffected by the PSFs, the time to perform the task is affected.

8.1.1 HCR Correlation.

The HCR model explained above can be expressed by the following mathematical correlation that is based on the simulator data and the approximate fitting of the response to a Weibull distribution

$$P(t) = \exp - [(t/T_{1/2} - B_i)/A_i]^{C_i}$$

t - is the time available to the crew to complete the set of actions following an annunciation before the onset of damage.

T1/2 - is the estimated median time taken for completion of set of actions.

Ai, Bi, Ci - are the correlation coefficients associated with the type of cognitive processing, i.e. skill, rule or knowledge based.

P (t) - is the crew non-response probability.

The values of the correlation coefficients are as follows:

TABLE-10: HCR PARAMETERS

Cognitive Processing Type	A_i	B_i	C_i
Skill	0.407	0.7	1.2
Rule	0.601	0.6	0.9
Knowledge	0.791	0.5	0.8

8.1.2 Effects of Performance Shaping Factors

The median time $T_{1/2}$ taken by the crew for completing the job is usually the nominal time, which is modified by the PSFs due to operator skill (K1), stress level (K2) and the quality of man machine interface (K3). The HCR model PSFs, and the related coefficients are indicated in Table-11:

TABLE-11: COEFFICIENTS

OPERATOR EXPERIENCE (K1)		
1.	Expert, well trained	- 0.22
2.	Average knowledge training	0.00
3.	Novice, minimum training	0.44
STRESS LEVEL (K2)		
1.	Situation of grave emergency	0.44
2.	Situation of potential emergency	0.28
3.	Active, no emergency	0.00
4.	Low activity, low vigilance	0.28
QUALITY OF OPERATOR/PLANT INTERFACE (K3)		
1.	Excellent	- 0.22
2.	Good	0.00
3.	Fair	0.44
4.	Poor	0.78
5.	Extremely poor	0.92

Thus, the actual time T to be used in the model is represented as

$T_{1/2} = T_{nom.}$ (1 + K1) (1 + K2) (1 + K3) where $T_{nom.}$ is the nominal estimated median time for the crew.

8.2 Nominal Diagnosis Model (NUREG/ CR-1278)

The nominal diagnosis model is used for estimating the human error probability of correct diagnosis of abnormal events within various system-allowable times after the annunciation of the event. Diagnosis is associated with identification of most likely causes of the abnormal event to the level required to identify the systems and components whose status can be changed to eliminate the problem. The model considers diagnosis time/HEP curve for the control room operators taken as a team. Some representative values are depicted in Table-12:

TABLE-12

Item	Diagnosis Time T (Minutes)	Nominal HEP	EF
1	1	1.0	
2	10	0.1	10
3	20	0.01	10
4	30	0.001	10
5	60	0.0001	30

The table depicts nominal values. Some guidelines for adjusting the nominal diagnosis HEPs are as follows:

1. Use upper bound if:

   - The event is not covered in training.

     or

   - The event is covered but not practiced, except in initial training of operators for becoming licensed.

     or

   - The talk-through and interviews show that not all operators know the pattern of stimuli associated with the event.

2. Use lower bound if:

   - The event is well recognised and the operators have practiced the event in the simulator requalification exercises.

     and

   - The talk-through and interviews indicate that all the operators have a good verbal recognition of the relevant stimulus patterns and know what to do or which written procedures to follow.

3. Use nominal HEP if:

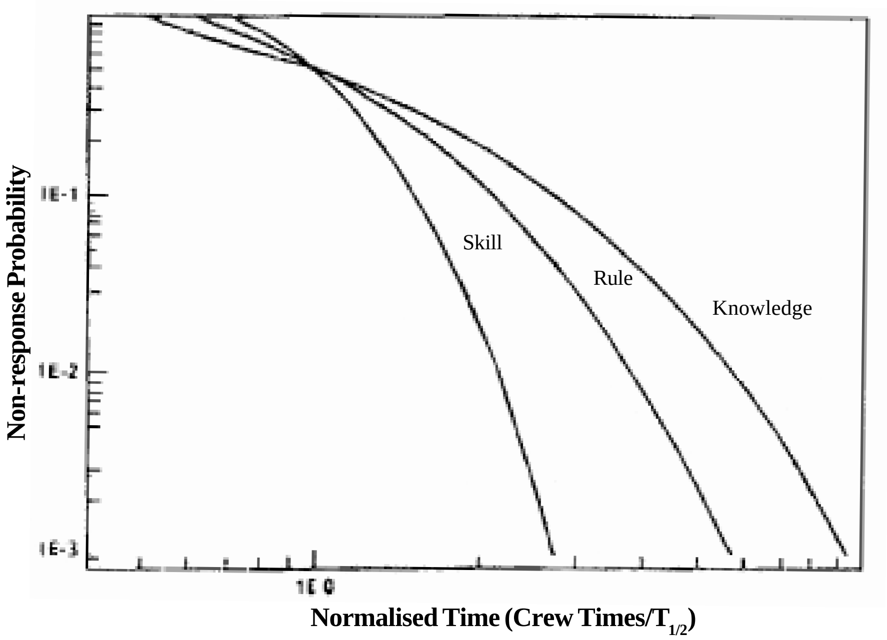
   - The only practice of the event is in simulator requalification exercises and all operators have had this experience.

     or

   - None of the rules for use of upper or lower bound apply.

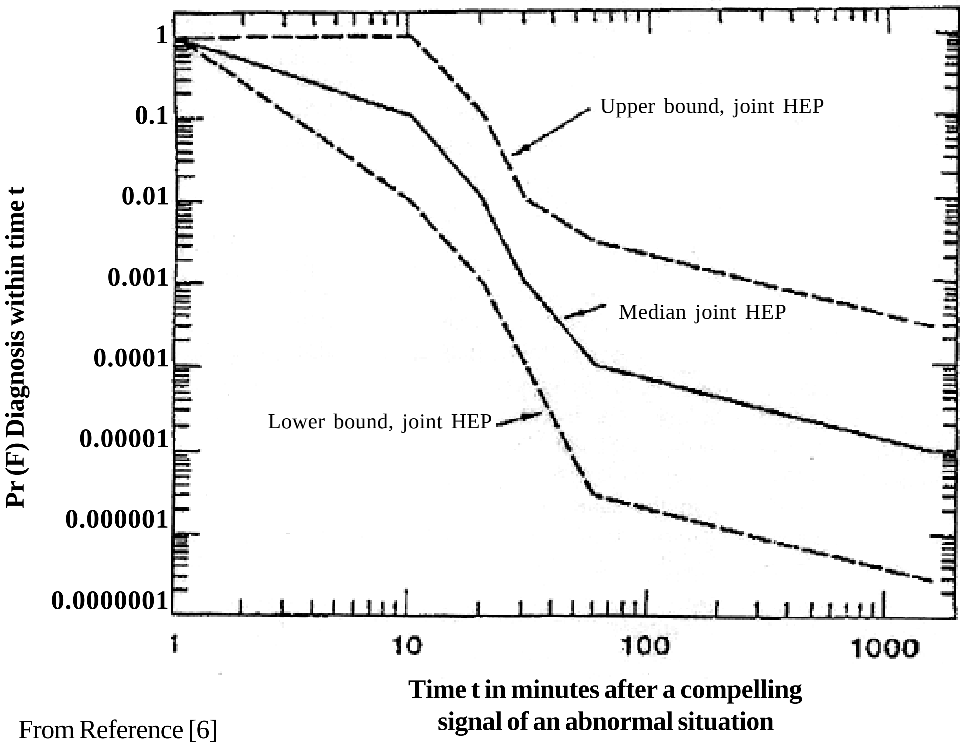
For execution tasks, THERP/ASEP methodology may be used. Some selected tables of HEPs from NUREG/CR /1278 are given in Appendix B. The graphs corresponding to HCR and nominal diagnostic model are included in this section. ASEP methodology is detailed in NUREG/CR/4772. [7]

HCR CORRELATION



From Reference [5]

NOMINAL DIAGNOSIS MODEL



From Reference [6]

9. RELIABILITY DATA ON FAST REACTORS

A note on the ‘reliability data on fast reactors’ has been issued by the safety analysis section, RPD, IGCAR wherein, failure data obtained from fast reactor operating experience has been compiled. The same is reproduced in Table-13. The references [8-16] used in the compilation are also included. It is seen that the failure rates of the majority of mechanical, electrical, instrumentation devices etc. are comparable with data collected for the other nuclear plants. The comments in cases where the data are significantly different are given below. It may be noted that the references for the fast reactor data generally reflect the operating experience that is plant specific and needs to be used with caution.

In case of shut down systems (Table-13 A) the failure rates in many cases are low, e.g. for the control rod failure [10], the probability 4E - 5/d is low. However, it is within the error factors of the generic data as quoted in WASH-1400. In some cases, in data for instrumentation [10], the failure rate contribution due to human error is also included. The contribution due to human error is in the range of 1E - 7/h - 1E - 6/h which is about 10 - 30 % of the respective failure rates. In case of various accident sequences [10] initiated by loss of offsite power (LOSP) or loss of flow accidents, etc. the frequency is in the range 1E - 7/y - 1E - 8/y, which is low. The total frequency of core degradation 9.2E - 7/y is quite low. In the same source, it appears to be contradictory that the frequency of core degradation due to all transients is depicted as 1.1E - 6/y, whereas due to internal initiators, it is 2E - 6/y.

In Table-13 B for decay heat removal systems, the frequency of feed water supply failure [10], 9.2E -7/y is very low. In case of failure rates of tanks, vessels and piping, etc. the failure rate is of the order of 1E -4/h, which is rather too high. In case of failure rate of emergency diesel generator, two values namely 3E -3/h and 1E -6/h have been quoted, which must be for two different failure modes. The failure rate 3E - 3/h usually pertains to the mode, fails to run for the given mission time, as quoted in a majority of the data sources. The mode of failure is not clear for the lower failure rate.

In Table-13 C, failure data - general, the frequency of core damage [13] is depicted as 2.4E -4/y, which is quite high and would require reliability enhancement. The failure rate of core catcher [11] for the period 0 -10 h into the accident is quoted as 1E - 01/d, and for the period 10- 100 h it is 8E - 1/d. The reliability of the system appears to be low. However, in the absence of any supporting data from other sources, it is difficult to comment on the likely reasons of such a high value.

TABLE-13A: SHUT DOWN SYSTEM

	Components	Failure Rate	Reference
1.	**Sensors/Detector**		
	a. Nuclear detecor		
	Neutron monitor sensors		
	(i) Fission count	6.00 E -06/h	8
	(ii) Compensated ion chamber	3.86 E -06/h 5.00 E -06/h 5.43 E -04/h	9 9 9
	(iii) Uncompensated ion chamber	3.83 E -06/h	9
	(iv) Fuel temperature meter	3.04 E -06/h	9
	(v) Control rod position indicator	7.83 E -06/h	9
	(vi) Rod drive mechanism	1.01 E -06/h	9
	(vii) Log channel recorder	0.21 E -06/h	9
	b. Thermocouple		
	(i) Catstrophic failure (sudden)	1.3 E -06/h	10
	(ii) Failure corresponding to a parameter drift	2.5 E -08/h	10
	(iii) Failure corresponding to a leak	1.7 E -08/h	10
	(iv) Failure corresponding to human error	3.0 E -07/h	10
	c. Flow meters		
	(i) Catastrophic failure	2.5 E -06/h	10
	(ii) Failure due to a parameter drift	4.2 E -07/h	10
	(iii) Failure due to leak	1.5 E -07/h	10
	(iv) Failure due to human error	1.5 E -07/h	10
2.	**Neutronic Compoments**		
	a. Instruments		
	(i) Power Supply	1.5 E -05/h	11
	(ii) Amplifiers	5.0 E -06/h	11
	(iii) Trip breaker	5.0 E -03/d	11
	(iv) Logic module	3.0 E -06/h	11
	(v) Scram failure (LOF Event)	4.97 E -06/d	9
	Scram failure (LOF Event)	4.72 E -06/d	9
	Scram failure (TOP Event)	1.69 E -04/d	9
	Scram failure (TOP Event)	9.1 E -06/d	9
	b. Electromagnetic clutch (disengagement)	1.0 E -06/h	8
	c. Drive mechanism (CRDM)	3.0 E -05/d	14
	d. Absorber rod	2.0 E -04/d	8
	e. Individual control rod	4.0 E -05/d	14
	f. Control (altogether)	1.0 E -04/d	14

TABLE-13A: SHUT DOWN SYSTEM (Contd.)

	Components	Failure Rate	Reference
3.	**Pressure**		
	(i) Catastrophic failure	1.4 E -06/h	10
	(ii) Failure due to parameter drift	1.2 E -07/h	10
	(iii) Failure due to leak	1.2 E -07/h	10
	(iv) Failure due to human error	3.5 E -06/h	10
	(v) Primary coolant pump	69.2 E -06/h	9
	(vi) Heat exchanger	0.44 E -06/h	9
	(vii) Argon exhaust fan	2.78 E -06/h	9
4.	Radiation monitor	8.0 E -06/h	9
5.	Primary logic train failrue (shutdown system)	2.8 E -08/h	10
6.	Secondary logic train failure (SDS)	4.0 E -06/h	10
7.	Scram breaker failure (SDS)	1.7 E -06/h	10
8.	Primary electrical system (SDS)	2.1 E -08/h	10
9.	Secondary electrical system (SDS)	8.3 E -06/h	10
10.	Secondary scram breakers (SDS)	8.2 E -06/h	10
11.	Individual control rod failure (SDS)	4.0 E -05/d	10
12.	Failure of two rods out of 12 (SDS)	1.1 E -07/d	10
13.	LWR shut down system (SDS)	3.0 E -05/h	10
14.	Total reactor shut down system (SDS) (Due to independent failures)	1.1 E -12/y	10
15.	LWR-primary and secondary systems	1.6 E -07/h	10
16.	LOSP (protected core disruptive accident) (loss of offsite power).	7.8 E -09/y	10
17.	LOSP (unprotected loss of flow accident)	7.8 E -08/y	10
18.	LOFW (protected core disruptive accident) (loss of main feed water)	5.5 E -09/y	10
19.	LOFW (unprotected loss of flow and unprotected loss of heat sink accident)	8.3 E -07/y	10
20.	The total frequency of core degradation	9.2 E -07/y	10
21.	For LMFBR, Pump trip system failure	0.1/d	10
22.	Core degradation frequency due to emergency shutdown	2.1 E -06/y	10
23.	Total frequency of core degradation due to all translents	1.1 E -06/y	10
24.	Core degradation due to internal initiators	2.0E -06/y	10

TABLE-13A: SHUT DOWN SYSTEM (Contd.)

	Components		Failure Rate	Reference
25.	LMFBR	LOSOP	LOFW	
	Active system	1.6 E -02/d	3. 0E -02/d	10
	Passive system	4.3 E -08/d	1.5 E -05/d	10
26.	Diesel generator		1.0E -06/h	10
27.	Sodium loop		1.0E -05/h	10
28.	Steam loop		1.0E -04/h	10
29.	Bellow valves		1.0E -06/h	10
30.	Frozen seal valves		2.0E -07/h	10
31.	Power electric motors		1.0E -05/h	10
32.	Motor		2.0 E -05/h	10
33.	Regulation and controlling system		8.0 E -05/h	10
34.	Sodium-air heat exchanger (due to ventilation)		4.0 E -05/h	10
35.	Sodium - air heat exchanger (due to leak)		3.0 E -06/h	10

TABLE-13B: DECAY HEAT REMOVAL SYSTEM

	Components	Failure Rate	Reference
I.	**Pump**		
	a. Motor driven	3.0 E -03/d	9
		3.0 E -05/h	9
	b. Turbine driven	3.0 E -02/d	9
		1.0 E -04/h	9
	c. Diesel driven	1.0 E -02/d	9
		5.0 E -03/h	9
	d. Electromanetic pumps	3.0 E -05/h	10
		1.4 E -06/h	10
II.	**Intermediate Heat Exchanger**	2.0 E -06/h	10
		3.2 E -05/h	10
III.	**Steam Generator**	5.0 E -05/h	10
		1.0 E -03/y	11
IV.	**Sodium-Air HX**		
	(due to ventilation problem)	4.0 E -05/h	11
	(due to leak)	3.0 E -06/h	11
	a. Sodium piping	2.6 E -04/h	8

TABLE-13B: DECAY HEAT REMOVAL SYSTEM (Contd.)

	Components	Failure Rate	Reference
	b. Traps for sodium	2.3 E -04/h	8
	c. Sodium valves	1.2 E -04/h	8
	d. Air driers	2.1 E -04/h	8
V.	**Feed Water Supply**	9.2 E -07/y	10
		2.0 E -09/d	10
VI.	**Power Supply**		
	a. Main	3.0 E -05/h	
	b. Grid	1.0 E -05/d	12
	c. Emergency		
	(i) Diesel generator	3.0 E -03/h	10
		1.0 E -06/h	10
	(ii) Battery operated	3.0 E -06/h	10
	d. Loss of off-site power (LOSP)	0.3/y	11
		3.0 E -08/d	11
	(i) Protected core disruptive accident	7.8 E -09/y	11
	(ii) Unprotected loss of flow accident	7.8 E -08/y	11
VII.	**Tanks and Vessels**	1.2 E -04/h	11
VIII.	**Pipe**	1.0 E -04/h	11
	a. Sodium loop	1.0 E -05/h	10
	b. Steam loop	1.0 E -06/h	10
IX.	**Valve**		
	a. Leakage	1.0 E -08/h	9
	b. Rupture (non-primary coolant system)	4.0 E -10/h	9
	(primary coolant system)	1.0 E -10/h	9
	c. Motor operated		
	Fail to open/close	3.0 E -03/h	9
	Spurious operation	5.0 E -08/h	9
	Plug	5.0 E -09/h	9
	Internal rupture	1.0 E -07/h	9
	d. Pneumatic operated		
	Fail to open/close	1.03 E -03/d	9
	Spurious operation	3.0 E -06/h	9
	Plug	3.0 E -08/h	9
	Internal leakage	1.0 E -06/h	9
	e. Solenoid		
	Fail to open/close	5.0 E -04/d	9

TABLE-13B: DECAY HEAT REMOVAL SYSTEM (Contd.)

	Components	Failure Rate	Reference
	Spurious operation	5.0 E -07/h	9
	Plug	3.0 E -09/h	9
	Internal leakage	1.0 E -06/h	9
f.	Manual valve		
	Fail to open/close	5.0 E -04/d	9
	Plug	3.0 E -07/h	9
	Internal rupture	5.0 E -08/h	9
g.	Check valve		
	Fail to open	5.0 E -05/d	9
	Fail to close	1.0 E -03/d	9
	Plug	5.0 E -09/h	9
	Internal leakage	3.0 E -06/h	9
h.	Vacuum		
	Breaker valves		
	Fail to open	3.0 E -04/d	13
	Premature opening	3.0 E -06/h	13
	Fail to reclose	3.0 E -03/h	13
	Relief valve		
	Fail to open	3.0 E -03/d	13
	Premature opening	5.0 E -06/h	13
	Fail to reclose	3.0 E -03/h	13
X.	**Sodium Level**		
	Catastrophic failure rate	3.5 E -06/h	10
	Failure rate due to parameter drift	2.0 E -07/h	10
	Failure rate due to leak	1.4 E -07/h	10
	Failure rate due to human error	1.0 E -06/h	10

TABLE-13C: FAILURE DATA - GENERAL

	Components	Failure Rate	Source
1.	**Switch Contacts**	1.0 E -07/h	13
2.	**Transformers Open Circuit Primary**	1.0 E -06/h	13
3.	**Solid State Devices Hi-power Application** (Diodes, transistors, etc.)		
	Fails to function	3.0 E -06/h	13
	Fails shorted	1.0 E -07/h	13

TABLE-13C: FAILURE DATA - GENERAL (Contd.)

	Components	Failure Rate	Reference
4.	**Solid State Devices Low Power**		
	Application		
	Fails shorted	1.0 E -07/h	13
5.	**Diesels (Complete Plant)**		
	Fail to start	3.0 E -02/d	13
6.	**Instrumentation**		
	(Transmitter, amplifier and output devices)		
	Fail to operate	1.0 E -06/h	13
	Shift in calibration	3.0 E -05/h	13
7.	**Fues**		
	Fail to open	1.0 E -05/d	13
	Premature to open	1.0 E -06/h	13
8.	**Wires (Typical Circuits and Joints)**		
	Open circuits	3.0 E -06/h	13
	Short to ground	3.0 E -07/h	13
	Short to power	3.0 E -08/h	13
9.	**Relays**		
	Fail to energise	1.0 E -04/d	13
	Coil open	1.0 E -07/h	13
	Coil short to power	3.0 E -08/h	13
10.	**Circuit Breakers**		
	Fail to transfer	1.0 E -03/d	13
	Premature transfer	1.0 E -06/h	13
11.	**Core Damage**	2.4 E -04/y	13
12.	**Control Rod**		
	Fail to insert	3.0 E -05/d	13
13.	**A.C. Unit**		
	Fail to start	1.0 E -02/d	13
	Fail to run	3.0 E -05/h	13
14.	**Compressor/Blower**		
	Fail to start	5.0 E -03/d	13
	Fail to run	1.0 E -04/h`	13
15.	**Damper**		
	Fail to open/close	3.0 E -0.3/d	13
	Spurious operation	3.0 E -07/h	13

TABLE-13C: FAILURE DATA - GENERAL (Contd.)

	Components	Failure Rate	Reference
16.	**Air Filter**		
	Plug	1.0 E -05/h	13
17.	**Strainer (Water)**		
	Plug	5.0 E -06/h	13
18.	**Clutch**		
	Fail to engage	3.0 E -04/d	13
19.	**Heater**		
	(i) Air, fail to heat	5.0 E - 06/h	13
	Overheat	1.0 E -06/h	13
	(ii) Immersion, fail to heat	1.0 E -06/h	13
	Overheat	1.0 E -07/h	13
	(iii) Pipe, fail to beat	1.0 E -06/h	13
20.	**Transformer**		
	Power failure	1.0 E -06/h	13
	Instrument failure	1.0 E -06/h	13
21.	**Instrumentation**		
	Element failure	1.0 E -06/h	13
	Transmitter failure	3.0 E -06/h	13
	Radiation failure	5.0 E -06/h	13
22.	**Generators**		
	(i) Diesel		
	Fail to start	1.0 E -02/d	13
	Fail to run	5.0 E -03/h	13
	(ii) Hydro-turbine		
	Fail to start	3.0 E -03/d	13
	(iii) Motor-driven		
	Fail to run	3.0 E -05/h	13
	(iv) Gas-turbine		
	Fail to start	3.0 E -02/d	13
	Fail to run	3.0 E -04/h	13
23.	**Reactor Trip Breaker**		
	Fail to open	5.0 E -03/d	13
24.	**EDHR System**		
	(Immediately following reactor trip after 1000 hours reactor operation)	5.0 E -06/d	13

TABLE-13C: FAILURE DATA - GENERAL (Contd.)

Components	Failure Rate	Reference
25. Secondary Heat Removal System		
DRACS-2 loop ***(Direct Reactor Auxiliary Cooling system)***		
Refueling	7.4 E -10/y	12
Fail of PHT loop	3.3 E -08y	12
Fail of primary pump	2.9 E -9/y	12
Fail to IHTS loop	9.1 E -11/y	12
Fail of internals of pump	2.0 E -10/y	12
Fail of SGs	1.1 E -09y	12
Fail of radioactive RHRS	1.0 E -07/y	12
Fail of Non-radioactive RHRS	5.6 E -09/y	12
Total failure of all mentioned above	1.4 E -07/y	12
DRACS -3 loop		
Refueling	1.1 E -12/y	12
Fail of PHT loop	2.5 E -10/y	12
Fail of primary pump	8.8 E -12/y	12
Fail of IHTS loop	1.2 E -13/y	12
Fail of internals of pump	2.6 E -13/y	12
Fail of SGs	1.5 E -12/y	12
Fail of radioactive RHRS	9.6 E -10/y	12
Fail of Non-radioactive RHRS	1.3 E -12/y	12
Total failure of all mentioned above	1.2 E -09/y	12
PRACS - 3 loop ***(Primary/Reactor/Auxiliary Cooling System)***		
Refueling	5.5 E -09/y	12
Fail of PHT loop	2.1 E -06/y	12
Fail of primary pump	8.8 E -07/y	12
Fail of IHTS loop	2.4 E -10/y	12
Fail of internals of pump	5.2 E -10/y	12
Fail of SGs	3.9 E -09/y	12
Fail of radioactive RHRS	7.8 E -07/y	12
Fail of Non-radioactive RHRS	1.7 E -09/y	12
Total failure of all mentioned above	3.8 E -06/y	12
DRACS - 3 loop		
Refueling	6.3 E -08/y	12
Fail of PHT loop	9.2 E -06/y	

TABLE-13C: FAILURE DATA - GENERAL (Contd.)

Components	Failure Rate	Reference
Fail of primary pump	4.4 E -06/y	
Fail of IHTS loop	5.0 E -07/y	
Fail of internals of pump	1.1 E -06/y	
Fail of SGs	2.4 E -08/y	
Fail of radioactive RHRS	0.0	
Fail of Non-radioactive RHRS	5.6 E -07/y	
Total failure ofall mentioned above	1.6 E -05/y	12
26. Innocuous or Spurious		
Reactor Trip	10/y	11
27. Main Turbine Trip	3/y	11
28. Loss of Coolant Trip		
(i) Loop	1.0 E -03/y	11
(ii) Pool	1.0 E -03/y	11
29. Loss of Coolant Accident	1.0 E -07/y	11
30. Sudden Severe Tube Failure in Steam Generator	1.0 E -03/y	11
31. Reactivity Faults		
(i) Rod withdrawal of power	1.0 E -02 to 1.0 E -03/y	11
(ii) Rod withdrawal during start up	1.0 E -03 to 1.0 E -04/y	11
(iii) R.W. due to operator error whilst shut down	1.0 E -04 to 1.0 E -05/y	11
(iv) Subassembly faults requiring trip action	1.0/y	11
(v) Loss of off-site power (not necessary a trip condition)	0.3/y	11
32. Failure of Secondary Containment (Self failure)	1.0 E -03/d	11
33. Failure Rate of Core Catcher		
(a) 0-10 h	1.0 E -01/d	11
(b) 10-100 h	8.0 E -01/d	11

10. FAILURE RATE COMPARISON WITH RECENT DATA

The majority of PSA studies were carried out during 1970s and 1980s and the data collection efforts were launched during this period. The generic data sources which have been employed in the PSA studies belong to the same period. Thus, the failure data pertains to components designed and operated during 70s and 80s. Some data collected recently for the 100 US commercial reactors by the Institute of Nuclear Power Operators (INPO) and processed by the equipment performance and information exchange database is presented in Table-14 [17], along with the two major sources of generic data, namely, WASH-1400 and NUREG-1150. It is observed that the recent generic failure rates are lower than the data collected earlier and normally used. An important aspect observed in the recent data analysis for the failure mode 'fail to run' has been in terms of differentiating the short mission time (upto 1 hour) and longer mission time (> 1 hour). It is seen that the FTR value for the lower mission time, is significantly higher than the value for the longer mission periods.

TABLE-14: FAILURE RATE DATA COMPARISON WITH SOME RECENT ESTIMATES
(EPIX represents the currently recommended generic data)

Component	Failure Mode	Source & Period of Data Coverage Mean Value (Error Factor)		
		WASH-1400 1960 to 1973	NUREG - 1150 1970 to 1983	EPIX 1999 to 2001
MOV	FTO/C	1.3E-3/d (3)	3E-3/d (10)	7E-4/d (3)
AOV	FTO/C	3.8E-4/d (3)	2E-3/d (3)	1E-3/d (5)
SOV	FTO/C	1.2E-3/d (3)	2E-3/d (3)	1E-3/d (3)
MDP	FTS FTR	1.2E-3/d (3) 8E-5/h (10)	3E-3/d (10) 3E-5/h (10)	1E-3/d (4) (0-1h) - 9E-4/h (10) (>1h) - 5E-5/h (3)
TDP	FTS FTR	1.2E-3/d (3) 8E-5/h (10)	3E-2/d (10) 5E-3/h (10)	1E-2/d (5) (0-1h) - 3E-3/h (9) (>1h) 2E-4/h (6)
DDP	FTS FTR	1.2E-3/d (3) 8E-5/h (10)	3E-2/d (3) 8E-4/h (10)	9E-3/d (8) (0-1h) 3E-3/h (6) (>1h) 2E-4/h (6)
EDG	FTS FTR	3.8E-2/d (3) 8E-3/h (10)	3E-2/d (3) 2E-3/h (10)	5E-3/d (4) (0-1h) 3E-3/h (6) (>1h) 8E-4/h (4)

MOV - Motor operated valve
AOV - Air operated valve
SOV - Solenoid operated valve
MDP - Motor driven pump
TDP -- Turbine driven pump
DDP - Diesel driven pump
EDG - Emergency diesel generator
FTO/C - Fails to open/close
FTS - Fails to start
FTR - Fails to run

10.1 External Leak and Rupture Frequency Estimates of Some Mechanical Components

In order to perform detailed internal flooding risk analysis of nuclear power plant, the data on external leakage and rupture frequencies would be required for various components namely, piping, valves, pumps, flanges, etc. The data in Table-15 [9] is based on a detailed analysis of information contained in nuclear power experience (which in turn is a compilation of the licensee event reports from US commercial NPPs) for the period September 1960 through June 1990. Leakage has been defined as less than or equal to 50 gpm and rupture as greater than 50 gpm. A noteworthy observation of this study is that, there is no significant difference in failure frequency, between piping with the diameter less than 3" and larger piping. Also, these values are generally lower than WASH-1400.

The failure frequency for the mode, rupture, is given for components belonging to both the primary coolant and other systems. These values usually differ and the difference may be due to better inspection and leak detection methods in primary coolant system.

TABLE-15: RECOMMENDED COMPONENT EXTERNAL AND RUPTURE FREQUENCIES

Component / Failure Mode	Mean Frequency (Error Factor)	No. of Events
Piping (including elbows)		
Leakage	3.9E-9/h-ft (10)	591
Rupture	1.2E-10/h-ft (30) (non-PCS)	17
	3.0E-11/h-ft (30) (PCS)	0
Valve		
Leakage	1.0E-8/h (10)	170
Rupture	4.0E-10/h (30) (non-PCS)	7
	1.0E-10/h (30) (PCS)	0
Pump		
Leakage	3.0E-8/h (10)	50
Rupture	1.2E-9/h (30) (non-PCS)	2
	3.0E-10/h (30) (PCS)	0
Flange		
Leakage	1.0E-8/h (10)	167
Rupture	1.0E-10/h (30) (non-PCS)	1
	1.0E-10/h (30) (PCS)	0
Heat Exchanger Tube		
Leakage	1.0E-7/h (10)	60
Rupture	4.0E-9/h (30) (non-PCS)	1
	1.0E-9/h (30) (PCS)	0
Shell		
Leakage	1.0E-8/h (10)	2
Rupture	4.0E-10/h (30) (non-PCS)	0
	1.0E-10/h (30) (PCS)	0
Tank		
Leakage	1.0E-8/h (10)	12
Rupture	4.0E-10/h (30) (non-PCS)	2
	1.0E-10/h (30) (PCS)	0

11. RECOMMENDATIONS

The need for a reliability database has been felt since the enforcement of regulatory review of the PSA studies. The present database has been prepared based on a large number of international data sources. In order to suggest the most likely values of the failure rate/probability for the components it would be appropriate to collect the information based on the operating experience to have an idea about the trend when compared with the generic data. However, based on the judgement of various data points, the likely value and an error factor have been suggested and included herewith. Assuming a log normal distribution for the various data points in the graphs, a geometric mean representing the median values has also been computed. These are included in Table-16 of recommended values. Table-17 includes the most likely values only, since graphs could not be plotted for such components.

It is seen that proper definition of the component boundary is essential along with the collected failure data to reduce the uncertainty while comparing the data and also during selection of a prior in Bayesian updating of the operating experience. It would be essential to study the qualification procedures of the components in a plant, to identify the specific components operating or likely to operate in abnormal/ emergency conditions, during the operating life of the plant. This would help in selecting proper data for a component in the generic reliability database.

Additional efforts are warranted in establishing a database for common cause failures and human error probability data. In view of the larger variability in such data, data based on the operating experience is absolutely essential. Further, in view of passive systems being incorporated in the design of advanced reactors for achieving higher safety targets, it is necessary to carry out a study on the reliability of passive safety systems.

TABLE-16: RECOMMENDED VALUES

S. No.	COMPONENT GROUP	FAILURE MODE	MEDIAN	RANGE (EF)	REMARKS
1	Battery	Fail to Function	1-2E-6/h	3	IEEE value is lowest
2	Battery Charger	Fail to Function	1E-6/h	3	IEEE value is lowest
3	Diesel Generator	Fail to Start	1-3E-2/d	3	5E - 3/d is suggested
4	Diesel Generator	Fail to Run	3E-3/h		IEEE value is lowest
5	Inverter	Fail to Function	2E-5/h	5	
6	Motor	Fail to Start	3E-4/d	3	IEEE value is lowest
7	Motor	Fail to Run	1E-5/h	3	
8	Diesel Driven Pump	Fail to Start	3E-3/d	10	
9	Diesel Driven Pump	Fail to Run	1E-3/h		
10	Motor Driven Pump	Fail to Start	3E-3/d	3	
11	Motor Driven Pump	Fail to Run	3E-5/h	10	3E-3/h (Extreme Environment)
12	Turbine Driven Pump	Fail to Start	3E-2/d	3	
13	Rectifier	Fail to Function	2E-6/h	10	
14	Relay	Fail to Remain in Position	1E-7/h	10	IEEE value is low
15	Transformer	Fail to Function	1E-6/h	3	
16	Switch	Fail to Function	1E-6/h	3	
17	Transmitter	Fail to Function	2E-6/h	3	
18	Air Operated Valve	Fail to Change Position	1E-3/d	3	
19	Air Operated Valve	Fail to Remain in Position	3E-7/h	3	
20	Check Valve	Fail to Open	1E-4/d	3	
21	Check Valve	Fail to Close	1E-3/d	3	
22	Manual Valve	Fail to Change Position	1E-4/d	3	
23	Manual Valve	Fail to Remain in Position	1E-7/h	10	
24	Motor Operated Valve	Fail to Change Position	3E-3/d	3	
25	Motor Operated Valve	Fail to Remain in Position	2E-7/h	3	
26	Relief Valve	Fail to Open	1E-3/d	3	
27	Relief Valve	Fail to Close	2E-2/d	3	
28	Safety Valve	Fail to Open	3E-3/d	3	
29	Safety Valve	Fail to Close	2E-2/d	3	
30	Solenoid Operated Valve	Fail to Change Position	1E-3/d	3	

TABLE-17: RECOMMENDED VALUES

S. No.	COMPONENT GROUP	FAILURE MODE	MEDIAN	RANGE (EF)	REMARKS
1	Cable, Control	Short	1.2E -6/h	10	
2	Circuit Breaker	Fail to Change Position	1E -3/d	3	
3	Clutch	Fail to Function	3E -4/d	3	
4	Compressor	Fail to Start	2.4E -2/d	3	
		Fail to Run	3E -4/h	3	
5	Control / Shut Off Rod	All Modes	2.0E -6/h	10	Including CR drive
6	Controller	All Modes	4E -6/h	10	
7	Fuse	Spurious Function	1E -6/h	10	
8	Heat Exchanger				See section 10.1
9	Orifice	Plug	3E -4/d	3	
10	Piping				See section 10.1
11	Relay, Coil	Open Circuit	1E -7/h	10	
		Short Circuit	1E -8/h	10	
	Contacts	Short	1E -8/h	10	
12	Valve, Solenoid	All Modes	3.75E –6/d	10	IEEE 500 Data for Solenoid Operator
13	Wire	Open Circuit	3E -6/h	3	
		Short to ground	3E -7/h	10	

APPENDIX-A

DATA SOURCES AND RESPECTIVE CODING

S. No.	SOURCE NAME	CODE
1	HWR Assessment	F
2	EPRI-NP-2433, Diesel-Generator Reliability at Nuclear Power Plants: Data and Preliminary Analysis, Science Application, Inc.June.1982.	R
3	German Risk Study (Deutsche Risikostudie Kerakraftwerke), GRS, FRG, 1979.	G
4	IEEE Standard 500. IEEE Guide to the Collection and Presentation of Electrical, Electronic, Sensing Component, and Mechanical Equipment Reliability Data for Nuclear-Power Generating Stations. Appendix D, Reliability Data for Nuclear-Power Generating Stations. IEEE 1984	E
5	NUREG/CR-2728 Interim Reliability Evaluation Program Procedure Guide, Sandia National Laboratories, January 1983	I
6	NUREG/CR-1205 Data Summaries of Licencee Events Reports of Pumps at US Commercial Nuclear Power Plants. EG&G Idaho. Inc. January 1982.	P
7	NUREG/CR-1331 Data Summaries of Licencee Event Reports of Control Rods and Drive Mechanisms at US Commercial Nuclear Power Plants, EC&G Idaho. February 1980.	C
8	NUREG/CR-1363 Date Summaries of Licencee Event Reports of Valves at US Commercial Nuclear Power Plants. EG&G Idaho, Inc., October 1982.	V
9	NUREG/CR-1740 Data Summaries of Licencee Event Reports of Selected Instrumentation and Control Components at US Commercial Nuclear Power Plants, EG&G Idaho. Inc., July 1984.	B
10	NUREG/CR-2815 Probabilistic Safety Analysis Procedure Guide, Bcookhaeven National Laboratory, August 1985.	B
11	NUREG/CR-2886 In-plant Reliability Data Base for Nuclear Plant Components: Interim Data Report, the Pump Component, and Oak Ridge National Lab. December 1982.	D
12	NUREG/CR-2886 In-Plant Reliability Data Base for Nuclear Plant Components: Interim Data Report, the Pump Component, and Oak Ridge National Lab. December 1982.	R
13	NUREG/CR-4550 Vol.1 Analysis of Core Damage Frequency from Internal Events: Methodology Guidelines September 1987.	J
14	NUREG/CR-4550 Vol.3. Analysis of Core Damage Frequency from Internal Events: Surry. Unit.1. Sandia National Laboratory, November 1986.	A
15	MASC 60, OCONEE PRA. A Probabilistic Risk Assessment of Oconne Unit-3. The Nuclear Safety Research Center. EPRI, and Duke Power Co., June. 1984.	O
16	Old PWR Reactor.	H
17	Shoreham Nuclear Power Station Probabilistic Safety Assessment. Science Application. Inc.	S

APPENDIX-A (Contd.)

DATA SOURCES AND RESPECTIVE CODING

S. No.	SOURCE NAME	CODE
18	PWR/RX 312 Sizewell 'B' PWR Pre-Construction Safety Report, Component Failure Date for PWR System Reliability Assessment, NNC, UK, June. 1982.	U
19	RKS 85-25 Reliability Data Book for Components in Swedish Nuclear Power Plants, RKS, SKI Sweden.	T
20	WASH-1400, Reactor Safety Study, An Assessment of Accident in US Commercial Nuclear Power Plants, US NRC, October 1975.	W
21	Zion Nuclear Power Station, Probabilistic Safety Study, Commonwealth Edison Co., 1981.	Z
22	VVER Component Reliability Date Base. IAEA RER/9/005, June 1988. In cases where for the same component type more than one record is available, a consecutive numbering system following the source ID was defined.	X

APPENDIX- B

SELECTED TABLES FROM THE HUMAN RELIABILITY HANDBOOK (NUREG/CR/1278)

TABLE B-1

ESTIMATED HEPs RELATED TO FAILURE OF ADMINISTRATIVE CONTROL (REF. (6), TABLE 20.6)

	Item Task	HEP	EF
(1)	Carry out a plant policy or scheduled tasks such as periodic tests or maintenance performed weekly, monthly or at longer intervals	0.01	5
(2)	Initiate a scheduled shiftily checking or inspection function Use written operations procedures under	0.001	3
(3)	Normal operating conditions	0.01	3
(4)	Abnormal operating conditions	0.005	10
(5)	Use a valve change or restoration list	0.01	3
(6)	Use written test or calibration procedures	0.05	5
(7)	Use written maintenance procedures	0.3	5
(8)	Use a checklist properly [(a)]	0.5	5

(a) Read a single item, perform the task, check off the item on the list. For any item in which a display reading or other entry must be written, assume correct use of the checklist for that item.

APPENDIX- B (Contd.)

TABLE B-2

ESTIMATED PROBABILITIES OF ERRORS OF OMISSION PER ITEM OF INSTRUCTION WHEN USE OF WRITTEN PROCEDURES IS SPECIFIED [a] (REF. (6), TABLE 20.7)

Item [b]	Omission of Item	HEP	EF
	When procedures with check off provisions are correctly used [c] :		
(1)	Short list, <10 items	0.001	3
(2)	Long list, >10 items	0.003	3
	When procedures without check off provisions are used, or when check off provisions are incorrectly used [d] :		
(3)	Short list, <10 items	0.003	3
(4)	Long list, >10 items	0.01	3
(5)	Written procedures are available but are not used [d]	0.05[e]	5

(a) The estimates for each item (or perceptual unit) presume zero dependence among the items (or units and must be modified by using the dependence model when a non-zero level of dependence is assumed.

(b) The term “item” for this column is the usual designator for tabled entries and does not refer to an item of instruction in a procedure.

(c) Correct use of check off provisions is assumed for items in which written entries such as numerical values are required of the user.

(d) Table 20.6 lists the estimated probabilities of incorrect use of check off provisions and of non-use of available written procedures.

(e) If the task is judged to be “second nature,” use the lower uncertainty bound for 05, i.e. use 01 (EF-05).

APPENDIX- B (Contd.)

TABLE B-3

ESTIMATED PROBABILITIES OF ERRORS OF TO MISSION IN OPERATING MANUAL CONTROLS [(a)] (Ref. (6) TABLE 20.12)

Item[(b)]	Potential Errors	HEP	EF
(1)	Inadvertent activation of a control select wrong control on a panel from an array of similar-appearing controls [(b)]	See text.	Ch.13
(2)	Identified by labels only	0.003	3
(3)	Arranged in well delineated functional groups	0.001	3
(4)	Which are part of a well defined mimic layout turn rotary control in wrong direction (for two position switches, see item (8))	0.005	10
(5)	When there is no violation of population stereotypes [(c)]	0.0005	10
(6)	When design violates a strong population stereotype and operating conditions are normal	0.05	5
(7)	When design violates a strong populational and operation is under high stress [(c)]	0.5	5
(8)	Turn a two position switch in wrong direction or leave it in the wrong setting	+	
(9)	Set a rotary control to an incorrect setting (for two position switches, see item (8))	0.001	10 [(d)]
(10)	Failure to complete change of state of a component switch must be held until change is completed selected wrong circuit breaker in a group of circuit breakers [(b)]	0.003	3
(11)	Densely grouped and identified by labels	0.005	3
(12)	In which the PSFs are more favorable	0.003	3
(13)	Improperly mate a connector (this includes failures to meet connectors completely and failure to test locking features of connectors for engagement)	0.003	3

(a) The HEPs are for errors of commission only and do not include any errors of decision as to which controls to activate.

(b) If controls or circuit breakers are to be restored and are tagged, adjust the tabled HEPs according to Table 20.15.

(c) Divide HEPs for rotary controls (items 5&7) by 5 (use same EFs).

(d) This error is a function of the clarity with which indicator position can be determined: designs of control knobs and their position indications vary greatly. For plant-specific analyses, an EF of 3 may be used.

APPENDIX- B (Contd.)

TABLE B-4

MODIFICATIONS OF ESTIMATED HEPs FOR THE EFFECTS OF STRESS AND EXPERIENCE LEVELS (REF. (6) TABLE 20.16)

	Stress Level	**Modifiers for Nominal HEPs** [(a)]	
	Item	**Skilled** [(b)] **(A)**	**Novice** [(b)] **(B)**
(1)	Very low (Very low task load) Optimum (Optimum task load)	X2	X2
(2)	Step-by-step [(c)]	X1	X1
(3)	Dynamic [(c)] Moderately high (Heavy task load)	X1	X2
(4)	Step-by-step [(c)]	X2	X4
(5)	Dynamic [(c)] Extremely High (Threat stress)	X5	X10
(6)	Step-by-step [(c)]	X5	X10
(7)	Dynamic + Diagnosis [(d)]	0.25 (EF=5) 0.5 (EF-5) These are the actual HEPs to use with dynamic tasks or diagnosis they are NOT modifiers.	

(a) The nominal HEPs are those in the data tables.

(b) A skilled person is one with six months or more experience in the tasks being assessed. A novice is one with less than six months experience. Both levels have the required licensing or certificates.

(c) Step-by step tasks are routine, procedurally guided, tasks, such as carrying out written calibration procedures. Dynamic tasks require a higher degree of man-machine interaction, such as decision making, keeping track of several functions, controlling several functions or any combination of these. These requirements are the basis of the distinction between step-by-step tasks, which are often involved in responding to an abnormal event.

(d) Diagnosis may be carried out under varying degrees of stress. Ranging from optimum to extremely high (threat stress). For threat stress, the HEP of 0.25 is used to estimate performance of an individual. Ordinarily, more than one person will be involved.

APPENDIX- B (Contd.)

TABLE B-5

ESTIMATED PROBABILITIES THAT A CHECKER WILL FAIL TO DETECT ERRORS MADE BY OTHERS [a] (REF. (6) TABLE 20-22)

Item	Checking Operation	HEP	EF
(1)	Checking routine tasks, checker using written materials (includes over the shoulder inspections, verifying position of locally operated valves, switches, circuit breakers, connectors, etc., and checking written lists, tags, or procedures for accuracy)	0.1	5
(2)	Same as above, but without written materials	0.2	5
(3)	Special short term, one-of-a kind checking with alerting factors	0.05	5
(4)	Checking that involves active participation, such as special measurements	0.01	5
	Given that the position of a locally operated valve is checked (item1 above), noticing that it is not completely opened or closed:	0.05	5
(5)	Position indicator [b] only	0.1	5
(6)	Position indicator [b] and a rising stem	0.5	5
(7)	Neither a position indicator [b] nor a rising stem	0.9	5
(8)	Checking by reader/checker of the task performer a two man team, or checking by a second checker, routine task (no credit for more than 2 checkers)	0.5	5
(9)	Checking the status of equipment if that status affects one's safety when performing his tasks	0.001	5
(10)	An operator checks change or restoration tasks performed by a maintainer	Above HEPs - 2	5

(a) This table applies to cases during normal operating conditions in which a person is directed to check the work performed by others either as the work is being performed or after its completion.

(b) A position indicator incorporates a scale that indicates the position of the valve relative to a fully opened or fully closed position. A rising stem qualifies as a position indicator if there is a scale associated with it.

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(5) INTERNATIONAL ATOMIC ENERGY AGENCY, 'Case Study on Human Reliability Analysis', TECDOC - 592, Vienna 1991.

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LIST OF PARTICIPANTS

COMMITTEE ON PSA FOR NUCLEAR FACILITIES

Dates of the meeting	:	November 4, 2003 January 22, 2004 February 17, 2004 March 25, 2004 July 1, 2004 November 10, 2004 December 23, 2004

Members and Invitees of the Committee:

Shri. P. Hajra (Chairman)	:	Head SADD, AERB (Former)
Dr. A. K. Ghosh, (Vice-Chairman)	:	Head, RSD, BARC
Shri. R. K. Saraf	:	BARC
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Shri. R. B. Solanki (Member-Secretary)	:	AERB
Shri. A. K. Babar (Invitee)*	:	BARC (Former)

* Author of the first draft of this Technical Document

PROVISIONAL LIST OF AERB SAFETY CODE, GUIDES, MANUALS AND TECHNICAL DOCUMENT ON OPERATION OF NUCLEAR POWER PLANTS

Safety Series No.	Provisional Title
AERB/SC/O	Code of Practice on Safety in Nuclear Power Plant Operation.
AERB/SG/O-1	Staffing, Recruitment, Training, Qualification and Certification of Operating Personnel of Nuclear Power Plants.
AERB/SG/O-2	In-Service-Inspection of Nuclear Power Plants.
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AERB/SG/O-6	Preparedness of Operating Organisation for Handling Emergencies at Nuclear Power Plants.
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AERB/SG/O-8	Surveillance of Items Important to Safety in Nuclear Power Plants.
AERB/SG/O-9	Management of Nuclear Power Plants for Safe Operation.
AERB/SG/O-10A	Core Management and Fuel Handling for Pressurised Heavy Water Reactors.
AERB/SG/O-10B	Core Management and Fuel Handling for Boiling Water Reactors.
AERB/SG/O-11	Management of Radioactive Waste Arising During Operation of Nuclear Power Plants.
AERB/SG/O-12	Renewal of Authorisation for Operation of Nuclear Power Plants.
AERB/SG/O-13	Operational Safety Experience Feedback for Nuclear Power Plants.
AERB/NPP/SG/O-14	Life Management of Nuclear Power Plants.
AERB/NPP/SG/O-15	Proof and Leakage Rate Testing of Reactor Containments.
AERB/NF/SM/O-1	Probabilistic Safety Assessment Guidelines.
AERB/NF/SM/O-2 (Rev. 4)	Radiation Protection for Nuclear Facilities.
AERB/NPP/TD/O-1	Compendium of Standard Generic Reliability Database for Probabilistic Safety Assessment of Nuclear Power Plants.

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