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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

ICDE PROJECT REPORT:
COLLECTION AND ANALYSIS OF COMMON-CAUSE FAILURES OF BATTERIES

September 2003

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

Pursuant to Article 1 of the Convention signed in Paris on 14th December 1960, and which came into force on 30th September 1961, the Organisation for Economic Co-operation and Development (OECD) shall promote policies designed:

- to achieve the highest sustainable economic growth and employment and a rising standard of living in Member countries, while maintaining financial stability, and thus to contribute to the development of the world economy;
- to contribute to sound economic expansion in Member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

The original Member countries of the OECD are Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The following countries became Members subsequently through accession at the dates indicated hereafter: Japan (28th April 1964), Finland (28th January 1969), Australia (7th June 1971), New Zealand (29th May 1973), Mexico (18th May 1994), the Czech Republic (21st December 1995), Hungary (7th May 1996), Poland (22nd November 1996), Korea (12th December 1996) and the Slovak Republic (14 December 2000). The Commission of the European Communities takes part in the work of the OECD (Article 13 of the OECD Convention).

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full Member. NEA membership today consists of 28 OECD Member countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, Republic of Korea, Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its Member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The Committee on the Safety of Nuclear Installations (CSNI) of the OECD Nuclear Energy Agency (NEA) is an international committee made up of senior scientists and engineers. It was set up in 1973 to develop, and co-ordinate the activities of the Nuclear Energy Agency concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations. The Committee's purpose is to foster international co-operation in nuclear safety among the OECD Member countries.

The CSNI constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development, engineering or regulation, to these activities and to the definition of the programme of work. It also reviews the state of knowledge on selected topics on nuclear safety technology and safety assessment, including operating experience. It initiates and conducts programmes identified by these reviews and assessments in order to overcome discrepancies, develop improvements and reach international consensus on technical issues of common interest. It promotes the co-ordination of work in different Member countries including the establishment of co-operative research projects and assists in the feedback of the results to participating organisations. Full use is also made of traditional methods of co-operation, such as information exchanges, establishment of working groups, and organisation of conferences and specialist meetings.

The greater part of the CSNI's current programme is concerned with the technology of water reactors. The principal areas covered are operating experience and the human factor, reactor coolant system behaviour, various aspects of reactor component integrity, the phenomenology of radioactive releases in reactor accidents and their confinement, containment performance, risk assessment, and severe accidents. The Committee also studies the safety of the nuclear fuel cycle, conducts periodic surveys of the reactor safety research programmes and operates an international mechanism for exchanging reports on safety related nuclear power plant accidents.

In implementing its programme, the CSNI establishes co-operative mechanisms with NEA's Committee on Nuclear Regulatory Activities (CNRA), responsible for the activities of the Agency concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with NEA's Committee on Radiation Protection and Public Health and NEA's Radioactive Waste Management Committee on matters of common interest.

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PREFACE

The purpose of the International Common Cause Data Exchange (ICDE) Project is to allow multiple countries to collaborate and exchange Common Cause Failure (CCF) data to enhance the quality of risk analyses that include CCF modelling. Because CCF events are typically rare events, most countries do not experience enough CCF events to perform meaningful analyses. Data combined from several countries, however, yields sufficient data for more rigorous analyses.

The objectives of the ICDE Project are:

- to collect and analyse CCF events in the long term so as to better understand such events, their causes, and their prevention,
- to generate qualitative insights into the root causes of CCF events, which can then be used to derive approaches or mechanisms for their prevention or for mitigating their consequences,
- to establish a mechanism for the efficient feedback of experience gained on CCF phenomena, including the development of defences against their occurrence, such as indicators for risk based inspections.

The qualitative insights gained from the analysis of CCF events are made available by reports that are distributed without restrictions. It is not the aim of those reports to provide direct access to the CCF raw data recorded in the ICDE databank. The confidentiality of the data is a prerequisite of operating the project. The ICDE database is accessible only to those members of the ICDE Project Working Group who have actually contributed data to the databank.

Database requirements are specified by the members of the ICDE Project working group and are fixed in guidelines. Each member with an access to the ICDE database is free in using the collected data. It is assumed that the data will be used by the members in the context of PSA/PRA reviews and application.

ACKNOWLEDGEMENT

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CONTENTS

EXECUTIVE SUMMARY 1

ACRONYMS 3

1. INTRODUCTION 4

2. ICDE PROJECT 5

2.1 BACKGROUND 5
2.2 OBJECTIVES OF THE ICDE PROJECT 5
2.3 SCOPE OF THE ICDE PROJECT 5
2.4 REPORTING AND DOCUMENTATION 6
2.5 DATA COLLECTION STATUS 6
2.6 ICDE CODING FORMAT AND CODING GUIDELINES 6
2.7 PROTECTION OF PROPRIETARY RIGHTS 6

3. DEFINITION OF COMMON-CAUSE EVENTS AND ICDE EVENTS 7

4. COMPONENT DESCRIPTION 8

4.1 GENERAL DESCRIPTION OF THE COMPONENT 8
4.2 COMPONENT BOUNDARIES 8
4.3 EVENT BOUNDARY 9

5. BATTERY EVENT COLLECTION AND CODING GUIDELINES 10

5.1 BASIC UNIT FOR ICDE EVENT COLLECTION 10
5.2 TIME FRAME FOR ICDE EVENT EXCHANGE 10
5.3 CODING RULES AND EXCEPTIONS 10
5.4 FUNCTIONAL FAILURE MODES 11

6. OVERVIEW OF DATABASE CONTENT 12

6.1 FAILURE MODE AND DEGREE OF FAILURE 12
6.2 GROUP SIZE 14
6.3 CAUSE, DETECTION AND CORRECTIVE ACTION 15
6.4 DETECTION METHODS 23
6.5 SHARED CAUSE FACTOR AND TIME FACTOR 25

7. TECHNICAL FAULT ASPECT OF BATTERY CCFS 28

7.1 FAILURE MECHANISM AND SYMPTOMS 28
7.2 PREVENTION METHODS, PROTECTIONS, AND CORRECTIVE ACTIONS 30
7.3 FAILURE CAUSAL CATEGORIES 34
7.4 CONSEQUENCES: EFFECT / RELIABILITY / DOWN TIME AND TIME TO FAILURE 34

8. SUMMARY AND CONCLUSIONS 37

9. REFERENCES 39

APPENDIX A FAILURE SYMPTOMS AND SUBCOMPONENTS 40

A1. CCF EVENT INTERPRETATION (FIELD C7) AND FAILURE SYMPTOMS 40
A2. PROPOSAL FOR THE SUB-COMPONENTS AND SUBSYSTEMS 42

APPENDIX B ADDITIONAL ANALYSIS OF ICDE BATTERIES DATABASE 43

B1. INTRODUCTION 43
B2. RESULTS 43
B3. CONCLUSION 46

FIGURES

Figure 4.1 Battery components and boundary.
Figure 6.1 Failure mode distribution.
Figure 6.2 Failure impairment distribution.
Figure 6.3 Group size distribution.
Figure 6.4 Root cause distribution.
Figure 6.5 Coupling factor distribution.
Figure 6.6 Corrective action distribution.
Figure 6.7 Root causes and coupling factors.
Figure 6.8 Corrective actions and root causes.
Figure 6.9 Corrective actions and coupling factors.
Figure 6.10 Detection method distribution.
Figure 6.11 Detection methods distribution (II).
Figure 7.1 Battery failure distribution.

TABLES

Table 6.1 Failure mode distribution.
Table 6.2 Component impairment distribution.
Table 6.3 Exposed components in the group / group size distribution.
Table 6.4 Root cause distribution.
Table 6.5 Coupling factor distribution.
Table 6.6 Corrective action distribution.
Table 6.7 Detection methods distribution.
Table 6.8 Shared cause factor distribution.
Table 6.9 Time factor distribution.
Table 7.1 Battery failures (causes, process, and symptoms).
Table 7.2 Combinations of failure cause and Symptoms.
Table 7.3 Effect, reliability significance and down time distribution.
Table 7.4 Time to failure distribution.

EXECUTIVE SUMMARY

This report documents a study performed on the set of Common Cause Failure (CCF) events of batteries (BT). The events studied here were derived from the International CCF Data Exchange (ICDE) database. Organizations from Canada, Finland, France, Germany, Spain, Sweden, Switzerland, United Kingdom, and United States contributed to this data exchange.

This study examines 50 events in the International CCF Data Exchange (ICDE) database by tabulating the data and observing trends. The data span a period from 1980 through 2000. The data is not necessarily complete for each country through this period. The database contains general information about even attributes like root cause, coupling factor, common cause component group (CCCG) size, and corrective action.

As part of the study documented in this report, the events contained in the ICDE database were reviewed again and additional categorizations of the data were included. The data tabulation and trend observation of this study cover these additional categorizations alongside the original data from the ICDE database. The additional categories include degree of failure, and detection method.

This study begins with an overview of the entire data set (Section Six). Charts and tables are provided showing the number of events for each of these event parameters.

Section Seven presents a qualitative assessment of the collected data, events are analyzed with respect to failure symptoms, failure causes, and prevention and protection methods.

Section Eight presents a summary and conclusions.

Two failure modes are specified, “failure to run” and “failure to start”. The most susceptible failure mode of batteries is "failure to run", representing 82% of events. A characteristic of batteries to fail over an extended period by slow degradation in capacity was noted.

6% of all ICDE events of batteries were complete CCFs (all redundant components had failed). Partial CCF events (at least two failed components in the group) accounted for a further 4%. The remaining 90% of events are not considered CCFs within the accepted definition, but fall within the ICDE event definition, “Impairment of two or more components (with respect to performing a specific function) that exists over a relevant time interval and is the direct result of a shared cause.”

Deficiencies in design were responsible for 50% of events. Of these,

- 92% occurred during battery manufacture and could be caused by inadequate selection of component materials for the plates, in the electrolyte, in separators, in cells, or in terminal connections.

- 8% occurred during the plant specification or modification process and could be caused by calculation errors in the capacity definition. In order to avoid this kind of failure, the suggested preventions are improvements to processes for the verification of plant design, modification or commissioning.

Deficiencies in maintenance / test were responsible for 42% of events. Of these;

- approximately half were due to physical failures in the battery subcomponents,
- nearly 30% were due to electrical failures,
- nearly 20% due to direct human actions, and
- one event was due to premature ageing caused by lack of maintenance.

The data suggests that the majority of maintenance / test events could be prevented with adequate test / maintenance practices and surveillance of the circuit continuity.

An additional analysis of batteries can be found in Appendix B.

ACRONYMS

AECB	Atomic Energy Control Board (Canada)
BT	Battery
BWR	Boiling Water Reactor
CCCG	Common Cause Component Group
CCF	Common Cause Failure
CH	Clearing House
CNSC	Canadian Nuclear Safety Commission (Canada)
CSN	Consejo de Seguridad Nuclear (Spain)
CSNI	Committee on the Safety of Nuclear Installations
DC	Direct Current (Continuous current)
ECCS	Emergency Core Cooling System
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HSK	Hauptabteilung für die Sicherheit der Kernanlagen (Switzerland)
I&C	Instrumentation and Control
ICDE	International Common Cause Failure Data Exchange
IRS	Incident Reporting System
IRSN	Institut de Radioprotection et de Sûreté Nucléare (France)
KAERI	Korea Atomic Energy Research Institute (Republic of Korea)
LOCA	Loss-of-Coolant Accident
LOSP	Loss of Offsite Power
NEA	Nuclear Energy Agency
NII	Nuclear Installations Inspectorate (UK)
NRC	Nuclear Regulatory Commission (USA)
NUPEC	Nuclear Power Engineering Corporation (Japan)
OECD	Organization for Economic Cooperation and Development
PRA	Probabilistic Risk Assessment.
PSA	Probabilistic Safety Assessment
PWG1	Principal Working Group 1
PWR	Pressurized Water Reactor
RPS	Reactor Protection System
SKI	Sweden Nuclear Inspectorate (Sweden)
STUK	Finish Centre for Radiation and Nuclear Safety (Finland)

ICDE Project Report
Collection and Analysis of Common-Cause Failures of Batteries

1. INTRODUCTION

This report presents an overview of the exchange of batteries common cause failure (CCF) data among several countries. The objectives of this report are:

- To describe the data profile in the ICDE database for batteries and to develop qualitative insights in the nature of the reported events, expressed by root causes, coupling factors, and corrective actions; and
- To develop the failure mechanisms and phenomena involved in the events, their relationship to the root causes, and possibilities for improvement.

The ICDE Project was organized to exchange CCF data among countries. A brief description of the project, its objectives, and the participating countries is contained in Section Two. Section Three presents the definition of common cause failure and ICDE event definitions. Section Four presents a description of the batteries and Section Five summarizes the coding guidelines for this component. Section Six and Seven contain the results of the study and Section Eight the summary and conclusions.

Appendix A includes several proposal for CCF event interpretation (failure symptoms) and subcomponents for the batteries. Appendix B includes an additional analysis of the database in order to define countermeasures.

2. ICDE PROJECT

This section contains information about the ICDE Project.

2.1 Background

Common-cause-failure (CCF) events can significantly impact the availability of safety systems of nuclear power plants. In recognition of this, CCF data are systematically being collected and analysed in several countries. A serious obstacle to the use of national qualitative and quantitative data collections by other countries is that the criteria and interpretations applied in the collection and analysis of events and data differ among the various countries. A further impediment is that descriptions of reported events and their root causes and coupling factors, which are important to the assessment of the events, are usually written in the native language of the countries where the events were observed.

To overcome these obstacles, the preparation for the international common-cause data exchange (ICDE) project was initiated in August of 1994. Since April 1998, the OECD/NEA has formally operated the project. The Phase II had an agreement period covered years 2000-2002 and phase III cover the period 2002-2005. Member countries under the Phase III Agreement of OECD/NEA and the organizations representing them in the project, are: Canada (CNSC), Finland (STUK), France (IRSN), Germany (GRS), Japan (NUPEC), Korea (KAERI), Spain (CSN), Sweden (SKI), Switzerland (HSK), United Kingdom (NII), United States (NRC).

2.2 Objectives of the ICDE Project

The objective of the ICDE activity is to provide a framework for a multinational co-operation:

- to generate qualitative insights on root causes of CCF events that can be used to derive provisions for preventing CCF events, or for mitigating their consequences, should they occur.
- to collect and analyse CCF events on a long term basis, based on broad international experience.
- to generate the framework for efficient experience feedback on CCF phenomena and on defence against CCF.

2.3 Scope of the ICDE Project

The ICDE Project aims to include all possible events of interest, comprising complete, partial, and incipient CCF events, called "ICDE events" in this report. The project covers the key components of the main safety systems, including centrifugal pumps, diesel generators, motor operated valves, power operated relief valves, safety relief valves, check valves, batteries, reactor protection system (RPS), circuit breakers and level measurement.

In the long term, a broad basis for quantification of CCF events could be established, if the participating organisations wish to do so.

2.4 Reporting and Documentation

All reports and documents related to the ICDE project can be accessed through the OECD/NEA web site [1].

2.5 Data Collection Status

Data are collected in an MS ACCESS based databank implemented and maintained at ES-Konsult, Sweden, the appointed NEA clearing house. The databank is regularly updated and it is operated by the clearinghouse and the project group.

2.6 ICDE Coding Format and Coding Guidelines

Data collection guidelines have been developed during the project and are continually revised. They describe the methods and documentation requirements necessary for the development of the ICDE databases and reports. The format for data collection is described in the generic coding guideline and in the component specific guidelines. Component specific guidelines are developed for all analysed component types as the ICDE plans evolve. The documentation consists of Descriptions, Format, Agreements, Definitions, Directory, Guides, Codes, Procedures etc [2].

2.7 Protection of Proprietary Rights

Incident Reporting System (IRS) procedures for protecting confidential information have been adopted. The co-ordinators in the participating countries are responsible for maintaining proprietary rights. The data collected in the clearinghouse database are password protected and are only available to ICDE participants who have provided data.

3. DEFINITION OF COMMON-CAUSE EVENTS AND ICDE EVENTS

In the modelling of common-cause failures in systems consisting of several redundant components, two kinds of events are identified:

- Unavailability of a specific set of components of the system, due to a common dependency, for example on a support function. If such dependencies are known, they can be explicitly modelled in a PSA.

- Unavailability of a specific set of components of the system due to shared causes that are not explicitly represented in the system logic model. Such events are also called "residual" CCFs, and are incorporated in PSA analyses by parametric models.

There is no rigid borderline between the two types of CCF events. There are examples in the PSA literature of CCF events that are explicitly modelled in one PSA and are treated as residual CCF in other PSAs (for example, CCF of auxiliary feed-water pumps due to steam binding, resulting from leaking check valves).

Several definitions of CCF events can be found in the literature, for example, "Common Cause Failure Data Collection and Analysis System, Vol. 1, NUREG/CR-6268": [3]

- Common-Cause Event: A dependent failure in which two or more component fault states exist simultaneously, or within a short time interval, and are a direct result of a shared cause.

Data collection in the ICDE project comprises complete as well as potential CCF. To include all events of interest, an 'ICDE event' is defined as follows:

- ICDE Event: Impairment[1] of two or more components (with respect to performing a specific function) that exists over a relevant time interval[2] and is the direct result of a shared cause.

The ICDE data analysts may add interesting events that fall outside the ICDE event definition but are examples of recurrent - eventually non random - failures.

With growing understanding of CCF events, the relative share of events that can only be modelled as "residual" CCF events will decrease.

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[1] Possible attributes of impairment are the following:
- Complete failure of the component to perform its function
- Degraded ability of the component to perform its function
- Incipient failure of the component

Default is component is working according to specifications.

[2] Relevant time interval: two pertinent inspection periods (for the particular impairment) or if unknown, a scheduled outage period.

4. COMPONENT DESCRIPTION

4.1 General Description of the Component

According to the Coding Guidelines for Batteries [4], the family of batteries is comprised of those batteries that provide DC emergency power in the event of a LOSP to DC buses that supply the safety systems of the reactor plant. The voltage to be supplied typically ranges from 24 to 500 V DC.

Battery data are collected for the systems/subsystems.

DC power system (3.EE in IRS coding system), consisting of the subsystems:

- DCS - DC System. Uninterrupted power supply for emergency DC system and secondary emergency DC system.
- DCS-1 - DC System. Uninterrupted power supply for emergency DC system.
- DCS-2 - DC System. Uninterrupted power supply for secondary emergency DC system.
- IAS-1- Indication and alarm system.
- IAS-2- Indication and alarm system of the fire protection.
- IAS-3- Indication and alarm system of the control rod drive system.
- TCS- Trip circuit supply.

For data evaluation purposes, the family of batteries is subdivided into the four subgroups:

- BVL - Very low voltage battery (V= 24).
- BL - Low- voltage battery (24< V< 50).
- BH - High- voltage battery (V>200).
- BM - Medium- voltage battery (50<V<200).

4.2 Component Boundaries

The component for this study is the battery, comprised of cell, casing, power leads and their respective output breakers and fuses. The component boundary is illustrated by figure 4-1.

Included within the Battery is the output breaker (failure to close or remain closed), which is located at the local control. In some cases batteries[3] may have a particular automatic system.

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[3] For French plants, 48 V batteries, installed this following an incident at a French NNP. This system is part of the 48 V batteries for all NNP in France.

4.3 Event Boundary

The mission for a battery is to provide DC emergency power in the event of a LOSP to DC buses that supply the safety systems of the reactor plant. Failure of the battery to perform its mission occurs if a battery that is required to supply rated voltage to the DC bus bar fails to do so.

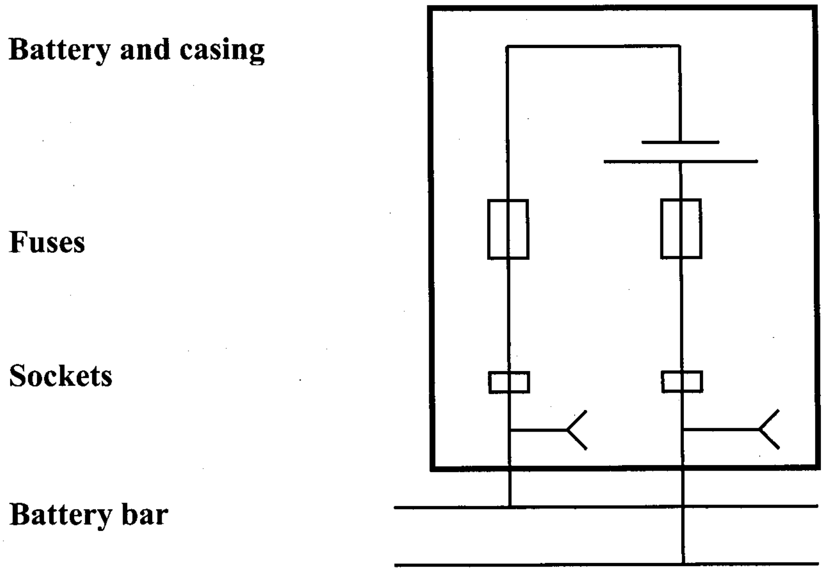

Figure 4.1. Battery components and boundary

Failure of the same cell on batteries supporting different voltages can be considered a valid Common Cause Failure (CCF).

5. BATTERY EVENT COLLECTION AND CODING GUIDELINES

5.1 Basic unit for ICDE event collection

The basic set for Battery data collection is the 'common-cause component group', (CCCG: set of identical components in a system, performing the same function).

5.2 Time frame for ICDE event exchange

The minimum period of exchange should cover 5 years for each plant.

5.3 Coding Rules and Exceptions

1. In general, the definition of the ICDE event given in section 2 of the General ICDE Coding Guidelines applies.

2. Complete Failure is when power is not maintained within specification e.g. unable to meet minimum capacity for all or some of the time.

3. Degraded: If cells within the Batteries show major physical, electrical or chemical damage but the batteries are still able to perform within specification OR (Incipient) when slight damage is evident. If there is "no damage" proposed coding should be "working".

4. Some reports discuss only one actual failure, and do not consider that the same cause will affect other BTs, but the licensee replaces the failed component on all BTs as a precautionary measure. This type of event will be coded as incipient impairment (0.1) of the components that did not actually fail.

5. Inoperability due to seismic or electrical separation criteria violations will not be included, unless an actual failure has occurred.

6. Inoperability due to administrative actions that does not cause the battery to fail to function is not included as failures. An example is a surveillance test not performed within the required time frame.

7. Guidance for CCF event interpretation (Field C7) and failure mechanism see appendix A.1.

8. Consideration of CCF of a single design of battery may be limited to a single location or may extend to different physical locations (e.g. different voltage battery rooms).

5.4 Functional Failure Modes

The following failure modes and criticality classifications are applicable for battery data collection.

1. Failure to run (Loss of performance): failure to maintain the rated DC power within specification for the duration of the mission.

2. Failure to start (No voltage): the power provided at the start of the mission is not within specification. Could be open circuit, high resistance, or discharged battery i.e. the rated DC power can not be delivered at the time of the demand.

3. French Plants only: Failure to cut off batteries after 1 hour.

6. OVERVIEW OF DATABASE CONTENT

CCF data have been collected for Battery component. Organisations from Canada, Finland, France, Germany, Spain, Sweden, Switzerland, United Kingdom, and United States have contributed to this data exchange. Fifty (50) ICDE events were reported from nuclear power plants (pressurized water reactors, boiling water reactors, Magnox and advanced gas reactors).

810 batteries were surveyed across 291 CCCGs (Common Cause Component Groups).

6.1 Failure Mode and Degree of Failure

Table 6.1 and figure 6.1 summarize the Battery ICDE events, used in this study, by failure mode. The definitions of the functional failure modes, as they apply to this data collection, are given in section 5.4.

Table 6.1. Failure mode distribution

FAILURE MODE	No. of events	Percentage of total	Degree of Failure	
			Partial	Complete
FR – Loss of performance (Failure to run)	41	82%	41	0
FS – No voltage/open circuit (Failure to start)	3	6%	1	2
No data	6	12%	5	1
TOTAL	50	100%	47	3

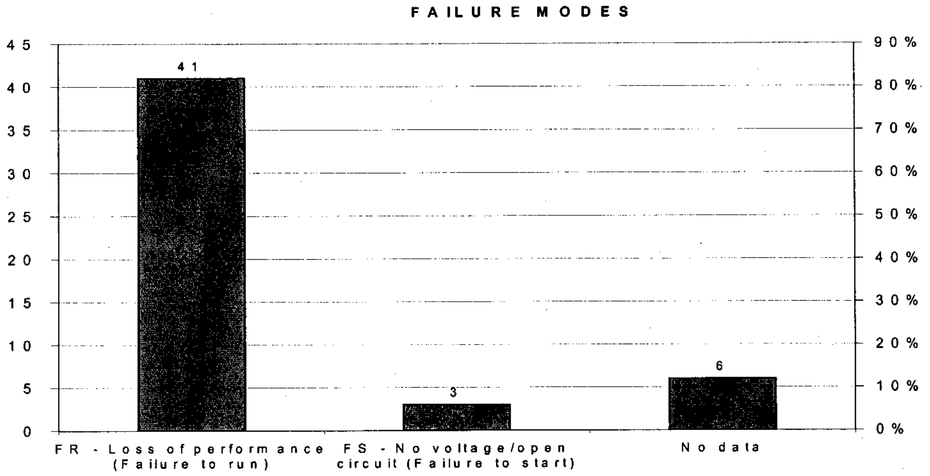

Figure 6.1. Failure mode distribution

There are 6 events for which failure mode has not been coded.

Regarding the coded failure modes, the main contribution is "Loss of performance ('failure to run')", representing 82% of events. This reflects the importance of the degraded capacity mode of failure amongst batteries. No "failure to run" events are complete failures.

Two of the three "failures to start" events (66%) are complete failures.

For each event in the ICDE database, the impairment of each component in the CCCG has been defined according to the categorisation of the general coding guidelines [2], with interpretation as presented in the battery coding guidelines (see section 5.3) and summarized here.

- C denotes complete failure. Complete Failure is when power is not maintained within specification e.g. unable to meet minimum capacity for all or some of the time.
- D denotes degraded. This coding is selected if cells within the batteries show major physical, electrical or chemical damage but the batteries are still able to perform within specification.
- I denotes incipient. This coding is selected when slight damage is evident.
- W denotes working, i.e. component has suffered no damage.

Table 6.2 and figure 6.2 summarize the numbers of complete, degraded and incipient CCF events. The events are grouped according to the most severe component impairment coding of the CCCG. For example, if one component suffers "complete" failure, the event is placed in the "At least one complete CCF" group, irrespective of the impairment coding of the remaining components.

Table 6.2. Component impairment distribution

COMPONENT IMPAIRMENT VECTOR	No. of events	Percentage of total
At least one complete failure	**22**	**44%**
• All components in the group are complete failures (Complete CCF)	3	6%
• More than 1 complete failure in the group	2	4%
• One complete failure only in CCCG	17	34%
At least one degraded failure, but no complete failure	**17**	**34%**
• All components in the group are degraded failures	8	16%
• Partial	9	18%
At least one incipient failure, but no degraded or complete failures	**11**	**22%**
• All components in the group are incipient failures	7	14%
• Partial	4	8%
TOTAL	**50**	**100%**

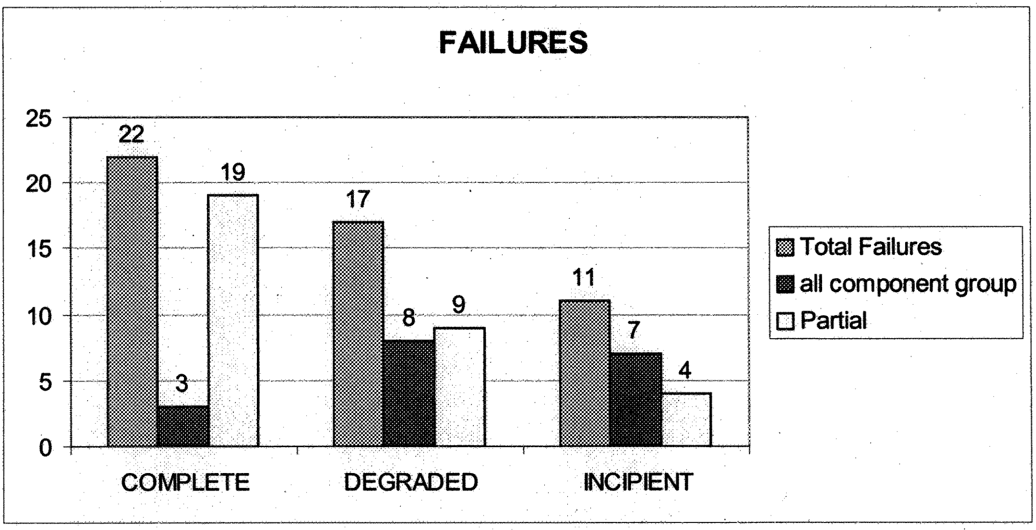

Figure 6.2. Component impairment distribution

Complete CCF represent 6% of events.

The largest of three categories defined above is that in which there is at least one complete failure amongst the group. This category accounts for 44% of events.

6.2 Group Size

Table 6.3 and figure 6.3 summarize the exposed population and the group size of CCF events. It can be seen that CCCG size and number of exposed components in the group are equivalent.

Table 6.3. Exposed components in the group / group size distribution

EXPOSED COMPONENTS IN THE GROUP			**GROUP SIZE**		
No. of exposed components	**No. of events**	**% of total**	**Group Size**	**No. of events**	**% of total**
Two	16	32%	Two	16	32%
Four	19[4]	38%	Four	19	38%
Five	3	6%	Five	3[5]	6%
Six	9	18%	Six	9	18%
Nine	1	2%	Nine	1	2%
Sixteen	2	4%	Sixteen	2	4%
TOTAL	**50**	**100%**	**TOTAL**	**50**	**100%**

The most significant populations are for groups of 4 and 2 batteries, with 38% and 32% of the events respectively.

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[4] There are two events for wich exposed population is not identified, but they correspond to a population of four.

[5] There is one event with group size = 1, but this is a mistake because the component impairment vector is composed by 5 elements.

The group size of 6 batteries is the next important group, representing 18%.

Groups of 5, 16 and 9 batteries account for 6%, 4% and 2% of the events.

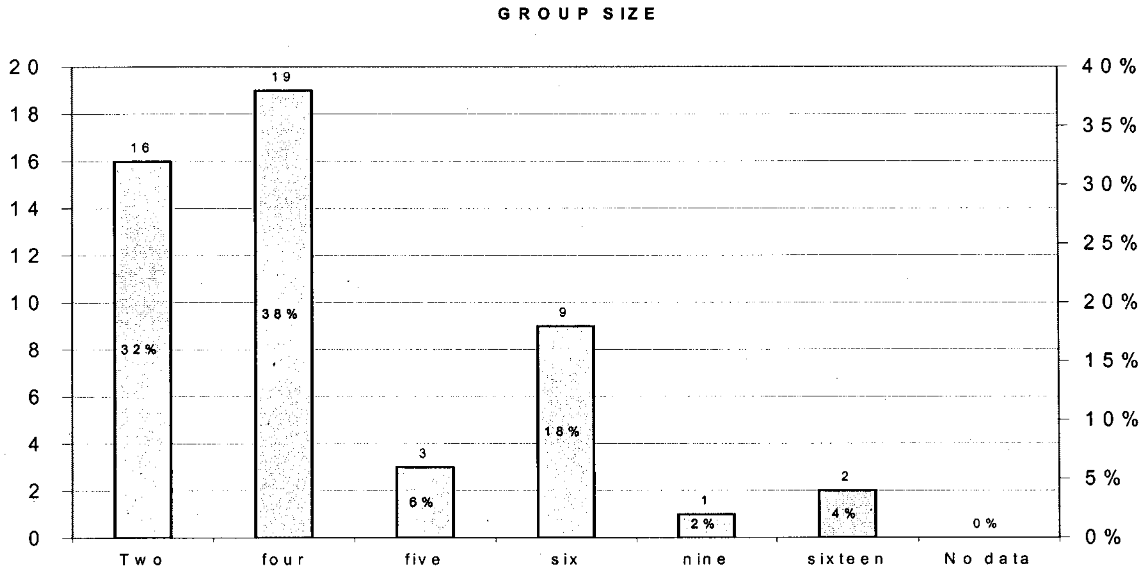

Figure 6.3. Group size distribution

6.3 Cause, Detection and Corrective Action

Table 6.4 and figure 6.4 summarize the root causes of the analyzed events as coded in the ICDE database.

The general coding guidelines [2] define root cause as follows. The cause field identifies the most basic reason for the component's failure. Most failure reports address an immediate cause and an underlying cause. For this project, the appropriate code is the one representing the common cause, or if all levels of causes are common cause, the most readily identifiable cause. The following coding is suggested:

- C – state of other component(s) (if not modeled in PSA). Examples are loss of power and loss of cooling.
- D – design, manufacture or construction inadequacy. This category encompasses actions and decisions taken during design, manufacture, or installation of components, both before and after the plant is operational.
- A – abnormal environmental stress. Represents causes related to a harsh environment that is not within component design specifications.
- H – human actions. Represents causes related to errors of omission or commission on the part of plant staff or contractor staff. This category includes accidental actions, failure to follow procedures and deficient training.

- M – maintenance. All maintenance not captured by H - human actions or P - procedure inadequacy.
- I – internal to component, piece part. Deals with malfunctioning of parts internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms. It includes the influence of the environment of the component. Specific mechanisms include erosion/corrosion, internal contamination, fatigue, and wear out/end of life.
- P – procedure inadequacy.
- O – other. The cause of events is known, but does not fit in one of the other categories.
- U – unknown. This cause category is used when the cause of the component state cannot be identified.

Table 6.4. Root cause distribution

ROOT CAUSE	**No. of events**	**Percentage**
A – Abnormal environmental stress	0	0%
C – State of other component(s)	1	2%
D – Design, manufacture or construction inadequacy	26	52%
H – Human actions, plant staff	6	12%
I – Internal to component, piece part	14	28%
M – Maintenance	0	0%
O – Other	0	0%
P – Procedure inadequacy	2	4%
U – Unknown	1	2%
TOTAL	**50**	**100%**

Design, Manufacture or Construction inadequacy accounts for the greatest number of events (52%).

Failure of internal battery parts accounts for 28%.

Human actions make a significant contribution, accounting for 12%.

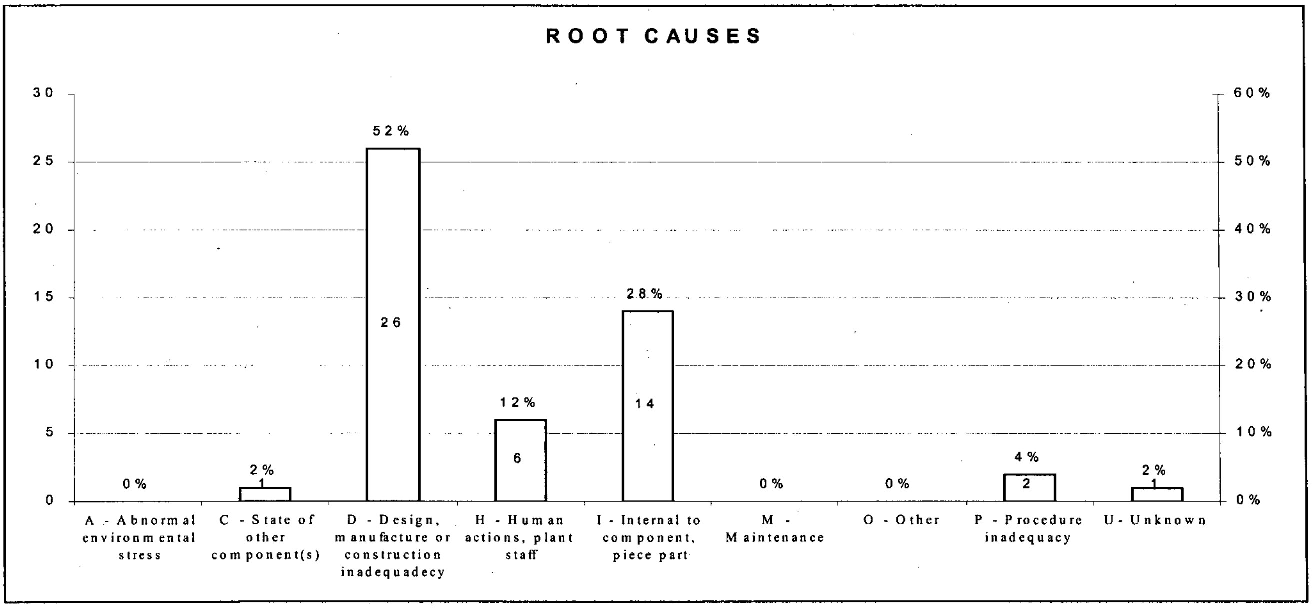

Figure 6.4. Root cause distribution

Table 6.5 and figure 6.5 show the coupling factors of the analyzed events as coded in the ICDE database.

The general coding guidelines [2] define coupling factor as follows. The coupling factor field describes the mechanism that ties multiple impairments together and identifies the influences that created the conditions for multiple components to be affected. For some events, there is a the root cause and coupling factor are broadly similar, with the combination of coding serving to give more detail as to the causal mechanisms.

Selection is made from the following codes:

- HC – hardware design. Components share the same design and internal parts.
- HS – system design. The CCF event is the result of design features within the system in which the components are located.
- HQ – hardware quality deficiency. Components share hardware quality deficiencies from the manufacturing process. Components share installation or construction features, from initial installation, construction, or subsequent modifications.
- OMS – maintenance/test (M/T) schedule. Components share maintenance and test schedules. For example, the component failed because maintenance was delayed until failure.
- OMP – M/T procedure. Components are affected by the same inadequate maintenance or test procedure. For example, the component failed because the maintenance procedure was incorrect or a calibration setpoint was incorrectly specified.

- OMF – M/T staff. Components are affected by a maintenance staff error.
- OP – operation procedure. Components are affected by an inadequate operations procedure.
- OF – operation staff. Components are affected by the same operations staff personnel error.
- EI – environmental internal. Components share the same internal environment. For example, the process fluid flowing through the component was too hot.
- EE – environmental external. Components share the same external environment.
- U – unknown.

Table 6.5. Coupling factor distribution

COUPLING FACTOR	**No. of events**	**Percentage**
H – Hardware	6	12%
HC – Hardware design	19	38%
HQ – Hardware quality deficiency	0	0%
HS – System design	3	6%
OMS – Maintenance/test schedule	0	0%
OMP – M/T procedure	5	10%
OMF – M/T Staff	3	6%
O – Operation	4	8%
OP – Operation procedure	2	4%
OF – Operation staff	0	0%
EI – Environmental internal	7	14%
EE – Environmental external	0	0%
U – Unknown	1	2%
TOTAL	**50**	**100%**

Table 6.5 shows that some of the ICDE events have been classified using the top-level categories, for example "Hardware", whereas others have used sub-categories, such as "Hardware quality deficiency". To get a view of mechanisms involved with the different events, figure 6.5 plots coupling factor in terms of the top-level categories only, but including the events associated with each sub-category within them.

The dominant coupling factor of the analyzed events is Hardware with 56% of events. Some of the ICDE events have been classified as H – Hardware (in general), and others used HC, HS codes. The same applies to Operation coupling factor and OP&OF codes. When the numbers of events coded using O, OP and OF codes are added together, the Operation factor accounts for 12% of events.

Within the "hardware" category, most events occur due to "hardware design", i.e. due to components sharing the same design and internal parts, rather than due to system hardware design or manufacturing quality.

Within the "maintenance" category, most events occur due to inadequate maintenance or test procedures, or incorrect maintenance / test action, rather than an inadequate schedule. The maintenance coupling factor accounts for a total of 16% (OMS, OMP and OMF codes).

There are 14% of events due to Environmental internal factor and a 2% has been classified as Unknown.

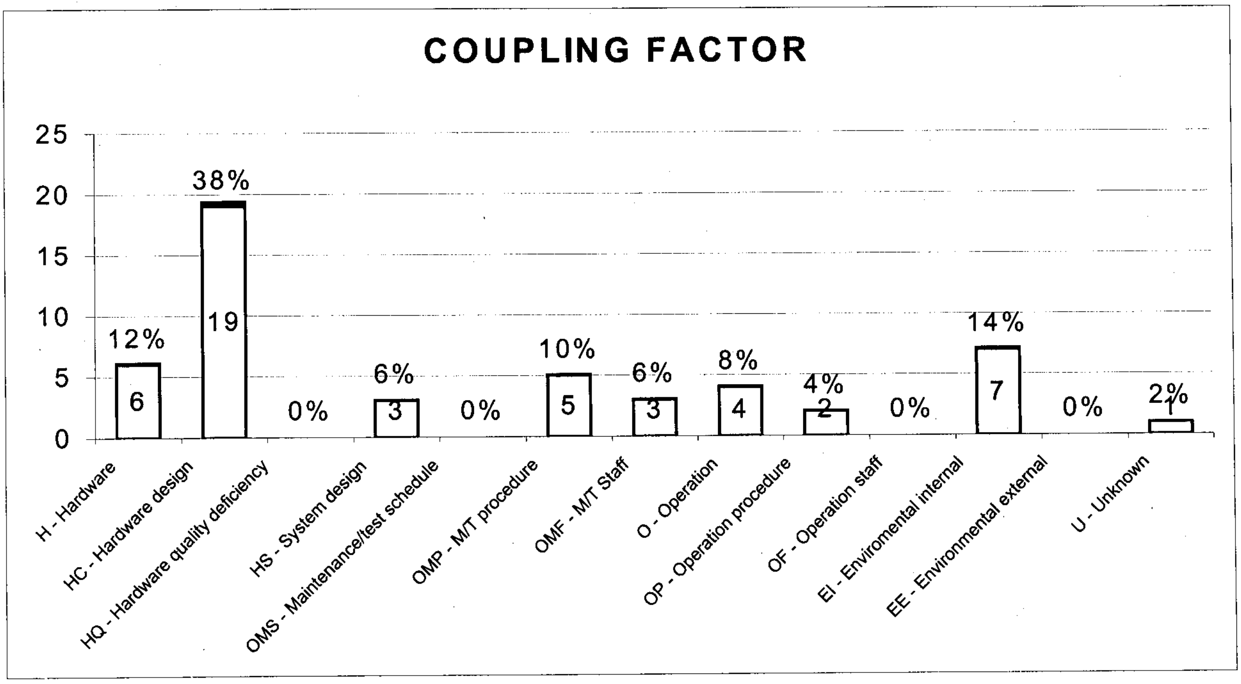

Figure 6.5. Coupling factor distribution

Table 6.6 and figure 6.6 summarize the corrective actions of the analyzed events as coded in the ICDE database.

Table 6.6. Corrective action distribution

CORRECTIVE ACTIONS	No. of events	Percentage
A – General administrative/procedure control	4	8%
B – Specific maintenance/operation practices	8	16%
C – Design modifications	21	42%
D – Diversity	3	6%
E – Functional/spatial separation	0	0%
F – Test and maintenance policies	2	4%
G – Fixing of component	8	16%
O – Other	4	8%
U – Unknown	0	0%
TOTAL	**50**	**100%**

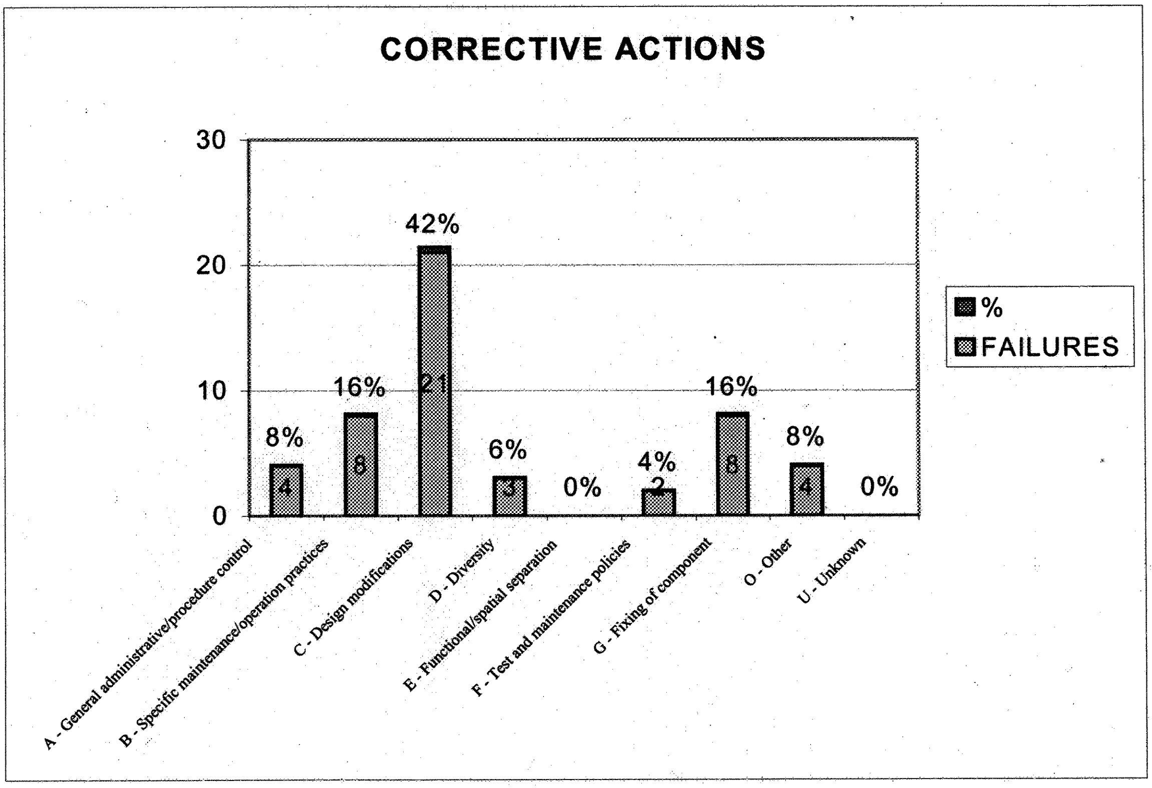

Figure 6.6. Corrective action distribution

The dominant corrective action, “Design modifications”, accounts for 42%. “Specific maintenance/operation practices” and “Fixing of component” account for 16% each.

“General administrative/procedure control”, “Diversity” and “Test and maintenance policies” account for 8%, 6% and 4% respectively.

There are 8% of events with a corrective action not considered in ICDE classification and no event with “Functional/spatial separation” as corrective action.

When the three largest groups from each of the coding categories; root cause, coupling factor and corrective action are regarded in combination, three rough groups of event type are suggested;

1. A very large group of events caused by battery design or manufacture inadequacy is suggested. Events of root cause “design, manufacture or construction inadequacy” (52%) may be largely the same events as the 56% for which the coupling factor is recorded as “hardware” (mainly of sub-category “hardware design”) and the 42% for which the corrective action is “design modifications”.

2. A smaller but still appreciable group of human, maintenance-induced failures is suggested. Human actions account for 12% of event root causes. 16% of events have coupling factor “maintenance / test” and around half of these are of sub-category “incorrect maintenance / test action”. “Specific maintenance/operation practices” is the suggested corrective action for 16% of events.

3. The results also suggest a group of events caused by some sort of internal malfunction, possibly itself caused by inadequate or incorrect maintenance. The malfunction of internal battery parts accounts for 28% of event root causes. "Internal environment" coupling factor accounts for 14% of events and the "inadequate maintenance or test procedures" subcategory of the "maintenance / test" coupling factor accounts for 10% of events. "Fixing of component" is the suggested corrective action for 16% of events.

Figures 6.7, 6.8 and 6.9 look at how the categories root cause, coupling factor and corrective action fit together.

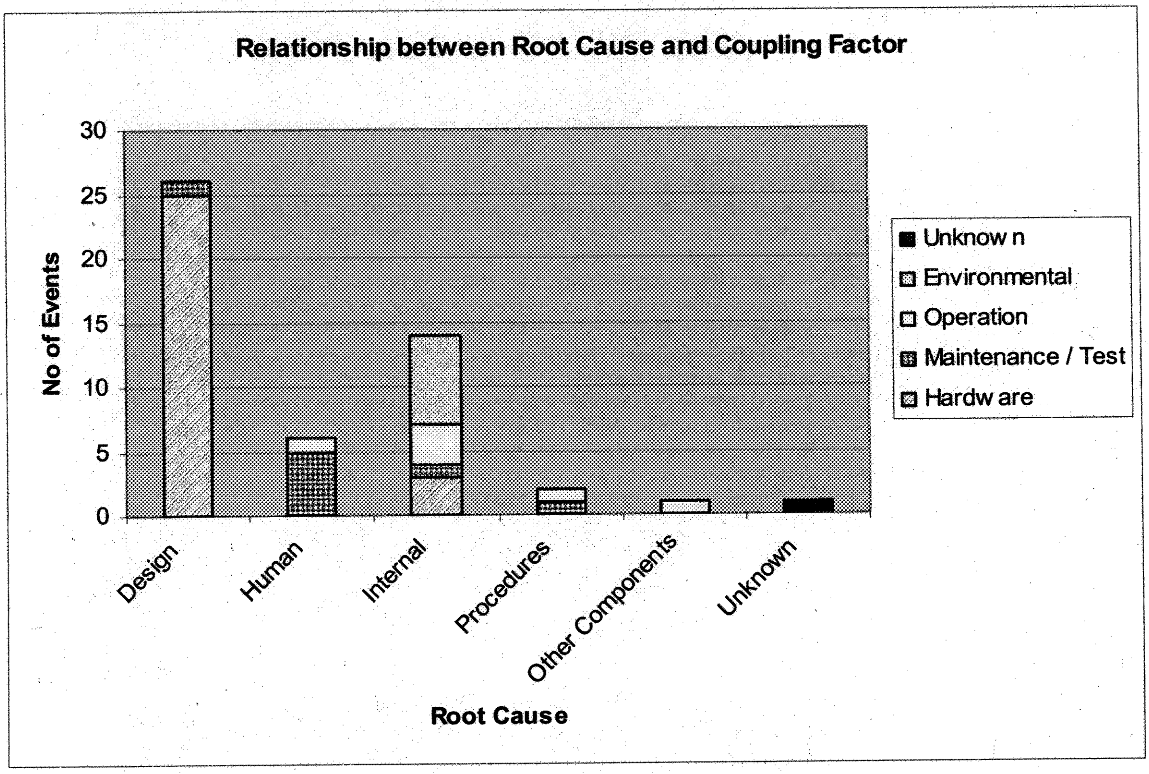

Figure 6.7. Root causes and coupling factors

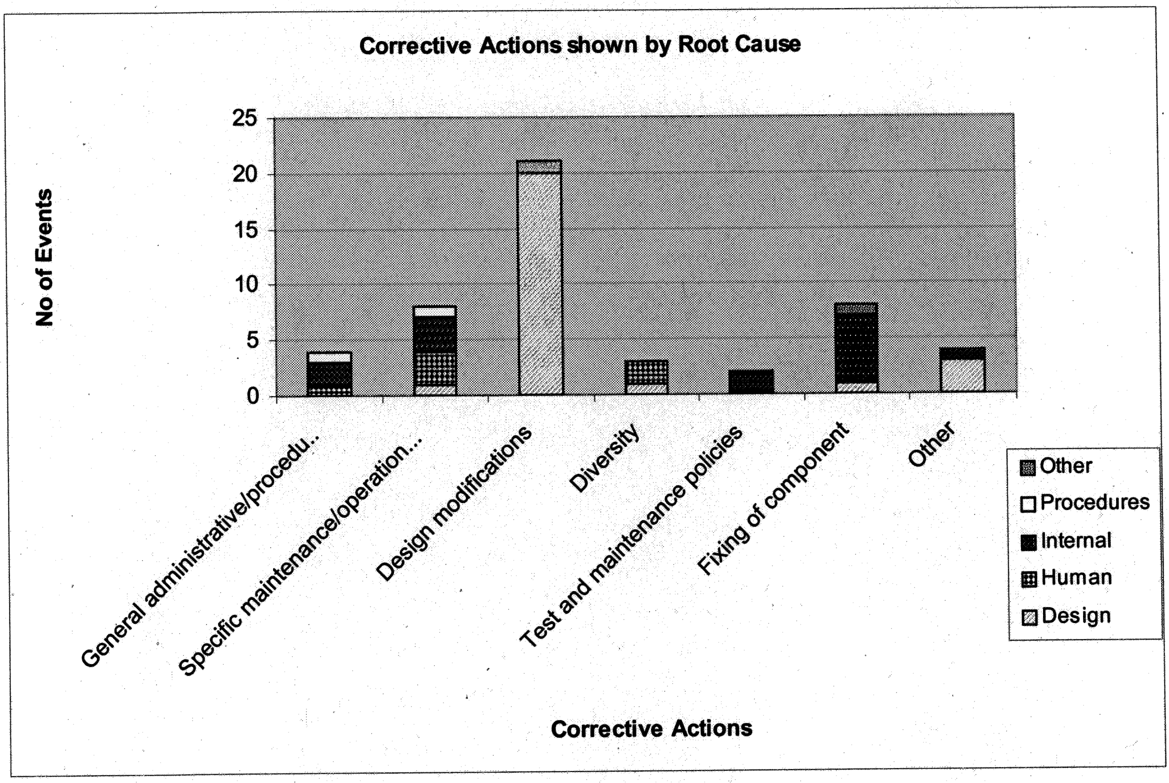

Figure 6.8. Corrective actions and root causes.

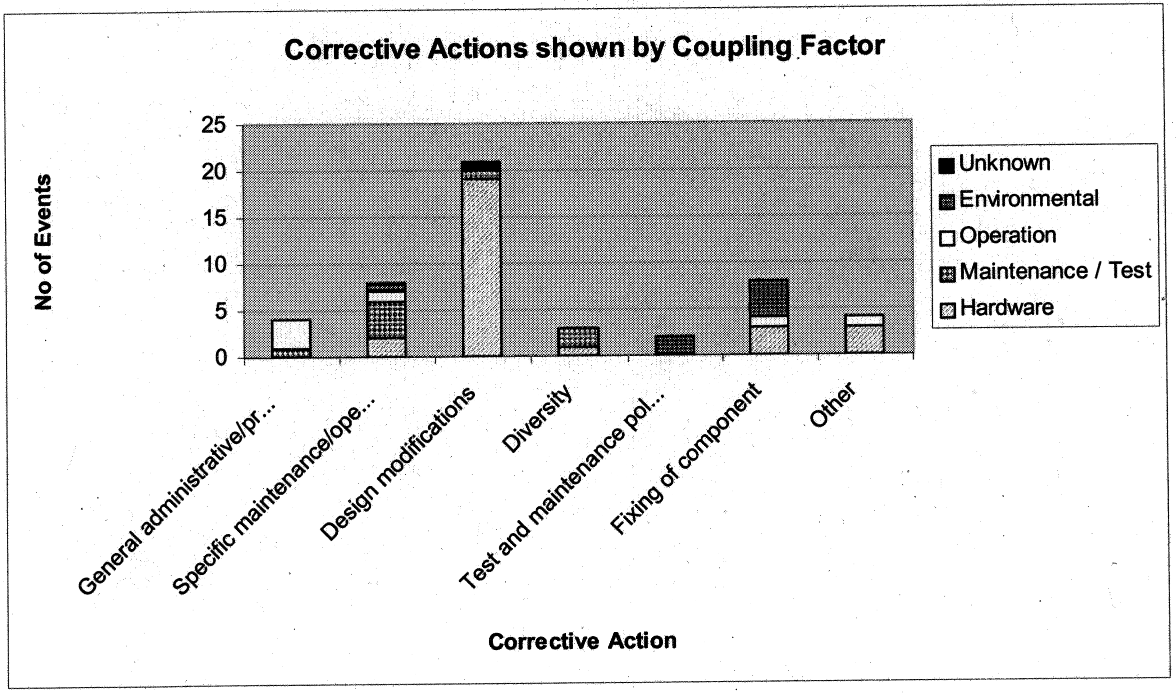

Figure 6.9. Corrective actions and coupling factors.

There is one causal mechanism that clearly dominates; 25 events (50%) have root cause of "design" and coupling factor "hardware". Nineteen of these events were corrected by "design modifications". This indicates a very high incidence of design/manufacture errors of batteries. Further investigation of coupling factor reveals 17 of these 19 events to be related to the battery hardware (coupling factor HC). These events relate to latent problems already within the batteries when they arrived on site. The remaining 2 of the 19 events relate to the system design (coupling factor HS or H), i.e. insufficient battery capacity in the system design.

Events with "maintenance/test" as the coupling factor are dominated by the root cause "human". These events are distributed between corrective actions "diversity", "specific maintenance/operation practices" and "general administrative procedure control". Five events (10%) have "human" root cause and "maintenance/test" coupling factor. This is a reasonable sized group, discernible as being caused by human error during maintenance/test.

All seven events of "environmental" coupling factor relate to the internal environment and are due to "internal" root cause. They mainly have suggested corrective actions of "test and maintenance policies" or "fixing of component", although one has corrective action of "specific maintenance/operation practices". The event descriptions of CCFs in this category reveal all events to be due to corrosion or incorrect electrolyte level. These internal problems may be caused by incorrect maintenance action, i.e. too little, too much or impure electrolyte added.

The "operation" coupling factor is dominated by root cause of "internal". Three events (6%) have this exact intersection of categories. The event descriptions of all three events attribute them to "ageing and electrical cycling over time". It is possible that these three events are caused by inadequate status monitoring.

In conclusion, we can recode cause as "Battery design / manufacture inadequacy" (17 events), "Plant / system design inadequacy" (2 events), "Human error during maintenance / test" (5 events), "Incorrect maintenance action" (7 events), "Inadequate status monitoring" (3 events) and "Unknown" (16 events).

6.4 Detection Methods

Table 6.7 and figure 6.10 summarize the detection methods of the analyzed events.

Table 6.7. Detection method distribution

DETECTION	EVENTS	%
DE – Demand event	0	0%
MA – Maintenance/Test	12	24%
MC – Monitoring in control room	2	4%
MW – Monitoring on walkdown	6	12%
TA – Test during annual overhaul	18	36%
TI – Test during operation	8	16%
TL – Test laboratory	1	2%
TU – Unscheduled test	1	2%
U – Unknown	2	4%
TOTAL	50	100%

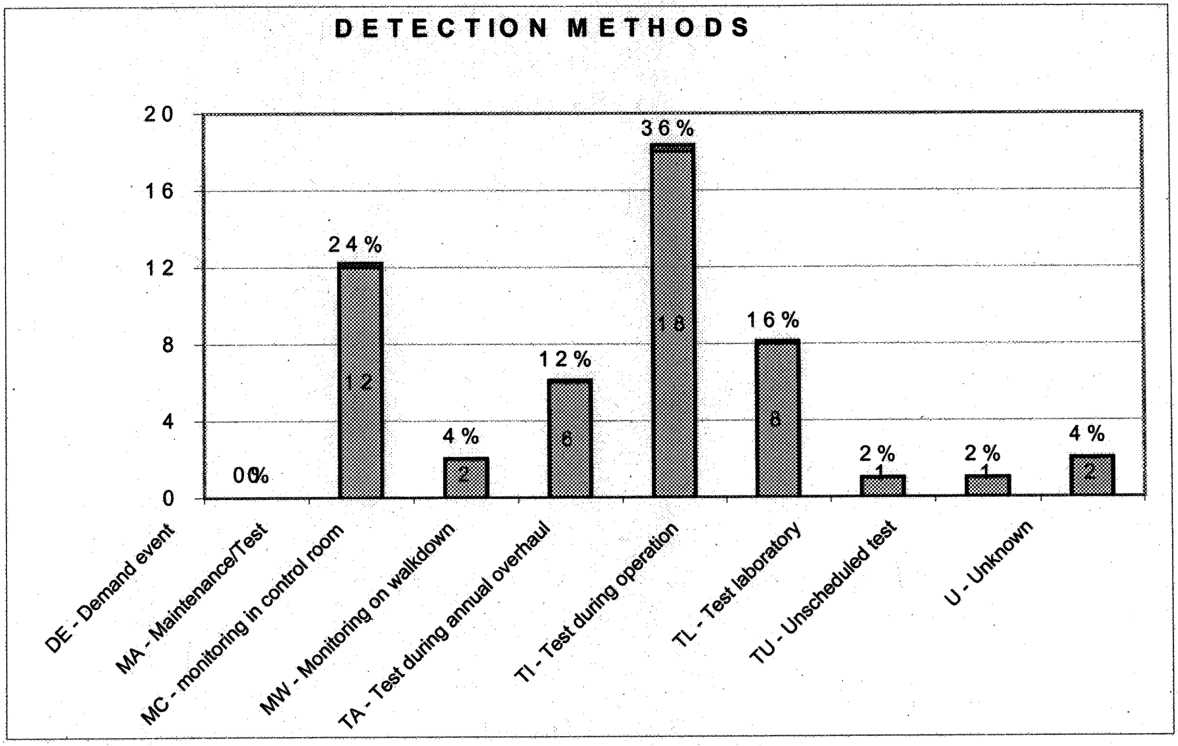

Figure 6.10. Detection method distribution

Most of CCF events were discovered during tests (56%) (TA, TI, TL, TU categories) and in the course of maintenance (24%), representing between them 80% of events studied.

Eight events were detected through monitoring (MC, MW), equating to 16% of events. Two events are unknown detection method (4%).

No events were revealed under demand.

To investigate the degree to which the events were revealed by the current regimes, the categories of "Detection Method" are regrouped according to whether or not the test /

inspection / maintenance was scheduled. It is assumed for this regrouping, that the categories, "MA – Maintenance/Test", "TA – Test during annual overhaul", "TI – Test during operation", and "MW – Monitoring on walkdown", "TL – Test laboratory" are scheduled, whereas, "TU – Unscheduled test" are unscheduled. The general coding guidelines do not specify this explicitly, and events were not coded with this in mind. Figure 6.10 should be viewed in this light.

Figure 6.11 shows that the majority of events were revealed through scheduled maintenance or test.

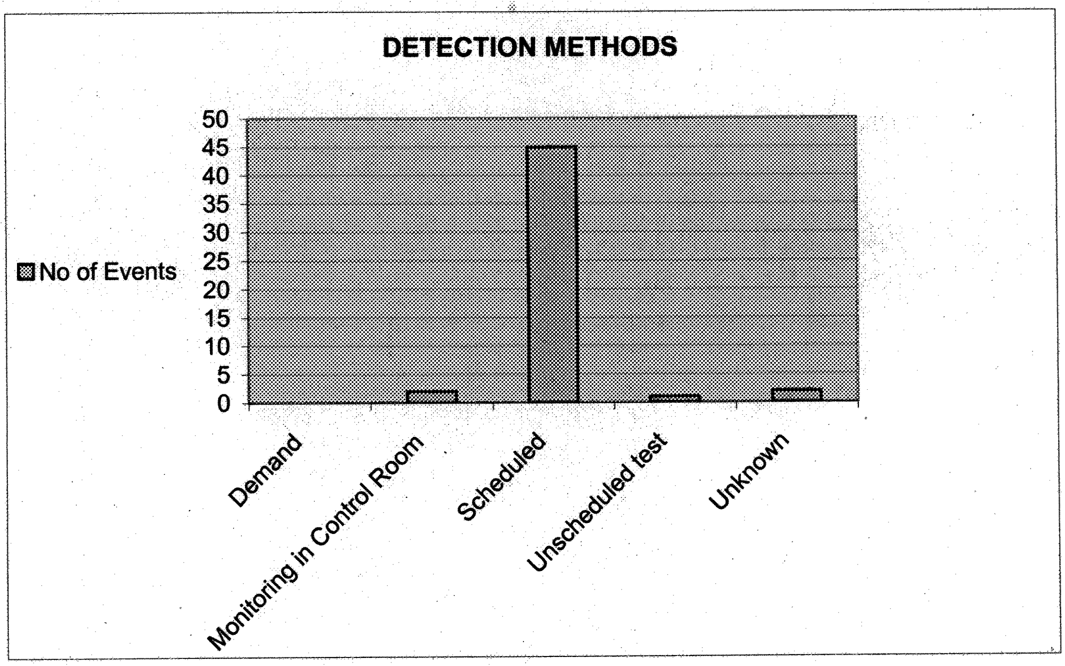

Figure 6.11. Detection method distribution (II)

6.5 Shared Cause Factor and Time Factor

Table 6.8 summarizes the shared cause of the analyzed events as coded in the ICDE database. The shared cause factor allows the analyst to express his degree of confidence about the multiple impairments resulting from the same cause.

- The coding "high" is used when the analyst is confident that multiple impairments are due to the same root cause. Typically, the failure/degradation mechanism, piece-parts affected and corrective action(s) would also be the same for each of the multiple components.

- The coding "medium" is used when the event description does not directly indicate that multiple impairments resulted from the same cause, involving the same failure mechanism, or affected the same piece-parts, but there is strong evidence that the underlying root cause of the multiple impairments is the same.

- The coding "low" is used when the event description indicates that multiple impairments resulted from different causes, involved different failure mechanisms, or affected different piece parts, but there is still some evidence that the underlying root cause of the multiple impairments is the same.

Table 6.8. Shared cause factor distribution

SHARED CAUSE FACTOR	No. of events	Percentage
H - High	43	86%
M - Medium	5	10%
L - Low	1	2%
No data	1	2%
TOTAL	**50**	**100%**

Table 6.9 summarizes the time factors of the analyzed events as coded in the ICDE database. Time factor is a measure of the "simultaneity" of multiple impairments. The attribute of the time factor (see below) is determined by the time between detection of individual impairments. In general, a weighting factor is assigned to the CCF event based on the time between individual impairments. The acceptable input for this field can be a decimal number from 0.1 to 1.0. The applied values depend on PRA mission time, failure mode, operating conditions, testing schemes and Technical Specification instructions on how to proceed after detection of a failed component. As some of these items differ in different plants and systems, it is not possible to generally account for them in the data collection. Therefore, tailoring of events for building PRA data sets may need a reassessment of time factor values.

Specific time factor attributes and values to be used for some common scenarios are:

Failure to run/operate of operating components and stand-by components in operating mode(s):

- High: Multiple component impairment occurring within PRA mission time. The weight factor is 1.0.

- Medium: Multiple component impairment occurring outside PRA mission time, but within one-month period (for operating components) or within double mission time (for stand-by components). The weight factor is 0.5.

- Low: Multiple component impairment occurring more than one month apart (for operating components) or more than double mission time (for stand-by components). The weight factor is 0.1.

Remark: for stand-by components operating times have to be summed up from running times during tests and operational demands.

Other failures (to start, stop, switch of position, etc.) of stand-by components and operating components with cyclical change of operation time (at a given time only x of n components are operating, with cyclical change).

- Staggered testing:

- High: Multiple component impairment discovered during testing or by observation within one test cycle of length T (test cycle T is the time between two consecutive tests of one component). The weight factor is 1.0.
- Medium: Multiple component impairment discovered during testing or by observation within two subsequent test cycles (length 2T). The weight factor is 0.5.
- Low: Multiple component impairment discovered during testing or by observation two or more test cycles apart (> 2T). The weight factor is 0.1.

Table 6.9. Time factor distribution

TIME FACTOR	No. of events	Percentage
H - High	44	88%
M - Medium	2	4%
L - Low	4	8%
TOTAL	**50**	**100%**

The dominant classification for both, the shared cause and time factors, are "High". This implies that the events reported on are mainly due to the same cause and have a tendency to be revealed together. This type of event has the most serious system consequences. However, it may be the case that the same proportion of events with "high" shared cause factor and/or "high" system consequence may be found in any dataset, irrespective of the component studied because:

- An event of high shared cause factor may be more likely to occur as it is not dependent on the coincident arrival of a number of different faults.
- An event of low time factor may be less likely to be identified as a CCF as the component failures are well-spaced over time.

7. TECHNICAL FAULT ASPECT OF BATTERY CCFS

7.1 Failure Mechanism and Symptoms

The ICDE events of battery failures have been analyzed and the failure mechanisms and symptoms taken into account in order to identify the real problems and, therefore, to establish the defences against them. Basically, the battery failures can be grouped into three aspects: Design, Maintenance / Tests, and Operation.

Table 7.1 and figure 7.1 summarize the battery failures. Table 7.2 tabulates the combinations of cause and failure symptom displayed by the events.

a) The design aspect can be subdivided again into two groups:

- Failures during the engineering process. These events could be caused by calculation errors in the capacity definition (e.g. several charges are not considered, error in the definition of discharge voltage limit). The failure symptom associated with this mechanism is an insufficient capacity of the battery.

  Two events are included in this group, which represent 4% of the failures.

- Failures during the construction process. These events could be caused by inadequate selection or manufacture of component materials for the plates (causing for example cracks / breaks, premature aging or loss of surface activity), for the electrolyte (causing for example high acid concentration), for the separators (causing for example decomposition of the electrolyte and reaction with it or loss of porosity), for the cells (causing for example cracks / breaks or loss of plasticity or voltage mechanical stress), or for the terminal connections (causing for example electrochemical reaction with joining wire or corrosion). In general, the failure symptoms are insufficient capacity and short-circuit.

  There are 23 events related to this group, which accounts for 46% of the failures.

Design problems represent 50% of the events.

In order to avoid this kind of failure, the prevention suggested during the analysis on batteries, was the improvement of design verification and commissioning or checking design modification (e.g. check list for plant modification proposal should include the effect on batteries).

b) The maintenance / test aspect can be subdivided into four groups:

- Physical failures in the sub-components of the battery:
  - Electrolyte problems (e.g. loss of density because of spilling, decomposition by pollution or evaporations which decreases the effective area and damages the plates) leading to density drop or low level.
  - Connection problems (e.g. insufficient tightening of connections)

  - · Breaker / switch problems (e.g. hardening of grease due to aging) leading to corrosion or increase of the resistance between terminal connections and wires or the discharge of the battery.

  There are 10 events related to this group, which accounts for 20% of the failures.

- Electrical failures could be produced by:

  - · Incomplete (unfinished) recharge leads to low density of the electrolyte.
  - · Prolonged operation of cells with low voltage reduces the capacity and causes low floating voltage and premature aging of the battery.

  There are 6 events related to this group, which accounts for 12% of the failures.

- Direct human actions as bad manipulation, blows during handling or the inadvertent insertion of objects into cells could cause cracks in cells or plates or short-circuit among plates.

  There are 4 events related to this group, which represents 8% of the failures.

- Lack of tests / preventive maintenance or control on batteries could make the component fail due to premature aging.

  There is one single event related to this group, which accounts for 2% of the failures.

Maintenance / test problems represent 42% of the events.

Most of this kind of failure could be prevented with adequate test / maintenance practices and surveillance of the circuit continuity, according to suggestions of the analysis carried out on batteries.

c) The operation aspect could be associated with spurious actuation of protections (e.g. fuse blowing or breaker shut off). None of the events in the ICDE database fell into this group.

Finally, there are 3 events in which it is possible to identify that the cause of loss of the battery voltage is a failure in another component (e.g. charger, bar isolator or switchgear between the battery and charger). These events represent 6% of the failures.

There exists one event with unknown cause and it is not possible to deduce what happened.

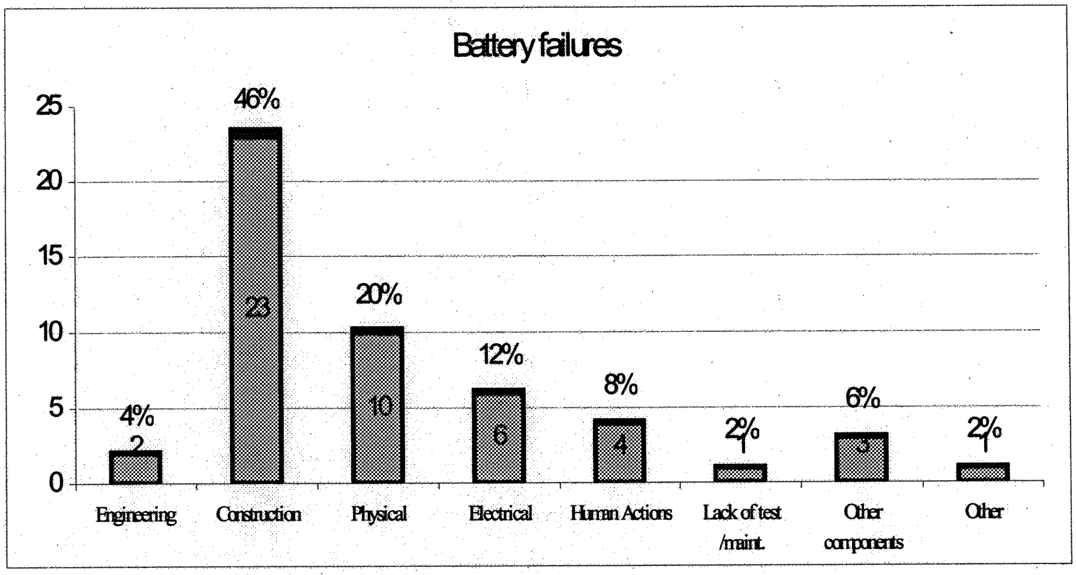

Figure 7.1. Battery failure distribution

7.2 Prevention methods, protections, and corrective actions

Prevention methods and corrective actions are often closely related. The ICDE definition of "corrective action" often constitutes a method to prevent future recurrence of the same event. A comparison of the results for "corrective action" as defined in the ICDE database with the results for "prevention" as defined through the additional categorization showed a close correlation. 50% of the events were caused by design problems and the most important prevention method identified was the improvement to design verification and commissioning. This is in line with that indicated in Section 6, where the dominant corrective action was "Design modifications", accounting for 42%. "Specific maintenance/operation practices" and "Fixing of component" accounted for 16% each, which is also supported by the analysis.

Additional protection methods identified include alarms and surveillance of the circuit continuity (for example an electronic monitoring system). According to Section 6, most of CCF events were discovered during tests (56%) and in the course of maintenance (24%). The fact that 80% of the events studied were revealed by maintenance or test may indicate that this protection mechanism is already effective and there is no scope for improved protection through improvements to maintenance/test methods. In general, it was felt that if there is no prevention mechanism, there is also no additional protection mechanism that can be implemented, particularly for events that cause immediate failure.

Table 7.1 Battery Failures (causes, process, and symptoms)

Failure Cause	Process / Error / Immediate Cause of Failure			Symptoms of Failure
Design	Engineering	Calculation errors in the capacity definition	Several charges are not considered	Insufficient capacity
			Error in the definition of discharge voltage limit	Insufficient capacity
	Construction	Inadequate selection for the component materials	Plates	Cracks / Breaks
				Insufficient capacity (Premature aging)
				Insufficient capacity (Loss of surface activity)
			High acid concentration in the electrolyte	Insufficient capacity (Corrosion)
				Short circuit
			Separators / Cells /Terminal conections	Decomposition of the electrolyte (Reaction with it) Insufficient capacity (Loss of porosity) Cracks / Breaks (Loss of plasticity or voltage mechanical stress) Corrosion (Electrochemical reaction with joining wire)

Table 7.1 Battery Failures (causes, process, and symptoms)

Failure Cause	**Process / Error / Immediate Cause of Failure**			**Symptoms of Failure**
Maintenance / Test	Physical	Electrolyte	Loss of the density in the electrolyte because of spilling	Density decreasing
			Decomposition of the electrolyte by pollution	Density decreasing
			Low level by evaporations, which decreases the effective area and damages the plates	Low level in the electrolyte
		Connections	Insufficient tightening of connections	Increasing of the resistance between terminal connections and wires
		Breaker /switch problems	Hardening of grease due to aging	Corrosion or increasing of the resistance between terminal conections and wires
	Electrical	Incomplete recharge	Unfinished recharge	Low density of the electrolyte
		Float voltage	Prolonged operation of cells with a low voltage reduce the capacity	Low float voltage
	Human	Blows during handling / bad manipulation		Cracks in cells
				Cracks in plates
	- Direct actions	Entry of objects		Short-circuit among plates
	- Procedure	Lack of test / preventive maintenance (premature aging)		Insufficient capacity
Other components	Charger / bar oslator / switchgear between the battery and charger			Loss of voltage

Table 7.2. Combinations of Failure Cause and Symptoms

Failure Cause Categories		**Failure symptoms**	**Percentage**
Design			**50%**
1. Engineering process:	• Calculation errors in the capacity definition	• Insufficient capacity of the battery.	4%
2. Construction process:	• Inadequate selection of component materials for the plates / electrolyte / separators / cells	• Insufficient capacity. • Short-circuit. • Low-voltage battery/cells.	46%
Maintenance /Test			**42%**
1. Physical failures in sub-components	• Electrolyte • Connections • Breaker / switch	• Loss of density • Low level in the electrolyte. • Insufficient tightening of connection • Corrosion or increasing of the resistance between terminal connections and wires. • Discharge of the battery.	20%
2. Electrical Failures	• Incomplete recharge • Prolonged operation of cells with low voltage	• Low density of the electrolyte. • Low-voltage battery/cells • Low floating voltage. • Premature aging	12%
3. Human			
- Direct actions	• Bad manipulation, blows during handling or entry of objects, etc.	• Cracks in cells or plates. • Short-circuit	8%
- Procedure	• Lack of test / preventive maintenance	• Premature aging • Low-voltage battery/cells	2%
Other components	• Charger / bar isolator / swithgear between the battery and the charger.	• Loss of voltage.	**6%**
Unknown	--	• Loss of voltage.	**2%**

7.3 Failure Causal Categories

Failure causal categories [5, 6] have been identified in a few of the events. Nevertheless, it has been possible to work out the most important events in the light of root causes, prevention methods, corrective actions and the event description. These are the following:

- Change management implies relatively important plant / system modifications and the root causes related to it are deficient operation readiness control, change not performed/identified in time, consequences of change not correctly analyzed, poor routines/change not correctly performed, and deficient information about performed change.

- Plant management includes deficiencies in all management systems, such as Quality Assurance, maintenance, test, operation experience feedback, training program, corrective action program, etc. It also includes deficient safety culture and safety analysis, insufficient staff compare with goals and objectives, etc.

- Supervisory methods encompass deficient assignment of responsibilities, deficient follow-up of tasks, expectations not communicated, too few contacts with workers, priority put on time and not on safety, etc.

- Hardware failure.

The three first categories account for over 40% of the events. The last category, hardware failure, is close to 50%.

7.4 Consequences: Effect / reliability / down time and time to failure

The ICDE events have been analyzed, with a view to deriving the event consequences.

The effects and their reliability significance could be classified in three categories:

- Catastrophic damage: the battery's loss of function is so important that it is necessary to repair or replace it immediately.

- Medium damage: the battery's loss of function is light, but it is recommendable to repair or replace it in a short term.

- Minor damage: the battery suffers degradation but it carries out its safety function and it is not necessary to repair it immediately.

The analysis of events yields the results displayed in table 7.3.

Table 7.3. Effect, reliability significance and down time distribution

Effect, reliability significance and down time	No. of events	Percentage
Catastrophic damage	11	22%
Medium damage	16	32%
Minor damage	20	40%
No information	3	6%

The studied events contributed significantly to the cases of catastrophic damage. The failure symptoms associated to this situation were:

- Insufficient capacity because of aging.
- Plate degradation because of aging.
- Casing breakage.
- Low voltage battery / Low voltage cells.
- Short-circuit.
- Breaker problems.

Normally, the medium and minor damages were caused by:

- Low voltage battery / Low voltage cells.
- Insufficient capacity by design.
- Corrosion of the terminal plates / insufficient tightening of terminal connections.

On the other hand, this study identified the time to failure of the events, classifying this concept in four categories:

- Long-term: the event involves the battery's loss of function in a period longer than one year (period between refuelling outage).
- Medium-term: the event involves the battery's loss of function in a period shorter than one year (period spanned between refuelling outage) and longer than one day.
- Short-term: the event involves the battery loss of function in a period shorter than one day but not immediately.
- Instantaneous: the loss of function of the battery is immediate.

The analysis of the events reflects the following data are included in table 7.4.

Table 7.4. Time to failure distribution

Time to failure	**No. of events**	**Percentage**
Long-term	8	16%
Medium-term	10	20%
Short-term	2	4%
Instantaneous	16	32%
No information	14	28%

The most important contribution is the "Instantaneous" failure (32%). This information should be considered together with the level of failure showed in Section 6, table 6.1, where it is said that only 6% of the events are complete failures and with the concept of time factor, reflected in table 6.9, in which the major contribution was High ("failure during mission time").

8. SUMMARY AND CONCLUSIONS

This study has examined 50 events in the International CCF Data Exchange (ICDE) database by tabulating the data and observing trends.

The database comprises information developed during the original entry of the events that was used in this study. The data span a period from 1980 through 2000. The data is not necessarily complete for each country through this period. The database contains general information about event attributes like root cause, coupling factor, common cause component group (CCCG) size, and corrective action. In addition, this study has included further categorizations of each ICDE event. The data tabulation and trend observation of this study has covered these new categorizations alongside the original data from ICDE database. The additional categories include degree of failure, and detection method.

The objectives of this report, as stated in section 1, are:

- To describe the data profile in the ICDE database for batteries and to develop qualitative insights in the nature of the reported events, expressed by root causes, coupling factors, and corrective actions; and
- To develop the failure mechanisms and phenomena involved in the events, their relationship to the root causes, and possibilities for improvement.

In respect of the first objective, section 6 of this report identified that only 10% of all ICDE events of batteries were complete or partial CCFs (at least two failed components in the group) according to the accepted definition. The remaining events fall within the ICDE event definition, but not the accepted CCF definition, i.e. impairment, rather than complete failure of two or more components over a relevant time interval and due to a shared cause. This result, alongside the small number of Battery events (50) recorded in the ICDE database, compared with the number recorded for other components, may indicate that relatively few CCFs occur in batteries and / or good defences against battery CCFs already exist.

The most susceptible failure mode of batteries is "failure to run". 82% of events were “fail to run”. A characteristic of batteries to fail over an extended period by slow degradation in capacity was noted.

In respect of the second objective, the additional categorizations revealed results that tied in closely with those derived in respect of the first objective.

The ICDE events of battery failures have been analyzed and the failure mechanisms and symptoms taken into account in order to identify the real problems and, therefore, to study the defences against them. Basically, the battery failures can be grouped into three aspects: Design, Maintenance / Tests, and Operation.

Deficiencies in design were responsible for 50% of the events. Most of these occurred during battery manufacture but a small number occurred during engineering process and could have been caused by calculation errors in the capacity definition. In order to avoid this kind of failure, the suggested preventions are improvements to processes for verification of plant design, modification or commissioning.

Deficiencies in maintenance / test were responsible for 42% of the events. The data suggests that the majority of this kind of failure could be prevented with adequate test / maintenance practices and surveillance of the circuit continuity.

Tables 7.1 and 7.2, in section 7, summarize the failure cause categories against failure symptoms.

The most significant failure symptoms are:

- "Insufficient capacity" by design (40% of the events). Events with this failure were caused by an inadequate selection for the component materials during the battery design/ construction process.
- "Low-voltage battery/cells" (22% of the events). Events with this failure had a number of causes; deficiencies in components materials, aging, inadequate tests / maintenance, etc.
- "Corrosion of the terminal plates / insufficient tightening of terminal connections". These events brought about physical damage in batteries and were caused by inadequacies in the maintenance process.

Additional categorization of the events and subsequent qualitative analysis has revealed that the "event description" field, C05, is in many cases the limiting factor in the terms of the quality of, or degree of confidence in, event interpretation. It would be beneficial to the results and conclusions of future studies if improvements to the quantity and quality of information in this field could be made.

It is for this reason that the degree of confidence in results derived through additional characterization of the data (results in respect of the second objective listed above) is necessarily lower than that for results derived directly from the ICDE database. However, some comparison of results was possible and this has in general shown correlation of the two sources.

Prevention methods and corrective actions are closely related. The ICDE definition of "corrective action" often constitutes a method to prevent future recurrence of the same event. A comparison of the results for "corrective action" as defined in the ICDE database with the results for "prevention" as defined through the additional categorization showed a close correlation. This result also lends credence to the results obtained from the additional characterization.

Additional protection methods identified include alarms and surveillance of the circuit continuity (for example an electronic monitoring system). According to Section 6, most of CCF events were discovered during tests (56%) and in the course of maintenance (24%). The fact that 80% of the events studied were revealed by maintenance or test may indicate that this protection mechanism is already effective and there is no scope for improved protection through improvements to maintenance/test methods. For events which cause failure by slow degradation in capacity, timely action on the event limits the degree of impairment and number of components affected. In general, it was felt that if there is no prevention mechanism, there is also no additional protection mechanism that can be implemented, particularly for events that cause immediate failure.

9. REFERENCES

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Appendix A Failure symptoms and subcomponents

A1. CCF event interpretation (Field C7) and failure symptoms

The CCF event description (Text description /Compulsory/) shall describe the (subjective) rationale used by the analyst to classify the event as a CCF event.

This is a proposal for description of the Failure Symptoms:

Code	Failure symptom
BF	Blown fuse
BP	Breaker problem
CB	Casing break
CTP	Corrosion of the terminal plates/insufficient tightening of terminal connections
ICD	Insufficient capacity (by design)
IE	Impurities in the electrolyte
LDE	Low density of the electrolyte
LLE	Low level of the electrolyte
LVB	Low-voltage battery
LVC	Low-voltage cells
OL	Overloading / excessive load
PDA	Plate degradation (by aging)
RCC	Inadequate room cooling/ventilation conditions
SC	Short-circuit

Remarks:

CB Casing break

Results in electrolyte loss.

CTP Corrosion of the terminal plates / insufficient tightening of terminal connections (improper maintenance)

Results in high electrical resistance due to poor contact between the current conductors; the process leads to a high voltage drop.

ICD Insufficient capacity (by design)

The battery design capacity is inadequate for the system. The battery is working properly, but its capacity is inadequate for supporting loads (i.e. due to design modifications that increased battery loads, or because the initial capacity is insufficient and the problem was only detected in a loss of offsite power incident).

IE Impurities in the electrolyte

The most frequent cause is the use or addition of improper water (i.e. for Pb batteries, the most common impurities are iron, chlorine, and copper. For Ni-Cd batteries, under special battery service conditions, such as high temperature or frequent cycling, the electrolyte absorbs carbon dioxide from the air and it is partially transformed in potassium carbonate, increasing the electric resistance and decreasing its capacity; in this situation it could be necessary to replace the electrolyte).

LDE Low density of the electrolyte

Results in progressive loss of the active plate area with the consequential loss of capacity, deformation and deterioration. The problem is detected by the low density of the battery electrolyte. If the sulfurisation is not significant, the battery could be recovered by one or more equalization loads until the proper value of the electrolyte density in all the elements is retained (Pb-batteries).

LLE Low level of the electrolyte

Results in progressive loss of the active area of the uncovered plate part and the same type of problems as described for the "insufficient load" case.

LVB Low-voltage battery

The total battery float is found to be less than the manufacturer recommended minimum value.

LVC Low-voltage cells

Cells voltage is not, by itself, an indication of the state of charge of the battery. Prolonged operation of cells below the value of specific gravity cells (V) can reduce the life expectancy of cells. If normal life is to be obtained from these cells, they should be given an equalizing charge.

OL Overloading / excessive load

This case is characterized by loss of the active material from the plates and the corrosion of the metallic structure in the positive plates. A clear indication of the battery overloading is excessive water use and, therefore, the frequent need to refill the elements in order to maintain the electrolyte level.

PDA Plate degradation (by aging)

The battery is aged, involving capacity loss of the plate. (For Ni-Cd batteries, the aging could be due to the graphite loss: increasing the resistance, causing low voltage and a lower autonomy).

RCC Inadequate Room Cooling/Ventilation Conditions

Room Temperatures:

- too low (for Pb batteries) or too high (for alkaline batteries).
- insufficient ventilation (leading to hydrogen generation).

SC Short-circuit

When two or more plates are in touch, a sudden discharge occurs with subsequent plate destruction.

The most frequent reasons for a short-circuit are:

- accidental introduction of electrically conducting particles into the element, simultaneously contacting two plates of different polarity.
- separator wear.
- excessive accumulation of sediment at the bottom of the casing (i.e. for Ni-Cd elements, the process is caused by plate carbonating).

This symptom also includes the short-circuit of the power leads from the battery to the bus.

A2. Proposal for the Sub-components and subsystems

Code	Sub-component
BR	Breaker
CE	Cell (elements)
FU	Fuse
PL	Power lead
Other	Other

Notes:

- The battery cells include the connections between cells and the casing.
- The power leads are the external connections from the batteries to the cabinet buses.

Appendix B Additional Analysis of ICDE Batteries Database

B1. Introduction

This appendix presents the key insights from additional analysis of the ICDE batteries database, based on a particular methodology. The methodology aims to gain a greater understanding of battery CCFs and to identify practical measures that can be implemented on site to reduce the occurrence or minimise the effect of battery CCFs. Initially all 50 events in the ICDE database were reclassified using a number of new fields, additional to those described by the ICDE project. These results were then analysed.

B2. Results

- **Cause**

Figure 1 shows the direct cause of events. Direct cause describes the cause of the multiple impairment. Note that this is a new field, additional to the ICDE fields.

Figure 1 shows that nearly half of all CCFs in the ICDE database are caused by a problem initiated during battery design or manufacture. Maintenance and test causes approximately a quarter of events. These two causes are considered in more detail in the following sub-sections.

Two events (4%) were found to be caused by critical system design errors, in this case inadequate capacity of the battery system. This number is small compared with the number of systems designed or modified, which suggests that the current approach is fairly robust.

There are also a fairly substantial number of events of unknown cause. The "unknown" category is attributed to events when the "event description" field in the ICDE database states what the impairment is but does not report how or why it occurred.

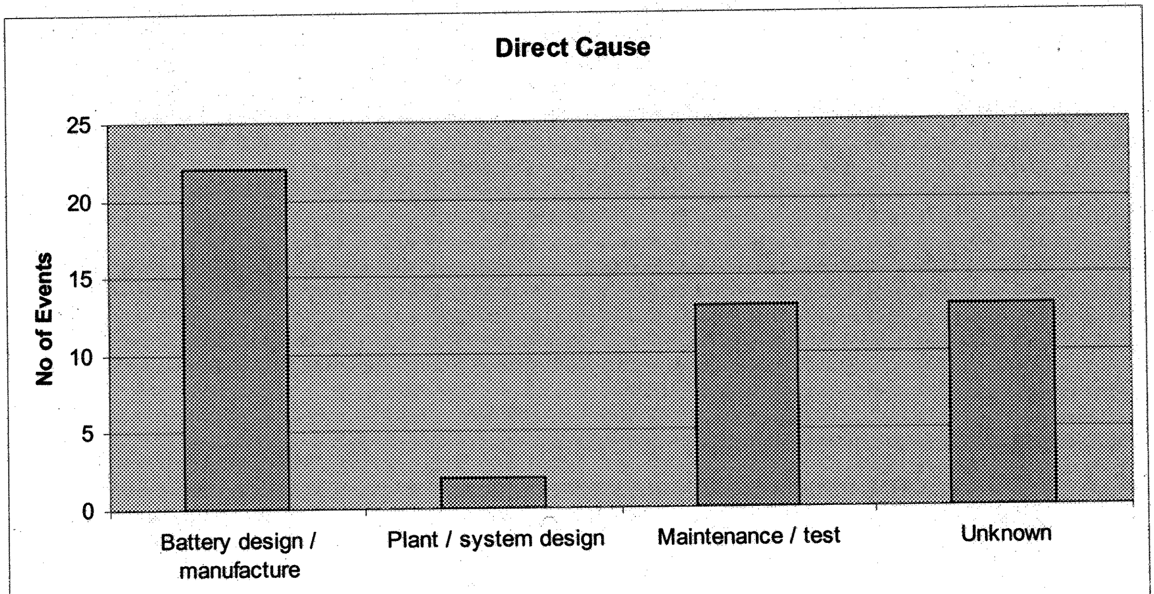

Figure 1

Design or Manufacture

All 22 faults pertaining to Design or Manufacture inadequacies were present in the batteries prior to their arrival on site. For each type of battery technology, figure 2 shows the number of design / manufacture CCFs as a percentage of the number of component groups (CCCGs) in the dataset. Nearly 90% of Nickel-Cadmium (Ni-Cd) CCCGs and over 40% of Lead-Calcium (Pb-Ca) CCCGs in the dataset experienced design / manufacture CCFs, compared with very small percentages across the remaining battery types. This is interesting, since Ni-Cd and Pb-Ca can be regarded as relatively new technologies, when compared with the other battery types. The significance of this result is reinforced when regarded in absolute terms. "New technologies" account for 77% of the total number of design / manufacture CCFs, whereas they account for only 8% of the total number of CCCGs.

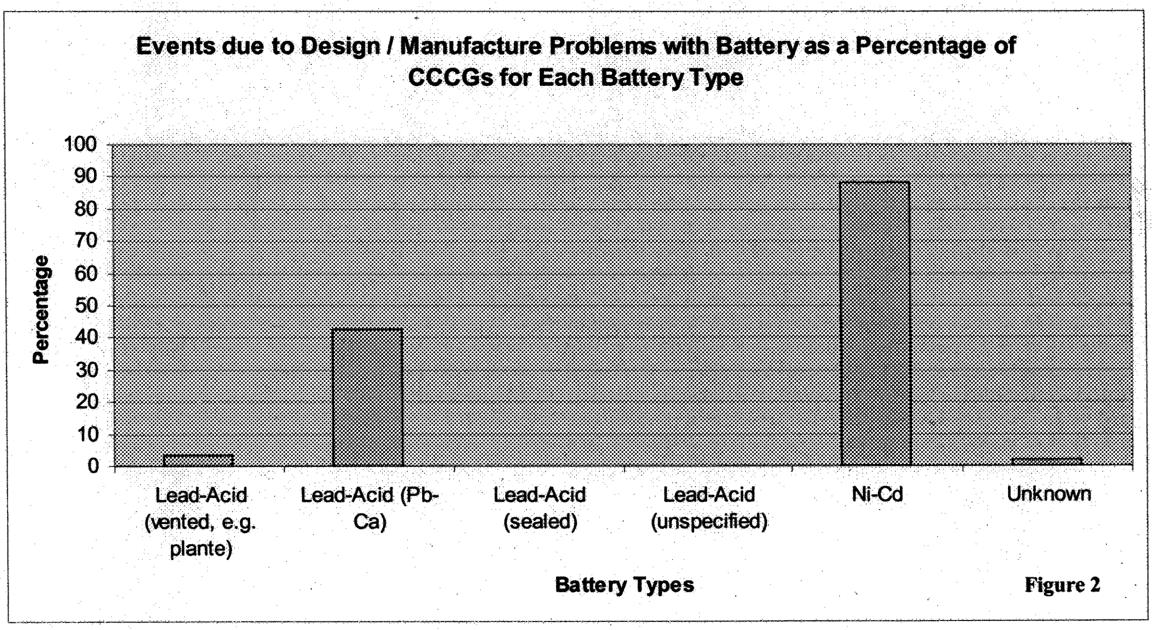

Figure 2

The data suggests that the deployment of new, rather than established technologies may be more likely to lead to CCFs.

Maintenance or Test

Approximately half of the events caused by deficiencies in maintenance or test were maintenance induced faults. The other half was caused by an inadequate test regime, in terms of frequency and / or content.

Root causes of maintenance induced errors may include factors such as inadequacies in the procedures, task organisation, communication or staff competency or a stress situation such as a cramped workplace. There is insufficient information in the ICDE database to allow specific advice on preventative mechanisms to be given for this type of event. Reliance is placed on the mechanisms put in place by each country or plant to gain an understanding of the root cause of maintenance induced faults, derive prevention mechanisms and incorporate these into procedures and processes.

Events caused by inadequate test regime are those where the ICDE event description attributes the event to natural end-of-life, but makes it clear that this occurred unanticipated. For some of these events, the event description mentions that the maintenance / test /

inspection regime was insufficient. It could be expected that an adequate test / inspection regime would track normal degradation of batteries, replacing them as necessary so that normal end of life does not occur whilst the battery is in service.

- **Time to Failure**

"Time to failure" is defined as the length of time between initiation of an event and complete component failure. It can be seen from figure 3, which shows the time to failure of the 50 events in the ICDE database, that events are generally divided into two categories; those that cause failure over a timescale of months or years, "long time to failure" and those that cause failure immediately or within a few days of the initiating event "short time to failure". Over three-quarters of the events in the database are of long time to failure.

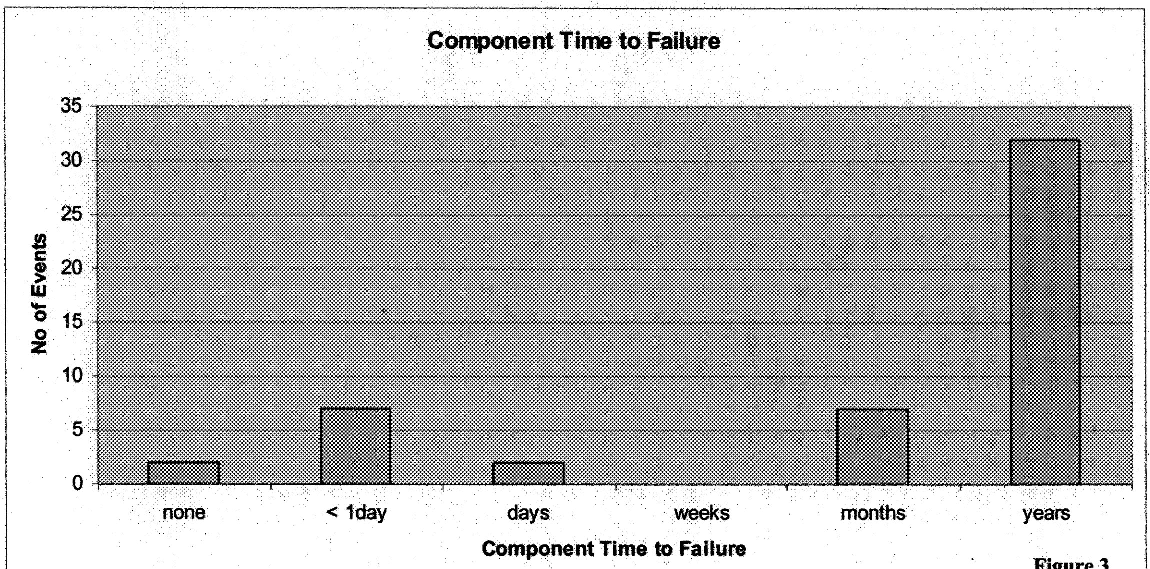

Figure 3

It was anticipated that testing would be able to pick up the onset of long time to failure events, before progression to more serious consequences. However, it was discovered that nearly half progress to one or more complete component failures. This would appear to indicate deficiencies in some test / inspection regimes. These could be expected to be either deficiencies of frequency or scope.

Figure 4 shows the test frequency of the 19 events of long time to failure that progress to one or more complete component failure. The data of figure 4 shows that components from five events were tested roughly monthly, i.e. for the long time to failure events in question, several tests on the component group must have been carried out during the period between event inception and complete component failure. This suggests that for these five events, the scope of tests is insufficient to highlight the type of event experienced. This is probably also true for the one event tested roughly six-monthly.

Thirteen of the events shown in figure 4 are tested yearly. It is possible that the severity of the system impairment could have been reduced had the groups in question been subject to a more regular test regime. However, it is likely that for many events, tests were carried out on impaired components during the long failure period and the event could only have been highlighted prior to failure had the test scope also been extended.

The ICDE database does not contain detailed information regarding the scope of test regimes currently implemented on different sites and in different countries. It is therefore not possible for this report to investigate specific suggestions for improvements to test scope. The onus is on the individual countries or sites to employ their own mechanisms to better understand what is missing in the scope of testing and to fill these gaps. This may involve investigation of:

- events that are tested for but still occur,
- the type of tests that successfully reveal events and whether there is any possibility that these tests can be implemented more regularly.

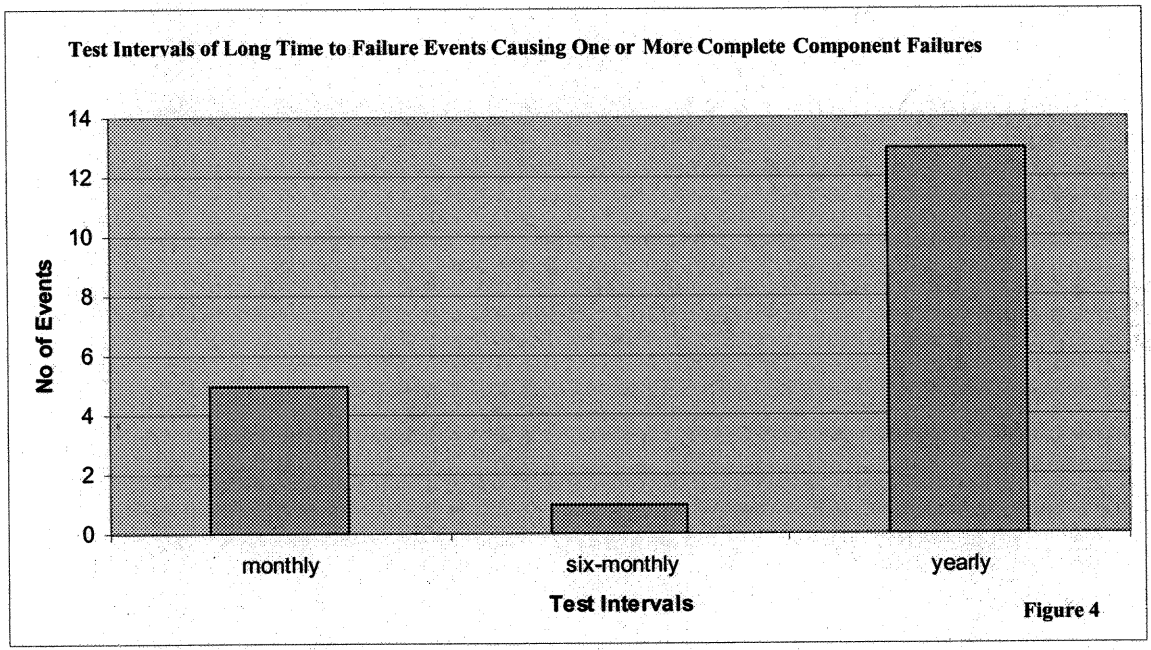

Figure 4

B3. Conclusion

Problems with design / manufacture caused approximately half the events in the database. The data suggests that the deployment of new, rather than established technologies may be more likely to lead to CCFs.

Problems with maintenance / test caused approximately a quarter of events in the database. Half of these are maintenance induced failures. Prevention of these relies on individual countries' regimes for investigation of maintenance induced failures, and derivation and implementation of relevant prevention mechanisms.

The other half of the events caused by maintenance / test are due to an inadequate test regime.

Analysis suggests that maintenance / test / inspection regimes are key to revealing the onset of events; particularly for the 78% of events which fail by slow degradation of capacity, i.e. have long time to failure. However, the data suggests that for nearly half the long time to failure events in the database, the test / inspection / maintenance regimes were of insufficient frequency or scope to detect the event prior to complete component failure.

These results suggest that the existence of maintenance / test / inspection regimes that monitor for degradation on a regular basis, and replace components before complete failure, coupled with countries' or sites' current mechanisms to investigate the causes of and prevention mechanisms for:

- faults which have occurred, despite having been tested for, and
- maintenance induced failures

are key to understanding and preventing CCFs in battery systems.