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ICDE Project Report: Lessons Learnt from Common-Cause Failures of Batteries

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NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

ICDE Project Report

Lessons Learnt from Common-Cause Failures of Batteries

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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;

– 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 the safety and regulation of nuclear activities, radioactive waste management and decommissioning, 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.

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COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)

The Committee on the Safety of Nuclear Installations (CSNI) addresses NEA programmes and activities that support maintaining and advancing the scientific and technical knowledge base of the safety of nuclear installations.

The Committee constitutes a forum for the exchange of technical information and for collaboration between organisations, which can contribute, from their respective backgrounds in research, development and engineering, to its activities. It has regard to the exchange of information between member countries and safety R&D programmes of various sizes in order to keep all member countries involved in and abreast of developments in technical safety matters.

The Committee reviews the state of knowledge on important topics of nuclear safety science and techniques and of safety assessments, and ensures that operating experience is appropriately accounted for in its activities. It initiates and conducts programmes identified by these reviews and assessments in order to confirm safety, overcome discrepancies, develop improvements and reach consensus on technical issues of common interest. It promotes the co-ordination of work in different member countries that serve to maintain and enhance competence in nuclear safety matters, including the establishment of joint undertakings (e.g. joint research and data projects), and assists in the feedback of the results to participating organisations. The Committee ensures that valuable end-products of the technical reviews and analyses are provided to members in a timely manner, and made publicly available when appropriate, to support broader nuclear safety.

The Committee focuses primarily on the safety aspects of existing power reactors, other nuclear installations and new power reactors; it also considers the safety implications of scientific and technical developments of future reactor technologies and designs. Further, the scope for the Committee includes human and organisational research activities and technical developments that affect nuclear safety.

Foreword

Common-cause failure (CCF) events can significantly impact the availability of safety systems of nuclear power plants. For this reason, the International Common-Cause Failure Data Exchange (ICDE) project was initiated by several countries in 1994. In 1997, the Nuclear Energy Agency (NEA) Committee on the Safety of Nuclear Installations (CSNI) formally approved the carrying out of this project within the NEA framework; since then the project has successfully operated over seven consecutive terms (the eighth term being 2019-2022).

The purpose of the ICDE project is to allow multiple countries to collaborate and exchange 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, yield sufficient data for more rigorous analyses.

The objectives of the ICDE project are to:

- collect and analyse CCF events over the long term to better understand such events, their causes and their prevention;
- 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;
- establish a mechanism for the efficient feedback of experience gained in connection with CCF phenomena, including the development of defences against their occurrence, such as indicators for risk-based inspections;
- generate quantitative insights and record event attributes to facilitate quantification of CCF frequencies in member countries; and
- use the ICDE data to estimate CCF parameters.

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 database. 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 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 access to the ICDE database is free to use the collected data. It is assumed that the data will be used by the members in the context of PSA/PRA reviews and application.

The ICDE project has produced the following reports, which can be accessed through the NEA website:

- NEA (2000), "Collection and Analysis of Common-Cause Failure of Centrifugal Pumps", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_16434.
- NEA (2001), "Collection and Analysis of Common-Cause Failure of Emergency Diesel Generators", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17470.

- NEA (2001), "Collection and Analysis of Common-Cause Failure of Motor-operated Valves", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17516.
- NEA (2002), "Collection and Analysis of Common-Cause Failure of Safety Valves and Relief Valves", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17748.
- NEA (2001), "Proceedings of ICDE Workshop on the Qualitative and Quantitative Use of ICDE Data", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17508.
- NEA (2003), "Collection and Analysis of Common-Cause Failure of Check Valves", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17948.
- NEA (2003), "Collection and Analysis of Common-Cause Failure of Batteries", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17978.
- NEA (2008), "Collection and Analysis of Common-Cause Failure of Switching Devices and Circuit Breakers", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_18524.
- NEA (2008), "Collection and Analysis of Common-Cause Failure of Level Measurement Components", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_18568.
- NEA (2013), "Collection and Analysis of Common-Cause Failure of Centrifugal Pumps", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19250.
- NEA (2013), "Collection and Analysis of Common-Cause Failure of Control Rod Drive Assemblies", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19274.
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- NEA (2019), "Summary of Phase VII of the International Common-Cause Data Exchange Project of Nuclear Power Plant Events", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19902.
- NEA (2020), "Collection and Analysis of Common-Cause Failures due to Plant Modifications", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_36527.
- NEA (2022), "Provision against Common-Cause Failures by Improving Testing", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_75196.

- NEA (2022), "Collection and Analysis of Multi-Unit Common-Cause Failure Events", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_75202.
- NEA (2022), "Collection and Analysis of Intersystem Common-Cause Failure Events", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_69830.
- NEA (2024), "Common-Cause Failures of Safety and Relief Valves", OECD Publishing, Paris, www.oecd-nea.org/upload/docs/application/pdf/2024-04/nea_csni_r_2020_17.pdf.
- NEA (2025), "Operational Experience on Common-Cause Failures due to External Environmental Factors", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_103188.
- ICDE Topical Report: Collection and Analysis of Common-Cause Pre-Initiator Human Failure Events, (forthcoming).
- NEA (2025), "Lessons Learnt from Common-Cause Failures of Motor-Operated Valves", OECD Publishing, Paris, www.oecd-nea.org/upload/docs/application/pdf/2025-04/nea_csni_r_2021_7.pdf.

This report was approved by the CSNI at its 72nd meeting on 1-2 December 2022.

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In addition, the ICDE Working Group and the people with whom they liaise in all participating countries are recognised as important contributors to the success of this study. Diego Escrig Forano was the administrative NEA officer and contributed to finalising the first version of the report.

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List of abbreviations and acronyms

ANVS	Autoriteit Nucleaire Veiligheid en Stralingsbescherming
	Authority for Nuclear Safety and Radiation Protection (Netherlands)
CCF	Common-cause failure
CNSC	Canadian Nuclear Safety Commission (Canada)
CSNI	Committee on the Safety of Nuclear Installations
DC	Direct current
EDG	Emergency diesel generator
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat /
	Swiss Federal Nuclear Safety Inspectorate (Switzerland)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HVAC	Heating, ventilation and air conditioning
ICDE	International Common-cause Failure Data Exchange
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
LOSP	Loss of station power
NRA	Nuclear Regulatory Authority (Japan)
NEA	Nuclear Energy Agency
NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
PRA	Probabilistic risk assessment
PSA	Probabilistic safety assessment
SSM	Swedish Radiation Safety Authority (Sweden)
STUK	Finnish Centre for Radiation and Nuclear Safety (Finland)
UJV	Nuclear Research Institute (Czechia)

The acronyms from the ICDE general coding guidelines (NEA, 2004) are presented in Appendix C.

Executive summary

This report presents a study performed on a set of common-cause failure (CCF) events for batteries within the International Common-Cause Failure Data Exchange (ICDE) project. In September 2003, the ICDE project published a report summarising the collection and analysis of data from 50 battery CCF events. Since that time, the ICDE project has continued collection of battery event data. The database now includes 85 events spanning a period from 1980 through 2019. However, the data are not necessarily complete for each country through this period.

The report is mainly intended for designers, operators and regulators to provide insights of the type of failure mechanisms and causes of the battery events in the ICDE database. The insights can prove valuable to support and improve the understanding of failure mechanisms and phenomena involved in the events, as well as their relationship to the CCF root cause, and to provide possibilities for improvement within multiple areas.

The analysis includes assessment of the event cause, coupling factor, corrective action, CCF root cause, event severity, detection method and latency. The CCF root cause analysis led to the following notable observations:

- Across all events deficiencies in the design of components or systems were most common.
- In general, the dominant CCF root causes are design errors, and the most common failure mechanism is insufficient battery capacity. Example failures include design errors resulting in the failure of batteries to reach the design capacity and system design errors where insufficient batteries were installed to meet the system demand.
- A design error resulting in a battery carbonation phenomenon was observed at multiple reactor sites, including two severe partial CCF events. The issue was corrected by exchanging the batteries for a different design from the manufacturer.

Different types of failure are observed when focusing on the most severe events.[1] Notable observations for the most severe events include:

- For the most severe events the dominating CCF root causes are human or procedural errors, e.g. inadequate surveillance frequency or testing. These failures can be avoided by improvements in procedures, monitoring and maintenance.
- The most severe failures tend to have short latency periods, i.e. events are identified soon after they occur. No complete CCF events with high latency (greater than 3 months) have been observed. High latency events tend to be less severe and/or slow developing events.
- All the severe events, which account for about 8% of the total events, happened before 1999, which may be an indicator that procedure-related issues have been addressed and that the battery design problems have been resolved due to experience feedback.

[1] Event severity is discussed in Section 3.2 with definitions of event severity categories. Complete CCF and partial CCF events are the event categories with the most severe impairments.

The analysis of the events gives the following qualitative insights, lessons learnt and recommendations:

- The most common types of observed battery CCF issues are associated design errors causing failures related to insufficient battery capacity.
- Most of the observed battery CCF events belong to lower event severity categories. They may be slow developing and have high latency until the time of detection. This may indicate a need to shorten test intervals or modify test procedures to ensure deficiencies are identified.
- The most severe battery CCF events tend to be associated with deficiencies in operation, specifically inadequate surveillance testing or frequency of tests.
- The decrease in the CCF event rate in recent years and the lack of any severe CCF events since the 1990s suggest that improvements in battery design, testing and maintenance have been implemented in response to operational feedback.

The occurrence of battery CCF events appears to have decreased in recent years. The event rate of battery events peaked in the 1990s and saw a drastic decrease beginning around the year 2000. Additional study of the event trends is planned as the ICDE project continues to expand data collection for the years after 2010. While the apparent trend suggests improvements in addressing CCF events, plant operators are encouraged to remain diligent in addressing battery design issues, adequate surveillance testing, ageing management programmes, and potential new failure mechanisms as batteries are replaced with new designs.

1. Introduction

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

- to describe the data profile for batteries;
- to develop qualitative insights into the nature of the reported events, expressed by event causes, coupling factors and corrective actions;
- to develop the failure mechanisms and phenomena involved in the events, their relationship to the event causes, and possibilities for improvement;
- to verify the dataset for quantification in national applications

Section 2 presents a description of the battery component. Section 3 presents an overview of the contents of the battery database and a summary of statistics. Section 4 contains some high-level engineering insights about the battery CCF events, supported by failure mechanisms and failure causes. Section 5 provides a summary and conclusions.

The ICDE project was organised to exchange CCF data among countries. A brief description of the project, its objectives and the participating countries is given in Appendix A.

Appendix B presents extracts from the ICDE general coding guideline (NEA, 2004).

Appendices C-D present the concluded failure mechanism descriptions according to the failure analysis assessment.

Appendix E presents the definition of CCF events.

1.1. Background

The first international common-cause data exchange (ICDE) project component study of batteries was published in 2003 (NEA, 2003). It examined 50 events in the ICDE database by tabulating the data and observing trends. Once trends were identified, individual events were reviewed for insights. The analysis focused on failure cause categories and the events were analysed and characterised regarding the human error aspects and the technical aspects of the observed failure.

Since that time, the ICDE project has continued collection of battery CCF events. The database now includes 85 events spanning a period from 1980 through 2019. However, the data are not necessarily complete for each country through the entire period. Much of the data collection is focused on the period around 1990 through 2010, with few participating countries contributing data from outside of this range. Since the time of the first battery CCF report, the ICDE engineering review of battery events has expanded to include failure mechanism and failure cause identification and categorisation. The continued collection of battery CCF events has also allowed for preliminary investigations of trends in CCF event occurrence rate.

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 ICDE project was initiated in August of 1994. Since April 1998, the NEA has formally operated the project. Since then, the project has successfully operated over seven consecutive terms (the eighth term being 2019-2022). Member countries under agreement of the NEA and the organisations representing them in the project are: Canada (CNSC), Finland (STUK), France (IRSN), Germany (GRS), Japan (NRA), the Netherlands (ANVS), Sweden (SSM), Switzerland (ENSI) and the United States (NRC).

2. Component description

2.1. General description of the component

According to the coding guidelines for batteries (NEA, 2004), the family of batteries is comprised of those batteries that provide DC emergency power in the event of a loss of station power (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 DC power system (3.EE in IRS coding system) and 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).
- BM - Medium-voltage battery (50<V<200).
- BH - High-voltage battery (V>200).

2.2. Component boundaries

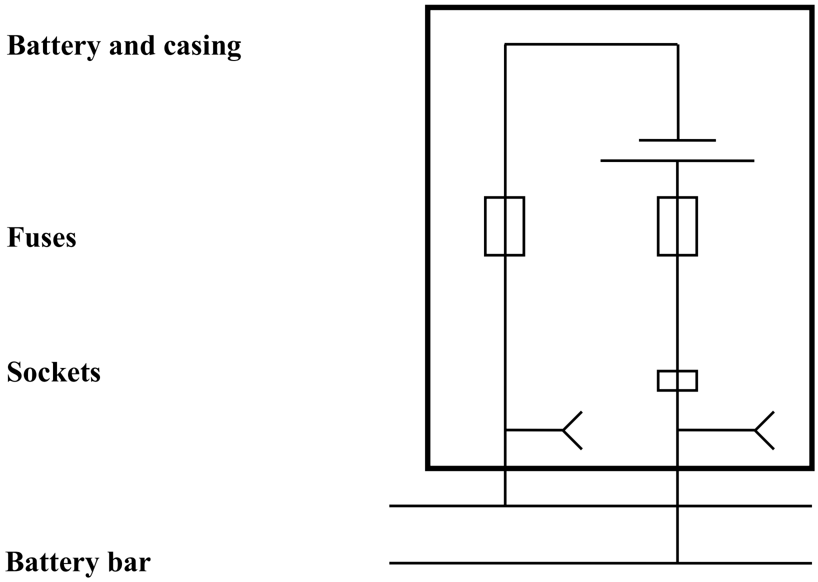
The component for this study is the battery, comprised of cell, casing, power leads and their respective output breakers and fuses. The component boundary is illustrated in Figure 2.1.

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 may have a particular function in automatic protection systems.

2.3. Event boundary

The mission for a battery is to provide DC emergency power in the event of an 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 2.1. Battery components and boundary



Failure of the same cell on batteries supporting different voltages can be considered a valid common-cause failure (CCF).

2.4. Coding rules and exceptions

In general, the definition of the ICDE event given in Section 2 of the ICDE general coding guidelines applies (NEA, 2004). Some reports discuss only one actual failure and do not consider that the same cause will affect other batteries, but the licensee replaces the failed component on all batteries as a precautionary measure. This type of event will be coded as incipient impairment (0.1) of the components that did not actually fail. In-operability due to seismic criteria violations will not be included unless an actual failure has occurred. Administrative inoperability that does not cause the battery to fail to function will not be included as failures. An example is a surveillance test not performed within the required time frame.

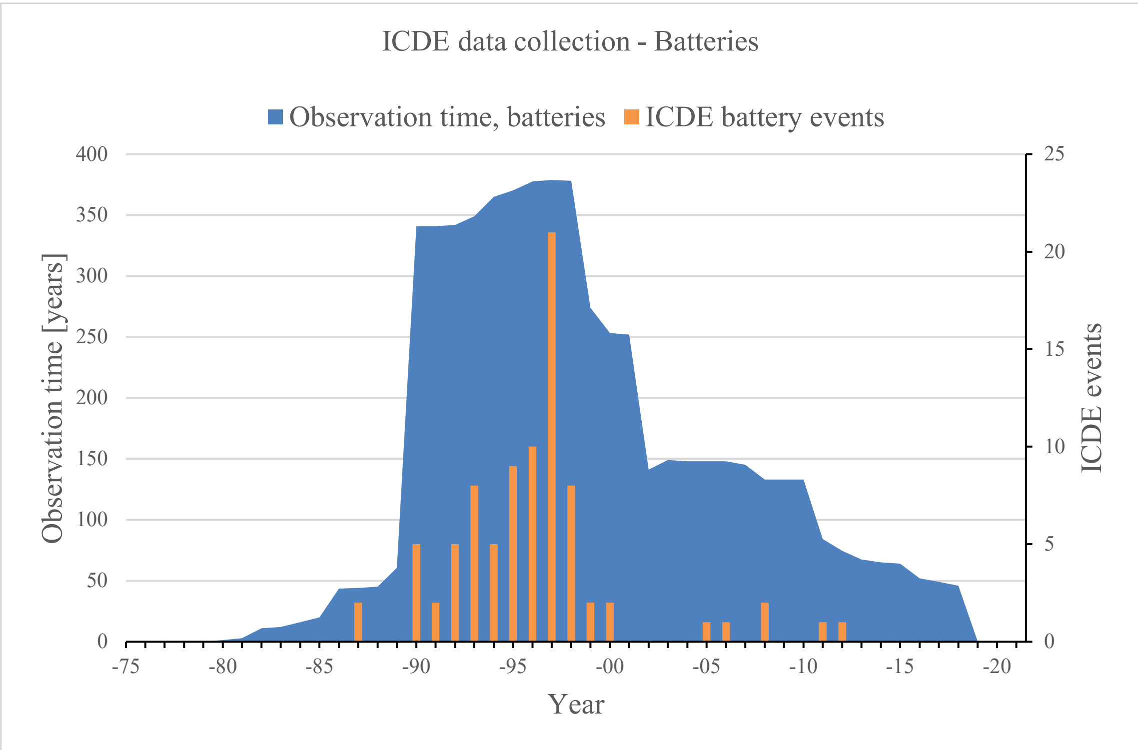
3. Overview of database content

3.1. Data collection overview

The data collection of batteries contains data from 13 countries. Organisations from Canada, Czechia, Finland, France, Germany, Japan, Korea, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States have contributed to this data exchange. Eighty-five (85) ICDE events were reported during the observation time 1980 through 2019.

In Figure 3.1, the observation time and the number of reported events per year are summarised.

Figure 3.1. Data collection: Group observation time and event count distribution over time



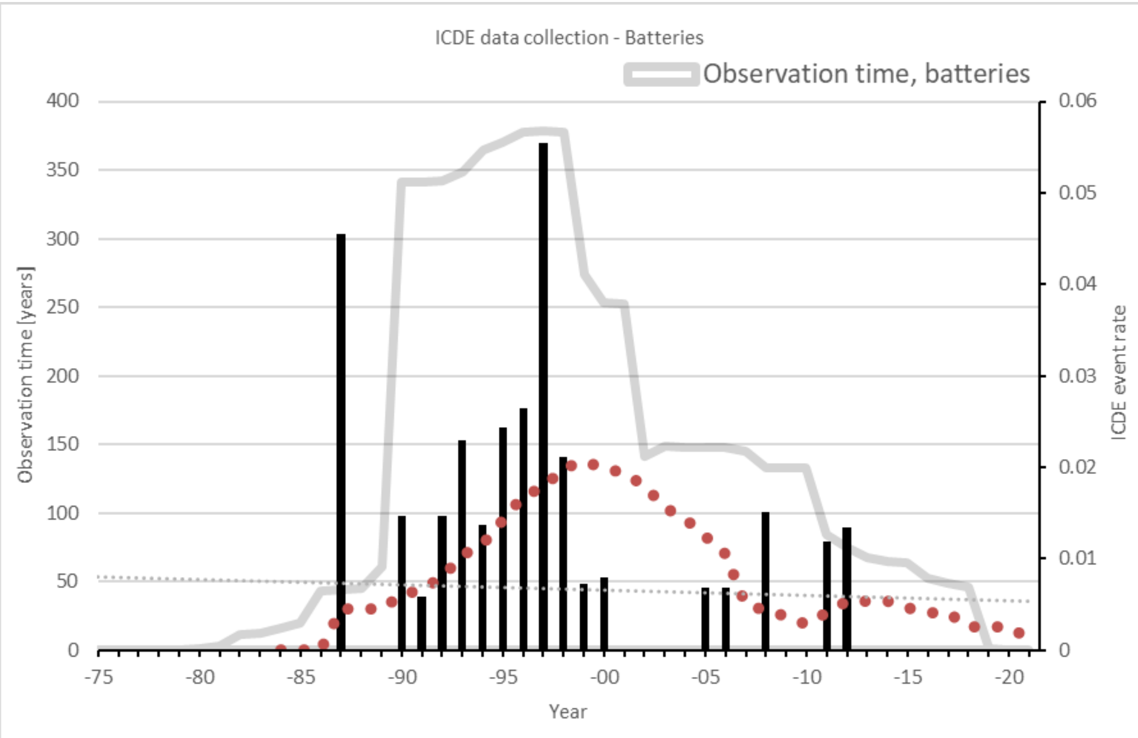
The ICDE event occurrence rate, shown in Table 3.1, is the ratio of the number of ICDE events in the database to the observation time, which is measured for each observed component group for the observation period. The ICDE event rate had its peek during the 90s and then drastically decreased. However, caution should be used in interpreting this result without further statistical analysis. Additional study of the event trends is planned as the ICDE project continues to expand the data collection for the years after 2010.

Table 3.1. Observation time and ICDE events per 5-year period

5-Year period	Observation time [yrs]	ICDE events	ICDE event rate
1975-1979	0	0	0%
1980-1984	43	0	0%
1985-1989	213	2	0.9%
1990-1994	1 738	25	1.4%
1995-1999	1 779	50	2.8%
2000-2004	943	2	0.2%
2005-2009	707	4	0.6%
2010-2014	424	2	0.5%
2015-	212	0	0%
Total	**6 059**	**85**	

Figure 3.2 shows a different representation of the data from Table 3.1 with points representing the ICDE event rate for the data from the previous 10-year period instead of 5-year period shown in Table 3.1. Again, caution should be used in interpreting these data without further statistical analysis.

Figure 3.2. Event rate floating timeline 10-year average



3.2. Failure mode and event severity

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

Essential failure modes:

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

Failure to start **FS** (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 cannot be delivered at the time of the demand.

The degree of severity is indicated by the severity category, as defined by the ICDE general coding guidelines (NEA, 2004).

Severity category

The severity category expresses the degree of severity of the event based on the individual component impairments in the exposed population. The categories are:

- Complete CCF - All components in the group are completely failed (i.e. all elements in impairment vector are C, time factor is high and shared cause factor is high.).
- Partial CCF - At least two components in the group are completely failed (i.e. at least two C in the impairment vector, but not complete CCF. Time factor is high and shared cause factor is high.).
- CCF Impaired - At least one component in the group is completely failed and others affected (i.e. at least one C and at least one I or one D in the impairment vector, but not partial CCF or complete CCF).
- Complete impairment - All components in the exposed population are affected, no complete failures but complete impairment. Only incipient degraded or degraded components. (i.e. all D or I in the impairment vector).
- Incipient impairment - Multiple impairments but at least one component working. No complete failure. Incomplete but multiple impairments with no C in the impairment vector.
- Single Impairment - The event does not contain multiple impairments. Only one component impaired. This is not a CCF event, but the event may be included in the ICDE database when a CCF shared cause is identified for other components outside of the CCF group, e.g. inter-system or multi-unit CCF event.

Table 3.2, Figure 3.3 and Figure 3.4 show the distribution of the events by failure mode and event severity. The failure mode most susceptible to failures is “Failure to run” (89%). Failure to start has only occurred for about 11% of the events. The most common event severity categories were “Complete impairment” and “Incipient Impairment” in the mode “Failure to run” and “Complete CCF” in the “Failure to start” mode.

Table 3.2. Distribution of severity per failure mode

	Severity Category						
Failure mode	Complete CCF	Partial CCF	CCF Impaired	Complete Impairment	Incipient Impairment	Single Impairment	Total
FR		2	15	34	21	4	76
FS	5		2	2			9
Total	5	2	17	36	21	4	85

Figure 3.3. Distribution of failure modes and event severity by quantity

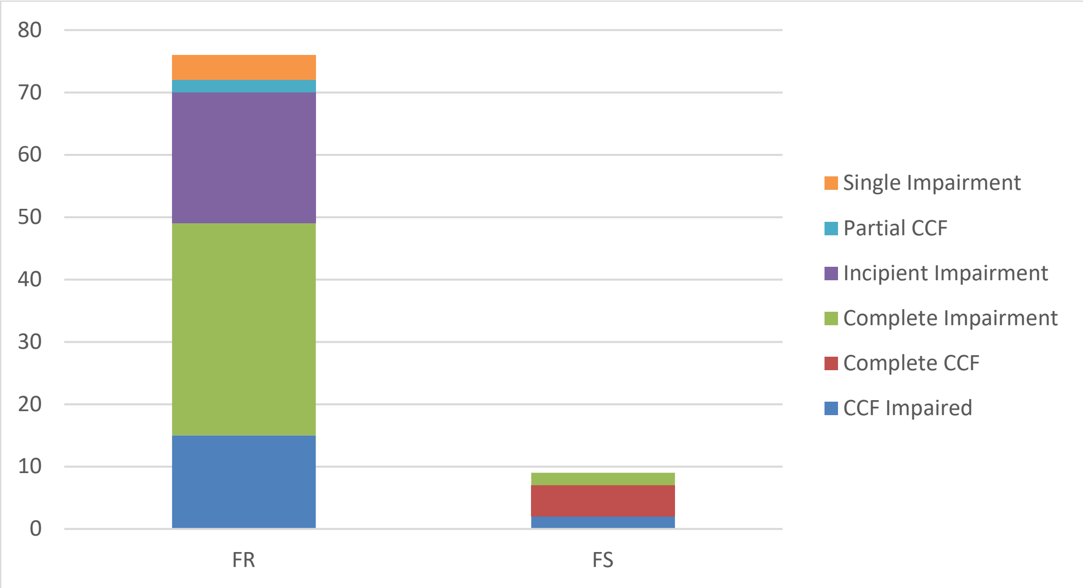
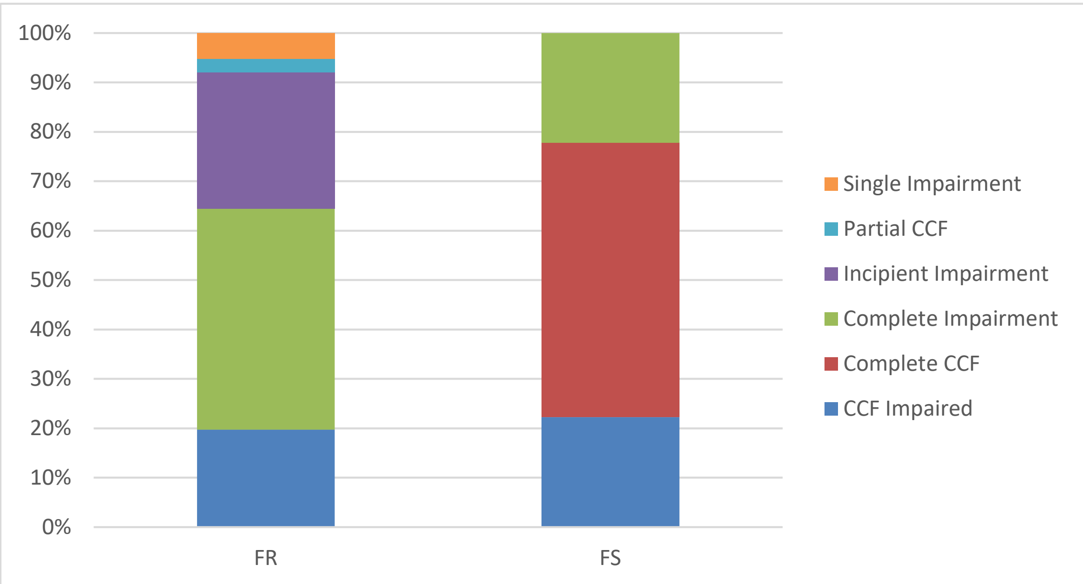


Figure 3.4. Distribution of failure modes and event severity by percentage



3.3. Event cause

In the ICDE database the event cause describes the direct reason for the component's failure. 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 suggested coding is presented in Appendix B.

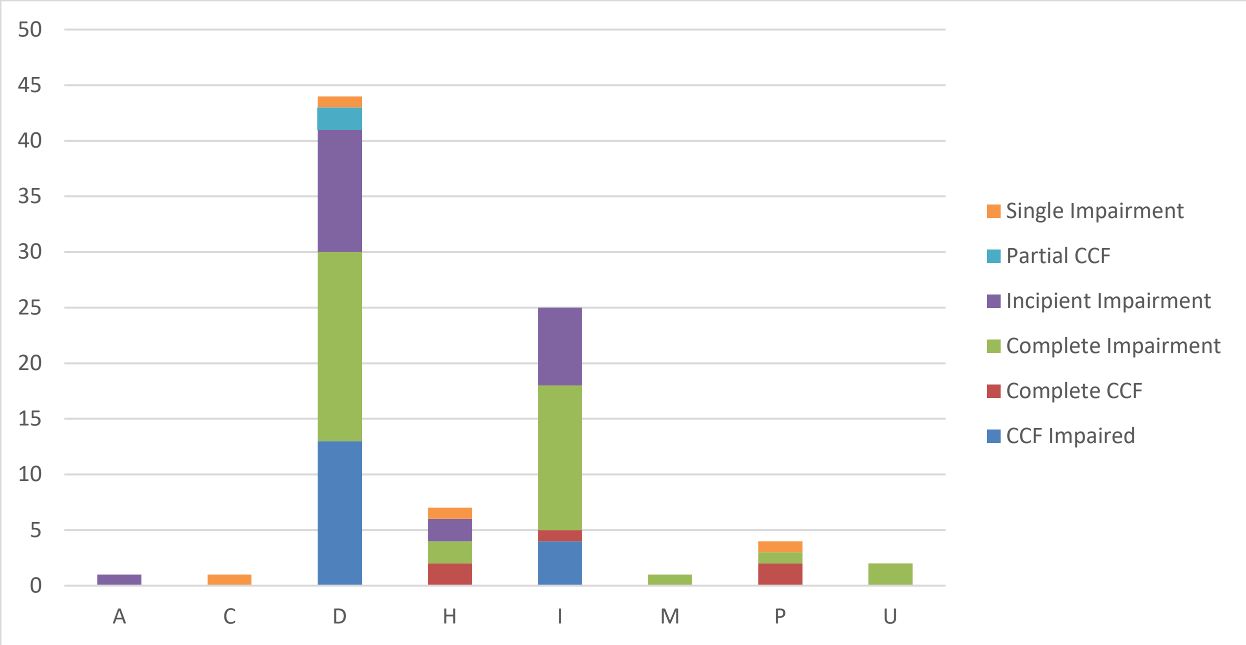
- Abnormal environmental stress (A)
- State of other component(s) (C)
- Design, manufacture or construction inadequacy (D)
- Human actions, plant staff (H)
- Internal to component, piece part (I)
- Maintenance (M)
- Other (O)
- Procedure inadequacy(P)
- Unknown (U)

Table 3.3 and Figure 3.5 show the distribution of the event cause**.** The primary event cause is *Design, manufacture or construction (D)* with about 52% followed *by Internal to component or piece part (I)* with 30%.

Table 3.3. Distribution of event cause per severity category

	Severity Category						
Event cause	Complete CCF	Partial CCF	CCF Impaired	Complete Impairment	Incipient Impairment	Single Impairment	Total
A					1		1
C						1	1
D		2	13	17	11	1	44
H	2			2	2	1	7
I	1		4	13	7		25
M				1			1
P	2			1		1	4
U				2			2
Total	5	2	17	36	21	4	85

Figure 3.5. Distribution of event cause per severity category



3.4. Coupling factor

The ICDE general coding guidelines (NEA, 2004) 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, the event cause and the coupling factor are broadly similar, with the combination of coding serving to give more detail as to the causal mechanisms.

These codes are grouped into the following coupling factor category groups and the suggested coding are presented in Appendix B:

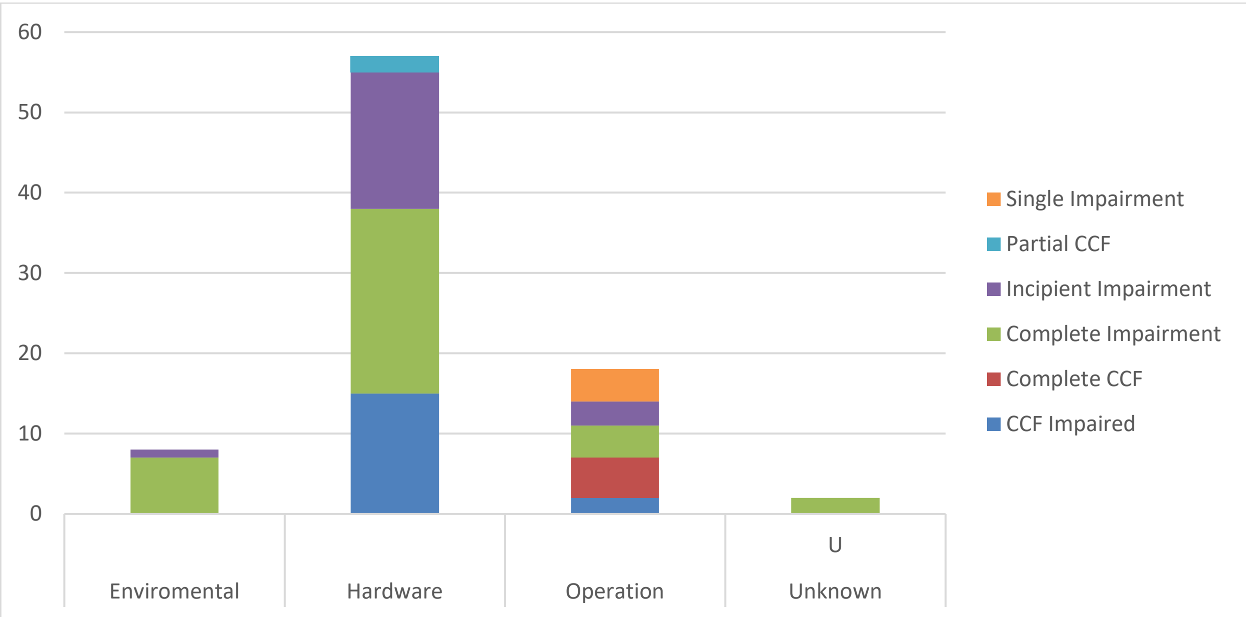
- Environmental: E, EE, EI
- Hardware: H, HC, HS, HQ
- Operation: O, OMF, OMP, OP, OF, OMS
- Unknown: U

Table 3.4 and Figure 3.6 show the distribution of the events by coupling factor. The dominant coupling factor category group is Hardware, which accounts for 67% of the battery events. Out of the 57 events in this category, 24 are due to hardware designs (category code HC). The second most prominent coupling factor category is Operation which accounts for 21% of the battery events. In the Operation category, the most common coupling factor is maintenance and testing procedures (category code OMP). All the complete CCF events have coupling factors in the Operation category.

Table 3.4. Distribution of coupling factors per severity category

	Severity Category						
Coupling factor	Complete CCF	Partial CCF	CCF Impaired	Complete Impairment	Incipient Impairment	Single Impairment	Total
Enviromental				**7**	**1**		**8**
EE					1		1
EI				7			7
Hardware		**2**	**15**	**23**	**17**		**57**
H			4	6	12		22
HC		2	11	10	1		24
HS				7	4		11
Operation	**5**		**2**	**4**	**3**	**4**	**18**
O	2		2		1		5
OMF					2	1	3
OMP	2			2		2	6
OMS	1			1			2
OP				1		1	2
Unknown				**2**			**2**
U				2			2
Total	5	2	17	36	21	4	85

Figure 3.6. Distribution of coupling factors



3.5. Corrective action

The ICDE general coding guidelines (NEA, 2004) define corrective action as follows: "The corrective actions field describes the actions taken by the licensee to prevent the CCF event from reoccurring." The defence mechanism selection is based on an assessment of the event cause and/or coupling factor between the impairments.

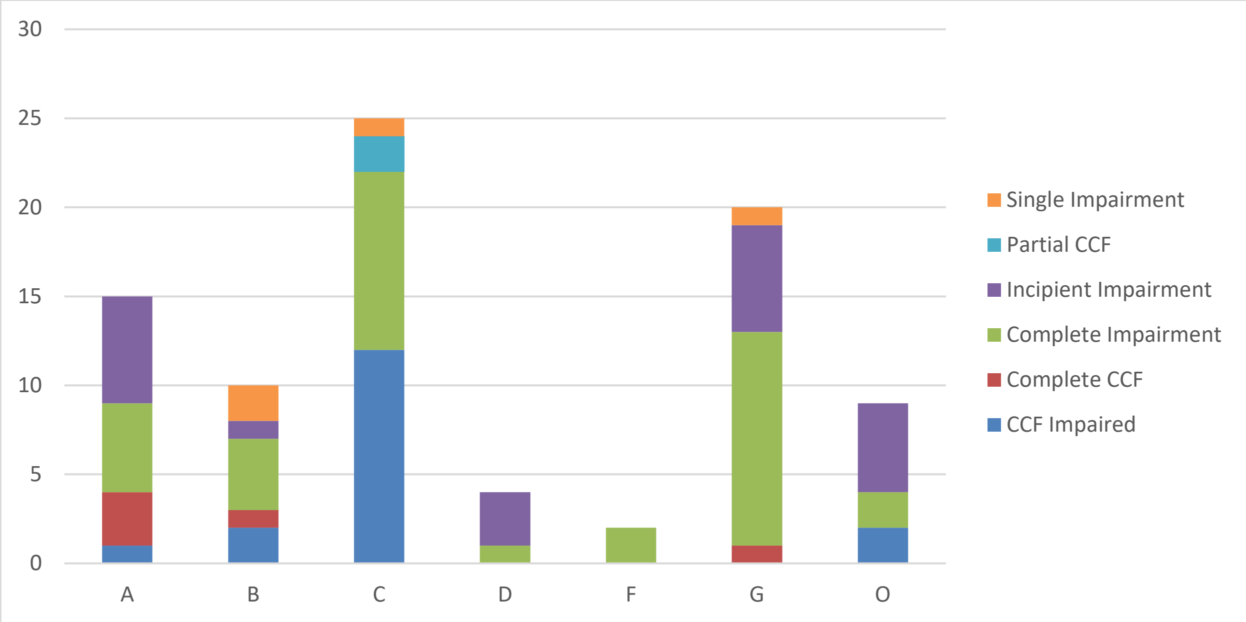
- General administrative/ procedure controls (A)
- Specific maintenance/ operation practices (B)
- Design modifications (C)
- Diversity (D)
- Functional/spatial separation (E)
- Test and maintenance policies (F)
- Fixing of component (G)
- Other (O)
- No Data (empty)

The distribution of events by corrective action is shown in Table 3.5 and Figure 3.7. For complete CCF events, the most common corrective actions taken are Design modifications (C) (25 events or 30% of CCF events) and Fixing of components (G) (20 events or 24 % of CCF events). For complete CCF events, the most common corrective action is General administrative/ procedure controls (A) (3 of 5 complete CCF events).

Table 3.5. Distribution of corrective actions per severity category

	Severity Category						
Corrective action	Complete CCF	Partial CCF	CCF Impaired	Complete Impairment	Incipient Impairment	Single Impairment	Total
A	3		1	5	6		15
B	1		2	4	1	2	10
C		2	12	10		1	25
D				1	3		4
F				2			2
G	1			12	6	1	20
O			2	2	5		9
Total	5	2	17	36	21	4	85

Figure 3.7. Distribution of battery event corrective actions



3.6. CCF root cause

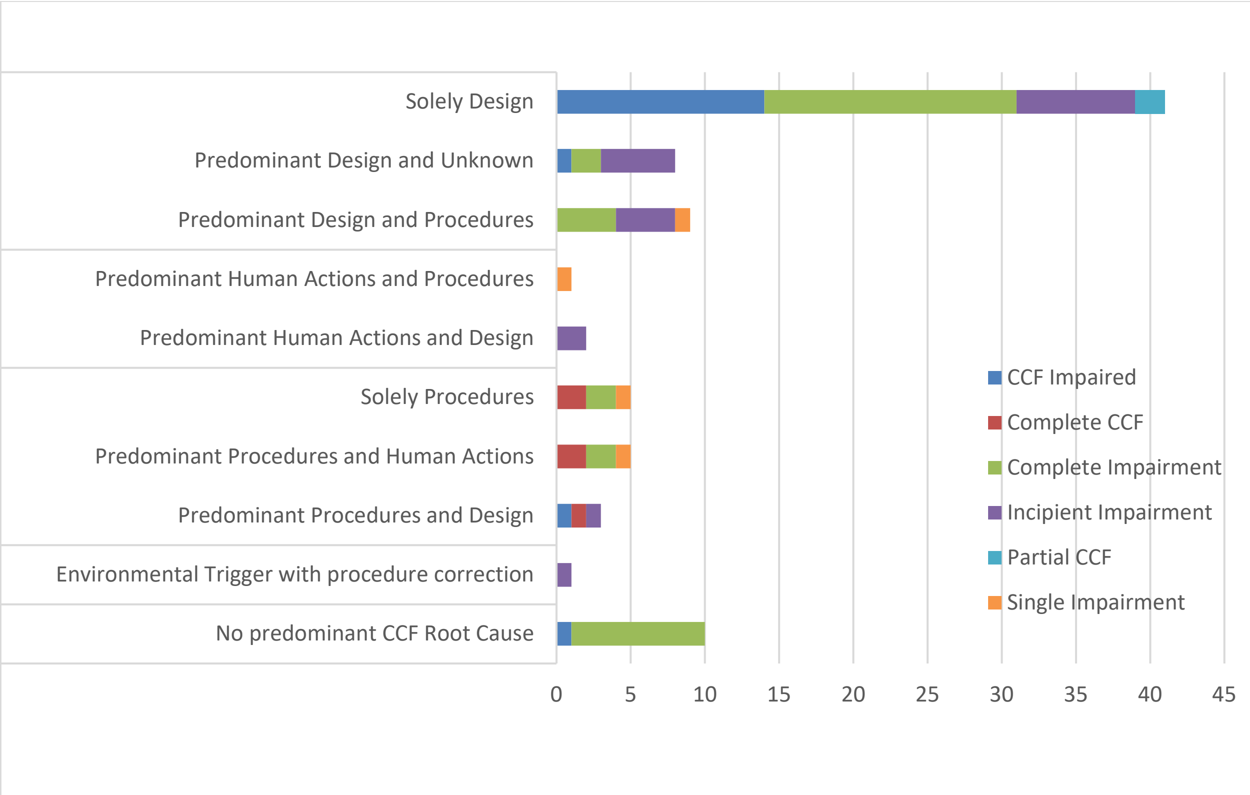
The root cause is "the most fundamental reason for an event or adverse condition, which if corrected will effectively prevent or minimise the recurrence of the event or condition" (US NRC, 2003). By combining the coded information for the (apparent) event cause, the corrective action and the coupling factor, insights regarding the CCF root cause of the events can be gained. The combination of the event parameters provides individual root cause aspects, which are combined into one CCF root cause. The possible CCF root cause aspects are:

- Deficiencies in the design of components or systems (Design)
- Deficiencies in procedures (Procedures)
- Deficiencies in human actions (Human actions)

In addition to these three basic aspects, the supporting aspects "Environmental" and "No predominant CCF root cause" are used in case of events due to external factors or events that are not completely coded. It is distinguished if all three aspects of an event are identical (e.g. 3 x Design) or if there is a predominant and a contributing root cause aspect (e.g. 2 x design and 1 x procedure). Details on how the CCF root cause aspects are determined are given in the ICDE general coding guidelines (NEA, 2004). The results of the CCF root cause assignment are given in Figure 3.8.

The CCF root causes involving deficiencies in the design of components or systems were most common with Solely Design deficiencies (41 events or 48%) being the most common category. However, all of the complete CCF events (5 events) had CCF root causes with some aspects associated with deficiencies in human actions. The CCF root cause categories for the complete CCF events include: Solely Procedures, Predominant Procedures and Human Actions and Predominant Procedures and Design. About 12% of the events had no predominant CCF root cause related to deficiencies.

Figure 3.8. Distribution of CCF root causes



3.7. Detection method

The ICDE general coding guidelines (NEA, 2004) suggest the following coding for the detection method for each failed component of the exposed population.

- Monitoring on walkdown (MW)
- Monitoring in control room (MC)
- Maintenance/test (MA)
- Demand event (failure when the response of the component(s) is required) (DE)
- Test during operation/annual overhaul/ laboratory (TI/TA/TL)
- Unscheduled test (TU)
- Unknown (U)

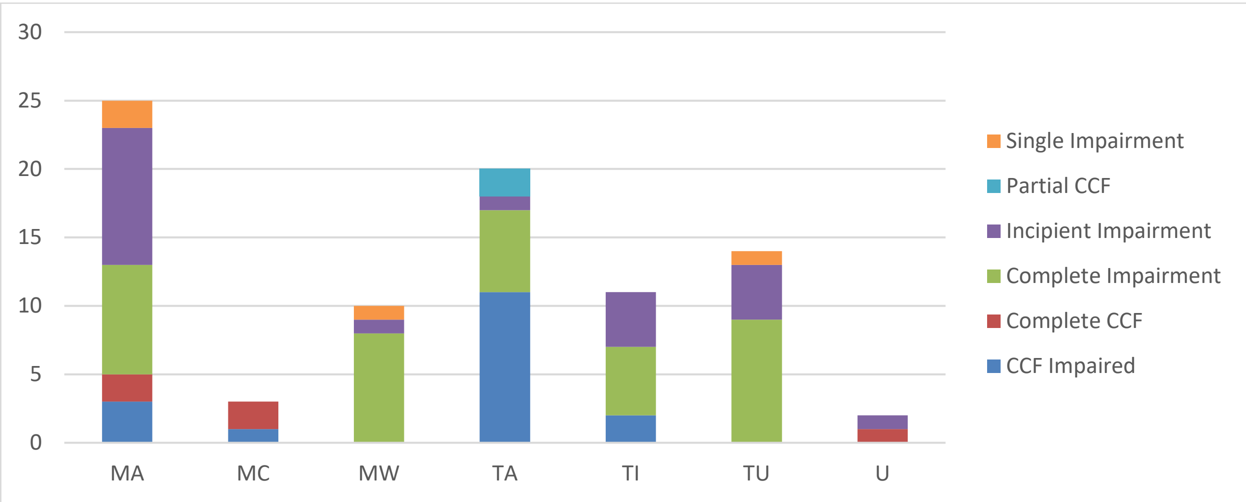
The distribution of events by detection method is shown in Table 3.6 and Figure 3.9. Two events were coded as detection method Unknown (U) where the detection method is known but does not fit one of the existing detection method codes. The vast majority (45 events or

53% of total) were discovered through testing, either through Maintenance/test (MA) (25 events or 29 % of total) or through Test during annual overhaul (TA) (20 events or 24% of total). No events were identified as being detected as a Demand event (DE).

Table 3.6. Distribution of detection methods per severity category

	Severity Category						
Detection method	Complete CCF	Partial CCF	CCF Impaired	Complete Impairment	Incipient impairment	Single Impairment	Total
MA	2		3	8	10	2	25
MC	2		1				3
MW				8	1	1	10
TA		2	11	6	1		20
TI			2	5	4		11
TU				9	4	1	14
U	1				1		2
Total	5	2	17	36	21	4	85

Figure 3.9. Distribution of detection methods



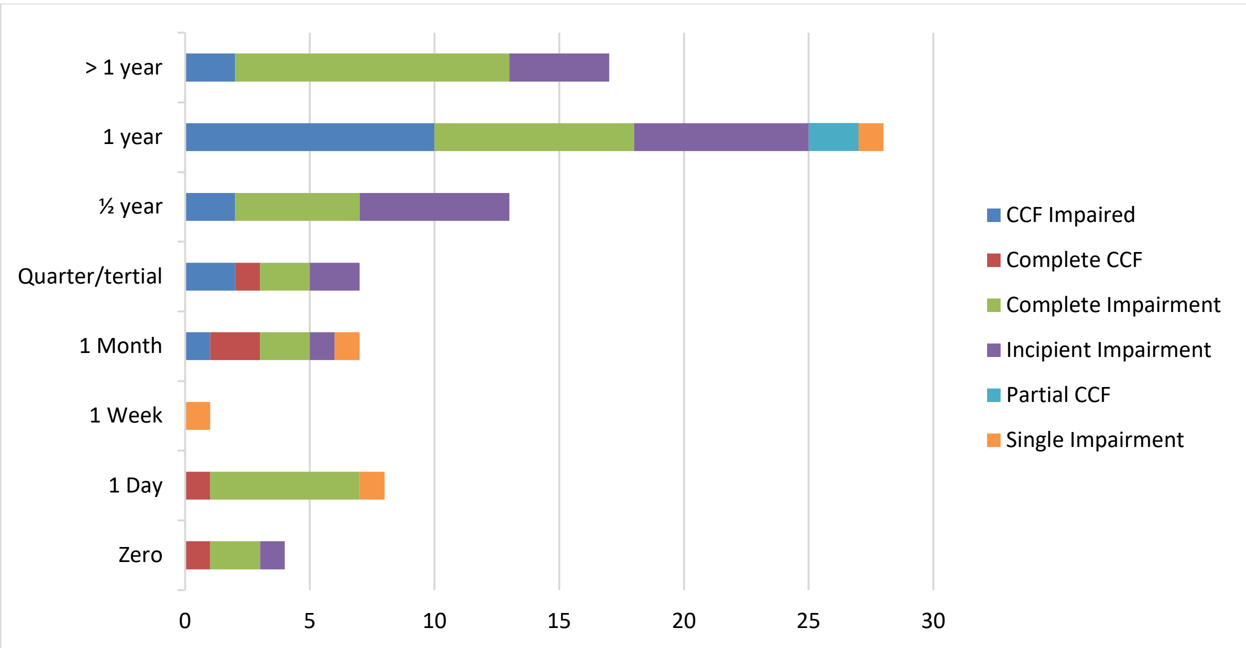
3.8. Latency

Table 3.7 and Figure 3.10 contain the distribution of the events by latent time until detection, i.e. the latency factor of the event. Most of the events had a latency greater than a quarter of a year. About 76% of the events had a latency time of more than quarter of a year, which may indicate a too short test interval of the batteries or inadequate test procedures.

Table 3.7. Distribution of latencies

Latency	Complete CCF	Partial CCF	CCF Impaired	Complete Impairment	Incipient Impairment	Single Impairment	Total	Percent
Zero	1			2	1		4	5%
1 Day	1			6		1	8	9%
1 Week						1	1	1%
1 Month	2		1	2	1	1	7	8%
Quarter/tertial	1		2	2	2		7	8%
½ year			2	5	6		13	15%
1 year		2	10	8	7	1	28	33%
> 1 year			2	11	4		17	20%
Total	5	2	17	36	21	4	85	100%

Figure 3.10. Distribution of latencies



4. Engineering aspects of the collected events

The following content contains an engineering review of the battery events. The analysis is based on results from a workshop at the 52nd ICDE meeting. The engineering aspects of the event analysis consist of identifying the failure mechanisms and failure causes.

4.1. Assessment basis

Failure mechanism description

The failure mechanism is a history describing the observed events and influences leading to a given failure. Elements of the failure mechanism could be a deviation or degradation or a chain of consequences. It is derived from the event description and should preferably consist of one sentence.

Failure cause category

Deficiencies in operation

This group comprises all ICDE events that involve human errors, expressed by a human error-related event cause, or a human error-related coupling factor. Note that, following this definition, events are included in this group if:

- The event cause is human error-related.
- The event cause is hardware-related but human errors have created the conditions for multiple components to be affected by a shared cause, i.e. if the coupling factor is human error-related.
- The event cause and coupling factor are human error-related.

Three failure cause categories have been identified as being important in this group:

- O1 Deficient procedures for maintenance and/or testing
- O2 Insufficient attention to ageing of piece parts
- O3 Insufficient qualification and/or work control after or during maintenance/test or operation

Deficiencies in design, construction, manufacturing

This group comprises all ICDE events with hardware-related event cause and hardware-related coupling factor. Thus, an event is only included, for example, in category D (design deficiency) if the event cause is coded as “design”, combined with any hardware-related coupling factor, or if the coupling factor is coded as “hardware design” or “system design”, combined with any hardware-related event cause. Three failure cause categories have been identified for this group:

- D Deficiency in design of hardware
- C/M Deficiency in construction or manufacturing of hardware
- D-MOD Deficient design modifications

Failure mechanism category and sub-category

A failure mechanism category is a group of similar failure mechanism sub-categories. Failure mechanism sub-categories are coded component-type-specific observed faults or non-conformities that have led to the ICDE event. For events where several failure mechanism sub-categories coding options exist, preference should be given to the code related to the first or the most important observed consequence of the event cause. The failure mechanism sub-categories are identified by engineering analysis of all component-type-specific events and appropriate binning of similar failure mechanisms. The result of this engineering analysis is summarised in this report and, similarly, for other components in ICDE component-specific reports.

The following failure mechanism categories and sub-categories were concluded for the battery events, see Table 4.1. The results of this matrix are the basis for the engineering aspects of the collected events.

Table 4.1. Failure mechanism categories and sub-categories

Failure mechanism category		Failure mechanism sub-category	
BA-FM1	Insufficient capacity	BA-a1	Premature ageing of plates
		BA-a2	Loss of surface activity of plates
		BA-a3	Corrosion due to high acid concentration of electrolytes
		BA-a4	Loss of porosity of separators
		BA-a5	Inadequate component material
BA-FM2	Low voltage	BA-b1	Low density of electrolyte
		BA-b2	Low level of electrolyte
		BA-b3	Short circuit among plates
		BA-b4	Incomplete recharging
		BA-b5	Increased resistance at connections
		BA-b6	High density of electrolyte
BA-FM3	Cracks in casing/plates	BA-c1	Handling problems
		BA-c2	H2 explosion
BA-FM4	Others	BA-d1	Intrusion of chemicals due to manufacturing fault

Interesting event categories

Table 4.2 and Table 4.3 present the failure mechanism categories, their sub-categories and the failure cause categories[2]. In Table 4.1, the failure mechanism categories are presented with respect to the failure cause category groups. The most common failure mechanism category is *Insufficient capacity* which was assigned to about half of the events. The main sub-category of these events *was Inadequate component material.*

4.2. Failure analysis assessment matrix

The following two tables (Table 4.2 and Table 4.3) show the distribution of the failure mechanism categories and failure cause categories.

[2] O1 Deficient procedures for maintenance and/or testing, O2 Insufficient attention to ageing of piece parts, O3 Insufficient qualification and/or work control during maintenance/test or operation, D Deficiency in design of hardware, C/M Deficiency in construction or manufacturing of hardware, D-MOD Deficient design modifications, U Unknown (6 events).

Table 4.2 and Table 4.3 present the failure mechanism categories, their sub-categories and the failure cause categories[3]. In Figure 4.1, the failure mechanism categories are presented with respect to the failure cause category groups. The most common failure mechanism category is *Insufficient capacity,* which was assigned to about half of the events. The main sub-category of these events was *Inadequate component material*.

Table 4.2. Distribution of failure mechanism categories of deficiencies in design, construction and manufacturing

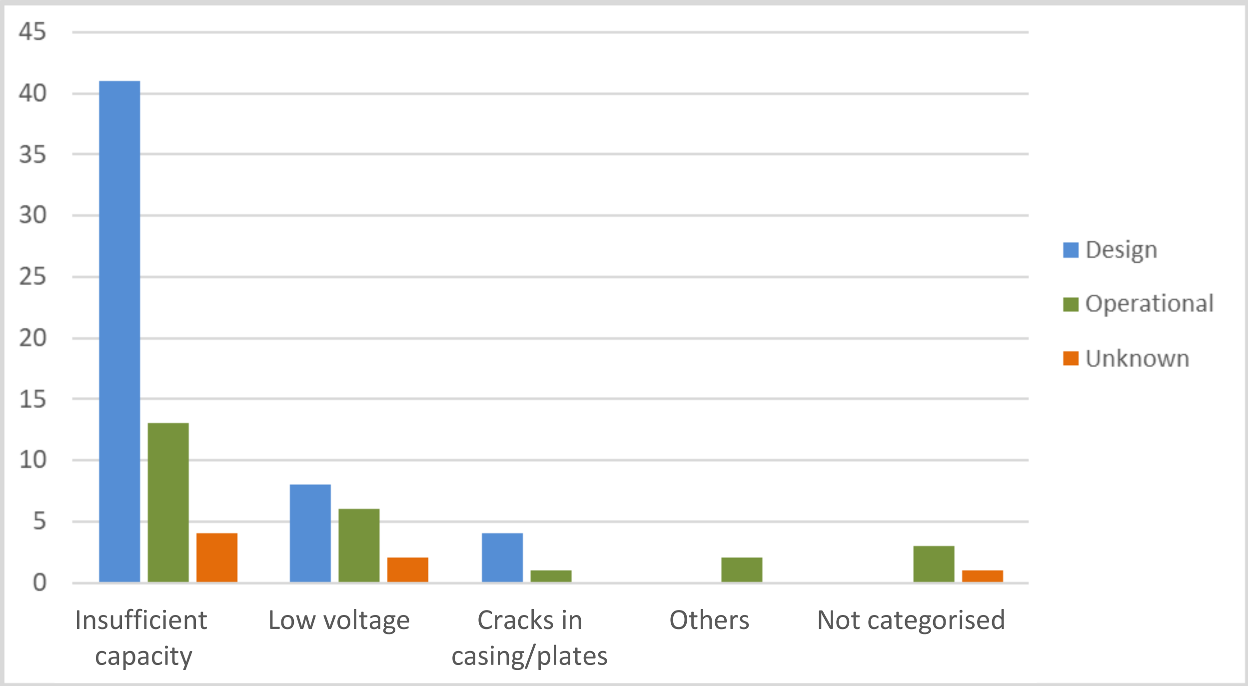
	Failure mechanism category		
Failure cause category	**Cracks in casing/plates**	**Insufficient capacity**	**Low voltage**
Deficiencies in design, construction, manufacturing	4	41	8
C/M	Cell failure - Manufact. Inadequate manufacturing quality led to crack indication in casings of battery cells. (2)	Reduced voltage- failure of manufacturing plates. External leakage of accumulator. Broken battery lid and internal leakage. Oxidised battery poles. Degraded battery capacity. (6)	Increased chloride concentration in electrolyte. Low voltage in cells- particle migration. (6)
D	Cracked cells due corrosion.(2)	A fault in the battery design. Battery with insufficient capacity installed. Carbonation of a particular form of graphite contained in the active material of the positive plate leading to decreased battery capacity and a non-sufficient voltage. Corroded connections. Degraded functions due to improper curing of positive plate during manufacturing. Discharge bar isolator not fully closed gave low Voltage. New battery led to a higher short circuit current. Loss of storage capacity due to carbonation of positive plate. Low battery capacity at surveillance test –due to carbonation of graphite –NIFe-batteries. Low individual cell voltages due to manufacturing defects. System design inadequacy led to implementation of undersized batteries. (35)	Low voltage in cells. Voltage under required value due to a corrosion of the plates caused by high chloride-acid concentration of the electrolyte (leading to too low density of electrolyte) (2)

[3] O1 Deficient procedures for maintenance and/or testing, O2 Insufficient attention to ageing of piece parts, O3 Insufficient qualification and/or work control during maintenance/test or operation, D Deficiency in design of hardware, C/M Deficiency in construction or manufacturing of hardware, D-MOD Deficient design modifications, U Unknown (6 events).

Table 4.3. Distribution of failure mechanism categories of deficiencies in operation

	Failure mechanism category				
Failure cause category	**Cracks in casing/plates**	**Insufficient capacity**	**Low voltage**	**Others**	
Deficiencies in operation	1	13	6	6	
O1		Premature ageing due to various factors: higher temperature than suggested for battery cabinets, flotation voltage do not adjust to batteries' performance temperature and behaviour of UPS rectifier. Sulfate deposition on negative pole- reduced capacity. Over-voltages from charging- could result in shorten cellplates. (4)	Lack of surveillance testing in the procedure and lack of monitoring led to undetected empty batteries for the HVAC systems. Low gravity on battery electrolyte gave low voltage –test switch in wrong position. (2)	Inadequate surveillance frequency in procedures resulted in dirty batteries causing ground fault. (1)	
O2		Degraded cells due to ageing and electrical cycling. (2)		Failed plant line-up – at maintenance. The event is interpreted as an ICDE event of two batteries due to human error (test in unsuitable configuration and unavailability of both batteries at the same time). (2)	
O3	Physical, electrical or chemical damage to battery cells. (1)	Because of previous testing method, the batteries were discharged beyond recommended levels which shortened their expected life. Corroded connections. Corrosion on cells. Cracking of cell top due to positive pillar corrosion. Degraded cells due to ageing and electrical cycling. (7)	Insufficient charging of batteries. Gravity below specified value. Low battery electrolyte levels. To be compliant with the work safety rules staff opened incorrect breaker as additional step, missing in procedure, which led to unavailable batteries. (4)	Cleaning of Batteries – destroyed battery. Static electricity cause explosion of battery. The event is interpreted as an ICDE event of two batteries due to human error (test in unsuitable configuration and unavailability of both batteries at the same time). (3)	Static electricity cause explosion of battery. The event is interpreted as an ICDE event of two batteries due to human error (test in unsuitable configuration and unavailability of both batteries at the same time). (2)

Figure 4.1. Distribution of failure cause category groups per failure mechanism category



4.3. Failure analysis assessment of complete and partial CCF events

In Table 4.4, the failure analysis assessment matrix is presented for the severe events. Refer to Section 3.2 for definitions of event severity categories.

The severe events, i.e. complete and partial CCFs, were entirely observed with a failure mechanism related to design and procedural problems.

The two partial CCF events were caused by a design error resulting in battery carbonation. Both events had the failure mode *Failure to run*. The issue was corrected by exchanging the batteries for a different design from the manufacturer.

For the complete CCF events the dominating CCF root causes are procedural errors, e.g. inadequate surveillance frequency, testing or system line-up – during maintenance. These failures can be avoided through improvements in procedures, monitoring and maintenance.

All the severe events, which account for about 8% of the total events that happened before 1999, which may be an indicator that procedure-related issues have been addressed and that the battery design problems have been resolved due to experience feedback.

Table 4.4. Failure analysis assessment of complete and partial CCF events

CCF Root cause group	CCF Root cause	Event severity	Failure mechanism description	Year	Event Id
Design					
	Solely Design	Partial CCF	Loss of storage capacity due to carbonation of positive plate.	1996	19
	Solely Design	Partial CCF	Loss of storage capacity due to carbonation of positive plate.	1998	35
Procedures					
	Predominant Procedures and Design	Complete CCF	Failed plant line-up – at maintenance. Due to grease hardening.	1993	47
	Predominant Procedures and Human Actions	Complete CCF	To be compliant with the work safety rules staff opened incorrect breaker as additional step, missing in procedure, which led to unavailable batteries.	1990	16337
	Predominant Procedures and Human Actions	Complete CCF	Work caused a short.	1993	40
	Solely Procedures	Complete CCF	Inadequate surveillance frequency in procedures resulted in dirty batteries causing ground fault.	1996	16012
	Solely Procedures	Complete CCF	Lack of surveillance testing in the procedure and lack of monitoring led to undetected empty batteries for the HVAC systems.	1994	23

4.4. Failure analysis assessment of deficiencies in design, construction and manufacturing

Deficiencies in the design of hardware involve about 65% of the events. The failure mechanism categories related to hardware, capacity and electrical problems differ greatly, with the highest percentage of failures related to capacity issues. The main failure cause category is deficiencies in the design.

Out of the 60 events a total of 37 events (62%) had the dominant failure mechanism insufficient capacity and were caused by deficiencies in the design. For events with construction or manufacturing deficiencies, the battery capacity and low voltage problems are equally common. There were no failures involving design modification issues. Only two events were due to battery casing cracks. The failure cause category could not be categorised for seven events due to insufficient information.

Table 4.5 provides a summary of the findings in each of the failure assessment matrix categories involving deficiencies in design, construction and manufacturing.

Table 4.5. Failure analysis assessment of deficiencies in design, construction and manufacturing

Failure cause category	Failure mechanism category					
Row Labels	**Not categorised**	**Cracks in casing/plates**	**Insufficient capacity**	**Low voltage**	**Others**	**Total**
Not categorised	1		4	2		7
C/M Deficiency in construction or manufacturing of hardware		2	6	6		14
D Deficiency in design of hardware			37	2		39
D-MOD Design modification						0
Total	**1**	**2**	**47**	**10**	**0**	**60**

4.5. Failure analysis assessment of deficiencies in operation

Insufficient qualification and/or work control during maintenance/test or operation is the most common failure cause category among the events assigned to deficiencies in operation and involves 30% of the events. Deficiencies due to procedures for maintenance and/or testing is the next most common failure cause category, followed by insufficient attention to ageing of piece parts.

The failure mechanism category related to insufficient capacity problems are again the most common.

These types of events are often slow developing and hard to be detected, and if these events go undetected, they could possibly progress into a more severe event.

Failure mechanisms across all categories are observed with insufficient qualification and/or work control during maintenance/test or operation but mainly for insufficient capacity which is the most often cause of failure through all types of events.

Table 4.6 provides a summary of the findings in each of the failure assessment matrix categories involving deficiencies in operation.

Table 4.6. Failure analysis assessment of deficiencies in operation

Failure cause category	Failure mechanism category					
Row Labels	**Not categorised**	**Cracks in casing/plates**	**Insufficient capacity**	**Low voltage**	**Others**	**Total**
O1 Deficient procedures for maintenance and/or testing			4	2	1	7
O2 Insufficient attention to ageing of piece parts	1		2			3
O3 Insufficient qualification and/or work control during maintenance/test or operation	2	1	7	4	1	15
Total	**3**	**1**	**13**	**6**	**2**	**25**

4.6. Interesting event categories

Table 4.7. Interesting CCF event codes applied to battery CCF events

Interesting CCF event codes	No. of events	Percent
Complete CCF	5	6%
CCF Outside planned test	6	7%
Component not-capable	0	0%
Multiple defences failed	0	0%
Sequence of multiple CCF failure mechanisms	7	8%
Multiple Systems affected	1	1%
Common Cause Initiator	0	0%
Safety culture	2	2%
Multi-Unit CCF	18	21%
No code applicable	2	2%
Blank	44	52%
Total	**85**	

The interesting CCF event codes are shown in Table 4.7. Forty-four (44) of the battery CCF events were not evaluated for applicability of the interesting CCF event codes.

Insights from the applied interesting event codes:

- Multi-unit CCF: A total of 18 events (21%) were marked as multi-unit CCFs. The share of multi-unit CCF events is quite high. A detailed analysis of multi-unit CCF events is addressed in another ICDE topical report, see (INL, 2018).
- Complete CCF: This event code sums up all the complete CCFs. It is noteworthy that the share of complete CCFs for batteries is lower compared to the other components covered in the full ICDE database.

- CCF outside planned test: Six events were marked as interesting due to the fact that they occurred outside the planned test. A detailed analysis of testing inadequacies is addressed in another ICDE topical report, see (NEA, 2019).

5. Summary and conclusions

The data collection of batteries contains data from 13 countries. Organisations from Canada, Czechia, Finland, France, Germany, Japan, Korea, the Netherlands, Spain, Sweden, Switzerland, the United Kingdom and the United States contributed to this data exchange. Eighty-five ICDE events were reported between 1980 through 2019. The report is an update of the first ICDE component study of batteries published in 2003. The family of batteries is comprised of those batteries that provide DC emergency power in the event of an LOSP to DC buses that supply the safety systems of the reactor plant.

The failure mechanism categories and sub-categories are identified by engineering analysis of all events and appropriate binning of similar failure mechanisms. The failure mechanism categories and sub-categories were developed by reviewing the battery events, see Table 4.1. The resulting matrix is the basis for the engineering aspects of the collected events.

The following notable observations were made:

- Across all events, deficiencies in the design of components or systems were most common.
- In general, the dominant CCF root causes are design errors, and the most common failure mechanism is insufficient battery capacity. Example failures include design errors resulting in failure of batteries to reach the design capacity and system design errors where insufficient batteries were installed to meet the system demand.
- A design error resulting in a battery carbonation phenomenon was observed at multiple reactor sites, including two severe partial CCF events. The issue was corrected by exchanging the Ni-Cd batteries for a different design from the manufacturer between 1998 and 2003. The graphite present in the positive plates of the former Ni-Fe battery cells has been removed, and the technology of the plates in the new batteries is different. The performance of the new Ni-Cd batteries is monitored to ensure adequate storage capacity. The electrolyte carbonation phenomenon linked to the graphite is indeed not observed anymore.

Different types of failures are observed when focusing on the most severe events. Notable observations for the most severe events include:

- The dominant CCF root causes are human or procedural errors, e.g. inadequate surveillance frequency or testing. These failures can be avoided by improvements in procedures, monitoring and maintenance.
- The most severe failures tend to have short latency periods, i.e. events are identified soon after they occur. No complete CCF events with high latency (greater than three months) have been observed. High latency events tend to be less severe and/or slow developing events.
- All the severe events, which account for about 8% of the total events, happened before 1999, which may be an indicator that procedure-related issues have been addressed and that the battery design problems have been resolved due to experience feedback.

The analysis of the events gives the following qualitative insights, lessons learnt and recommendations:

- The most common types of observed battery CCF issues are associated with design errors causing failures related to insufficient battery capacity.
- Most of the observed battery CCF events belong to lower event severity categories. They may be slow developing and have high latency until time of detection. About 76% of the events had a latent time of more than a quarter of a year. This may indicate a need to shorten test intervals or modify test procedures to ensure deficiencies are identified.
- The most severe battery CCF events tend to be associated with deficiencies in operation, specifically inadequate surveillance testing or frequency of tests.
- The decrease in CCF event rate in recent years and the lack of any severe CCF events since the 1990s suggest that improvements in battery design, testing and maintenance have been implemented in response to operational feedback.

The occurrence of battery CCF events appears to have decreased in recent years. The event rate of battery events peaked in the 1990s and had a drastic decrease beginning around the year 2000. Additional study of the event trends is planned as the ICDE project continues to expand the data collection for years after 2010. While the apparent trend suggests improvements in addressing CCF events, plant operators are encouraged to remain diligent in addressing battery design issues, adequate surveillance testing, ageing management programmes, and potential new failure mechanisms as batteries are replaced with new designs.

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Glossary

Common-cause failure 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.

CCF root cause: The CCF root cause describes the combined information of the event cause, the corrective action and the coupling factor, to determine and gain insights of the most fundamental reason for the common-cause failure. Depending on the coding, the possible CCF root cause aspects are deficiencies in the design of components or systems, procedural or organisational deficiencies, or deficiencies in human actions.

Component boundary: The component boundary encompasses the set of piece parts that are considered to form the component.

Coupling factor: The coupling factor describes the mechanism that ties multiple impairments together and identifies the influences that created the conditions for multiple components to be affected.

Corrective action: The corrective action describes the actions taken by the licensee to prevent the CCF event from reoccurring. The defence mechanism selection is based on an assessment of the event cause and/or coupling factor between the impairments.

Defence: Any operational, maintenance, and design measures taken to diminish the probability and/or consequences of common-cause failures.

Detection method: The detection method describes how the exposed components were detected.

Event cause: In the ICDE database, the event cause describes the direct reason for the component's failure. 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.

Event severity: The severity category expresses the degree of severity of the event based on the individual component impairments in the exposed population. The *Severe events* include the categories complete CCF and partial CCF. The *Less severe events* include the categories CCF impaired and complete/incipient/single impairment.

Failure cause categories: A high level and generalised list of deficiencies in operation and in design, construction and manufacturing which caused an ICDE event to occur.

Failure mechanism: Describes the observed event and influences leading to a given failure. Elements of the failure mechanism could be a deviation or degradation or a chain of consequences. It is derived from the event description.

Failure mechanism categories: Are component-type-specific groups of similar *Failure mechanism sub-Categories*.

Failure mechanism sub-categories: Are coded component-type-specific observed faults or non-conformities which have led to the ICDE event.

Failure mode: The failure mode describes the function the components failed to perform.

ICDE event: Refers to all events accepted into the ICDE database. This includes events meeting the typical definition of CCF event (as described in Appendix B). ICDE events also include less severe events, such as those with 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**.**

Interesting CCF event categories: Marking of events as interesting via event codes. The idea of these codes is to highlight a small subset of ICDE events which are in some way "extraordinary" or provide "major" insights.

Latency: The time between the first occurrence of a failure or degradation mechanism and the time of detection of the failed or degraded condition.

Observed population (OP): A set of similar or identical components that are considered to have a potential for failure due to a common cause. A specific OP contains a fixed number of components. Sets of similar OPs form the statistical basis for calculating common-cause failure rates or probabilities.

Appendix A - Overview of the ICDE Project

Appendix A contains information regarding the ICDE project.

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 NEA has formally operated the project, following which the project was successfully operated over seven consecutive terms from 1998 to 2018. The current phase started in 2019 and is due to run until the end of 2022. Member countries under the current Agreement of the NEA and the organisations representing them in the project are: Canada (CNSC), Czechia (UJV), Finland (STUK), France (IRSN), Germany (GRS), Japan (NRA), the Netherlands (ANVS), Sweden (SSM), Switzerland (ENSI), and the United States (NRC).

More information about the ICDE project can be found at the NEA website: www.nea.fr/html/jointproj/icde.html. Additional information can also be found at the website https://projectportal.afconsult.com/ProjectPortal/icde.

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, main steam isolation valves, heat exchangers, fans, batteries, control rod drive assemblies, circuit breakers, level measurement and digital instrumentation and control (I&C) equipment.

Data Collection Status

Data are collected in an MS.NET based database implemented and maintained at ÅF, Sweden, the appointed ICDE Operating Agent. The database is regularly updated. It is operated by the Operating Agent following the decisions of the ICDE Steering Group.

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 necessary for the development of the ICDE databases and reports. The format for data collection is described in the general coding guidelines and in the component-specific guidelines. Component-specific guidelines are developed for all analysed component types as the ICDE plans evolve (NEA, 2004).

Protection of Proprietary Rights

Procedures for protecting confidential information have been developed and are documented in the Terms and Conditions of the ICDE project. The coordinators in the participating countries are responsible for maintaining proprietary rights. The data collected in the database are password protected and are only available to ICDE participants who have provided data.

Appendix B - ICDE General Coding Guidelines

Event Cause

In the ICDE database, the Event cause describes the direct reason for the component's failure. 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 was suggested:

C State of other components. The cause of the state of the component under consideration is due to the state of another component.

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. Included in the design process are the equipment and system specification, material specification, and initial construction that would not be considered a maintenance function. This category also includes design modifications.

A Abnormal environmental stress. This represents causes related to a harsh environment that is not within component design specifications. Specific mechanisms include chemical reactions, electromagnetic interference, fire/smoke, impact loads, moisture, radiation, abnormally high or low temperature, vibration load, and severe natural events.

H Human actions. This represents causes related to errors of omission or commission on the part of plant staff or contractor staff. This category includes accidental actions, and failure to follow procedures for construction, modification, operation, maintenance, calibration and testing. This category also includes deficient training.

M Maintenance. All maintenance not captured by H – human actions or P – procedure inadequacy.

I Internal to component or piece part. This deals with malfunctioning of internal parts to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms. It includes the influence of the environment on the component. Specific mechanisms include corrosion/erosion, internal contamination, fatigue, and wear out/end of life.

P Procedure inadequacy. Refers to ambiguity, incompleteness, or error in procedures, for operation and maintenance of equipment. This includes inadequacy in construction, modification, administrative, operational, maintenance, test and calibration procedures. This can also include the administrative control procedures, such as change control.

O Other. The cause of event is known, but does not fit in one of the other categories.

U Unknown. This category is used when the cause of the component state cannot be identified.

Coupling factor

The ICDE general coding guidelines (NEA, 2004) 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, the event cause and the 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:

H Hardware (component, system configuration, manufacturing quality, installation, configuration quality). Coded if none of or more than one of HC, HS or HQ applies, or if there is not enough information to identify the specific "hardware" coupling factor.

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

O Operational (maintenance/test (M/T) schedule, M/T procedures, M/T staff, operation procedure, operation staff). Coded if none or more than one of OMS, OMP, OMF, OP or OF applies, or if there is not enough information to identify the specific "maintenance or operation" coupling factor.

OMS M/T schedule. Components share maintenance and test schedules. For example, the component failed because maintenance procedure 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 calibration set point was incorrectly specified.

OMF M/T staff. Components are affected by maintenance staff error.

OP Operation procedure. Components are affected by inadequate operations procedure.

OF Operation staff. Components are affected by the same operations staff personnel error.

E Environmental, internal and external.

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. For example, the room that contains the components was too hot.

U Unknown. Sufficient information was not available in the event report to determine a definitive coupling factor.

Detection method

The ICDE general coding guidelines (NEA, 2004) suggest the following coding for the detection method for each failed component of the exposed population:

MW Monitoring on walkdown

MC Monitoring in control room

MA Maintenance/test

DE Demand event (failure when the response of the component(s) is required)

TI Test during operation

TA Test during annual overhaul

TL Test during laboratory

TU Unscheduled test

U Unknown

Corrective action

The ICDE general coding guidelines (NEA, 2004) define corrective action as follows. The corrective actions field describes the actions taken by the licensee to prevent the CCF event from reoccurring. The defence mechanism selection is based on an assessment of the event cause and/or coupling factor between impairments. Selection is made from the following codes:

A General administrative/procedure controls

B Specific maintenance/operation practices

C Design modifications

D Diversity. This includes diversity in equipment, types of equipment, procedures, equipment functions, manufacturers, suppliers, personnel, etc.

E Functional/spatial separation. Modification of the equipment barrier (functional and/or physical interconnections). Physical restriction, barrier or separation.

F Test and maintenance policies. Maintenance programme modification. The modification includes items such as staggered testing and maintenance/ operation staff diversity.

G Fixing component

O Other. The corrective action is not included in the classification scheme.

CCF root cause

For each event, the event cause, the corrective action and the coupling factor are assigned to one of the three basic CCF root cause aspects listed below:

Deficiencies in the design of components or systems (D): This category comprises all events where safety-relevant components or systems were not available or otherwise impaired due to deficiencies in the design. This although they were operated and maintained procedurally correct and under circumstances (ambient temperature, fluid temperature, pressure, etc.) within the expected limits. In general, these events require changes to hardware as corrective action.

Procedural or organisational deficiencies (P): This category comprises all events where a) wrong or incomplete procedures were applied and followed and b) events which happened because of organisational deficiencies of one or more of the involved entities (utilities, subcontractors, TSO, regulating bodies, etc.). In general, these events require changes to procedures or organisational improvements as corrective action.

Deficiencies in human actions (H): This category comprises all events which happened because of erroneous human actions. Corrective actions for these events may involve training measures, further improvements of procedures and instructions or organisational improvements (e.g. more personal).

The CCF root causes are further discussed in the ICDE general coding guidelines (NEA, 2004).

Event severity

The severity category expresses the degree of severity of the event based on the individual component impairments in the exposed population. The categories are:

A) Complete CCF	All components in the Group are completely failed (i.e. all elements in impairment vector are C, Time factor high and shared cause factor high.)
B) Partial CCF	At least two components in the Group are completely failed (i.e. at least two C in the impairment vector, but not complete CCF. Time factor high and shared cause factor high.)
C) CCF Impaired	At least one component in the group is completely failed and others affected (i.e. at least one C and at least one I or one D in the impairment vector, but not partial CCF or complete CCF).
D) Complete impairment	All components in the exposed population are affected, no complete failures but complete impairment. Only incipient degraded or degraded components (all D or I in the impairment vector).
E) Incipient impairment	Multiple impairments but at least one component working. No complete failure. Incomplete but multiple impairments with no C in the impairment vector.
F) Single Impairment	The event does not contain multiple impairments. Only one component impaired. No CCF event.
G) No impairment	All components working or no impairment data given.

The ICDE interesting CCF event categories are defined in Table A B.1.

Table A B.1. Interesting CCF event categories

Interesting CCF event codes	**Description** ***Purpose***
Complete CCF (1)	Event has led to a complete CCF. *This code sums up all complete CCFs, for any component type.*
CCF Outside planned test (2)	The CCF event was detected outside of normal periodic and planned testing and inspections. *The code gives information about test efficiency when CCFs are observed by other means than ordinary periodic testing – information about weaknesses in the defence-in-depth level 2.*

Interesting CCF event codes	**Description** ***Purpose***
Component not-capable (3)	The event revealed that a set of components was not capable to perform its safety function over a long period of time. *The code gives information about a deviation from deterministic approaches when it is revealed that two or more exposed components would not perform the licensed safety function during the mission time.*
Multiple defences failed (4)	Several lines of defence failed *More than one line of defence against CCF failed e.g. in the QA processes of designer, manufacturer, TSO and utility during construction and installation of a set of components.*
NO LONGER USED **CCF New Failure mechanism (5)**	The event revealed an unattended or not foreseen failure mechanism. *The code gives information about a new CCF event revealed and a new failure mechanism, not earlier documented in the licensing documentation or operating history.*
Sequence of multiple CCF failure mechanisms (6)	Events with a sequence of multiple CCF failure mechanisms. *The code gives information about incidents which revealed that during the event sequence more than one CCF failure mechanism was observed. The code focuses on the sequence of failures in the observed CCF failure mechanisms, regardless of how many CCCGs were affected.*
NO LONGER USED **CCF Causes Modification (7)**	The event causes major modification *The code gives information about a CCF event revealed that has led to or will lead to a major plant or system or component modification.*
Multiple Systems affected (8)	Events where a single CCF failure mechanism affected multiple systems. *This code indicates events where a single CCF failure mechanism affected components in more than one different system or affected more than one different safety function. In most cases, these events are Cross Component Group CCFs (X-CCF).*
Common Cause Initiator (9)	A dependency event originating from an initiating event of type common cause initiator (CCI) – a CCF event which is at the same time an initiator and a loss of a needed safety system. *The code gives information about an event with direct interrelations between the accident mitigation systems through common support systems. An event of interest for e.g. PSA analysts, regulators.*
Safety culture (10)	The reason why the event happened originates from safety culture management. Understanding, communication and management of requirements have failed. *The code gives information about CCF events that have occurred that can be attributed as originating from the management and safety culture factors.*

Interesting CCF event codes	Description *Purpose*
Multi-Unit CCF (11)	CCF affecting a fleet of reactors or multiple units at one site *The code gives information about CCF events that have occurred and affected several plants at a site. The events have to originate from a common event cause.*
No code applicable (12)	Indicates that event has been analysed but the event is not considered to be highlighted and therefore none of the codes is applicable.
Other remarkable events (13)	Other remarkable events not covered by the other codes but worth to mark. *The code gives information e.g. about an important new CCF failure mechanism, not earlier documented in the licensing documentation or operating history, or about a CCF event that has led to or will lead to a major plant or system modification.*
Questionable coding (14)	Indicates that there are comments on the event coding in the analyst comment field.
Shutdown and Decommissioning (15)	Events with a special interest for plants planning for permanent shutdown or decommissioning state *This code indicates events where CCF-phenomena were observed which might be of special interest for non-power operation modes. It should not be used for components like the EDGs where the importance in all plant states is obvious.*

Appendix C – Failure analysis Matrix – Deficiencies in operation

Table A C.1. Failure cause, failure mechanism category and sub-category of deficiencies in operation

FCC	FM Cat	FM Sub	EventSeverity	Root Cause	Failure Mechanism Description	Event ID
O1	FM1	a1	CCF Impaired	I	Premature ageing due to various factors: higher temperature than the suggested for battery cabinets, flotation voltage do not adjust to batteries' performance temperature and behaviour of UPS rectifier.	16386
			CCF Impaired	I	Premature ageing due to various factors: higher temperature than the suggested for battery cabinets, flotation voltage do not adjust to batteries' performance temperature and behaviour of UPS rectifier.	16411
			Single Impairment	C	Over-voltages from charging- could result in shorten cell plates.	32
			Single Impairment	D	Sulfate deposition on negative pole- reduced capacity.	41
	FM2	b1	Complete Impairment	H	Low gravity on battery electrolyte gave low voltage –test switch in wrong position.	52
		b4	Complete CCF	P	Lack of surveillance testing in the procedure and lack of monitoring led to undetected empty batteries for the HVAC systems.	23
	FM4		Complete CCF	P	Inadequate surveillance frequency in procedures resulted in dirty batteries causing ground fault.	16012
		d2	Complete CCF	P	Work caused a short.	40
O2			Complete CCF	I	Failed plant line-up – at maintenance.	47
	FM1	a1	CCF Impaired	I	Degraded cells due to ageing and electrical cycling.	3
			CCF Impaired	I	Degraded cells due to ageing and electrical cycling.	21
O3			Incipient Impairment	H	The event is interpreted as an ICDE event of two batteries due to human error (test in unsuitable configuration and unavailability of both batteries at the same time).	20
			Single Impairment	P	Static electricity cause explosion of battery.	17
	FM3		Incipient Impairment	H	Physical, electrical or chemical damage to battery cells.	50
	FM1		Complete Impairment	I	Corroded connections.	31
			Complete Impairment	I	Corroded connections.	43
			Complete Impairment	I	Cracking of cell top due to positive pillar corrosion.	28
			Complete Impairment	I	Cracking of cell top due to positive pillar corrosion.	54
		a1	Complete Impairment	P	Because of previous testing method, the batteries were discharged beyond recommended levels which shortened their expected life.	15466
			Incipient Impairment	I	Degraded cells due to ageing and electrical cycling.	30
		a5	Complete Impairment	I	Corroision on cells.	13
	FM2		Complete CCF	H	To be compliant with the work safety rules staff opened incorrect breaker as additional step, missing in procedure, which led to unavailable batteries.	16337
		b1	Complete Impairment	H	Insufficient charging of batteries . Gravity below specified value.	5
			Complete Impairment	U	Low Specific gravity in cell.	16026
		b2	Complete Impairment	M	Low battery electrolyte levels.	16016
	FM4		Single Impairment	H	Cleaning of Batteries –destroyed battery.	6

Appendix D – Failure analysis Matrix – Deficiencies in design, construction and manufacturing

Table A D.1. Failure cause, failure mechanism category and sub-category of deficiencies in design, construction and manufacturing

FCC	FM Cat	FM Sub	EventSeverity	Root Cause	Failure Mechanism Description	Event Id
D	FM1	a1	Complete Impairment	I	Cracked battery cell lids- due to pillar corrosion.	38
		a4	CCF Impaired	D	Discharge bar isolator not fully closed gave low Voltage.	24
		a5	CCF Impaired	D	A fault in the battery design.	14
			CCF Impaired	D	A fault in the battery design.	15
			CCF Impaired	D	Carbonation of a particular form of graphite contained in the active material of their positive plate leading to decreased battery capacity and a non-sufficient voltage.	10
			CCF Impaired	D	Carbonation of a particular form of graphite contained in the active material of their positive plate leading to decreased battery capacity and a non-sufficient voltage.	25
			CCF Impaired	D	Design error led to the depletion of charge carriers in the electrolyte and to reduced voltage under discharge conditions.	39
			CCF Impaired	D	Design error led to the depletion of charge carriers in the electrolyte and to reduced voltage under discharge conditions. Low battery capacity at surveillance test –due to carbonation of graphite –NIFe-batteries.	7
			CCF Impaired	D	Loss of storage capacity due to carbonation of positive plate.	12
			CCF Impaired	D	Loss of storage capacity due to carbonation of positive plate.	18
			CCF Impaired	D	Loss of storage capacity due to carbonation of positive plate.	55
			CCF Impaired	D	Low battery capacity at surveillance test –due to carbonation of graphite –NIFe-batteries.	4
			Complete Impairment	D	Battery bank is not capable of supplying required loads by design error. The utility had never attempted to operate with a single battery bank.	9
			Complete Impairment	D	Battery bank is not capable of supplying required loads by design error. The utility had never attempted to operate with a single battery bank.	16014
			Complete Impairment	D	Battery bank is not capable of supplying required loads by design error. The utility had never attempted to operate with a single battery bank.	16018
			Complete Impairment	D	Battery bank is not capable of supplying required loads by design error. The utility had never attempted to operate with a single battery bank.	16022
			Complete Impairment	D	Battery bank is not capable of supplying required loads by design error. The utility had never attempted to operate with a single battery bank.	16028
			Complete Impairment	D	Battery with insufficient capacity installed.	36
			Complete Impairment	D	Degraded functions due to Improper curing of positive plate during manufacturing.	42
			Complete Impairment	D	In case of short circuit, the fault current may destroy the switchgear because the new battery led to a higher short circuit current than it is designed for.	16013
			Complete Impairment	D	In case of short circuit, the fault current may destroy the switchgear because the new battery led to a higher short circuit current than it is designed for.	16017
			Complete Impairment	D	In case of short circuit, the fault current may destroy the switchgear because the new battery led to a higher short circuit current than it is designed for.	16021
			Complete Impairment	D	In case of short circuit, the fault current may destroy the switchgear because the new battery led to a higher short circuit current than it is designed for.	16027
			Complete Impairment	D	Low battery capacity at surveillance test –due to carbonation of graphite –NIFe-batteries.	1

			Complete Impairment	D	Low battery capacity at surveillance test –due to carbonation of graphite –NIFe-batteries.	2
			Complete Impairment	D	Low battery capacity at surveillance test –due to carbonation of graphite –NIFe-batteries.	11
			Complete Impairment	I	Corroded connections.	16020
			Complete Impairment	I	Cracked cells due corrosion.	37
			Complete Impairment	I	Cracked cells due corrosion.	51
			Complete Impairment	I	Low battery capacity at surveillance test.	15465
			Incipient Impairment	D	Low individual cell voltages due to manufacturing defects.	49
			Incipient Impairment	D	System design inadequacy led to implementation of undersized batteries.	15980
			Incipient Impairment	D	System design inadequacy led to implementation of undersized batteries.	15984
			Incipient Impairment	D	System design inadequacy led to implementation of undersized batteries.	15989
			Incipient Impairment	D	System design inadequacy led to implementation of undersized batteries.	15990
			Partial CCF	D	Loss of storage capacity due to carbonation of positive plate.	19
			Partial CCF	D	Loss of storage capacity due to carbonation of positive plate.	35
	FM2	b5	Incipient Impairment	I	Low voltage in cells.	26
		b6	CCF Impaired	D	voltage under required value due to a corrosion of the plates caused by high chloride-acid concentration of the electrolyte (leading to too low density of electrolyte).	29
C/M	FM3		CCF Impaired	D	Cell failure - Manufact.	8
			Incipient Impairment	D	Inadequate manufacturing quality led to crack indication in casings of battery cells.	15938
	FM1	a5	Incipient Impairment	D	Reduced voltage- failure of manufacturing plates.	44
			Incipient Impairment	D	Reduced voltage- failure of manufacturing plates.	46
			Incipient Impairment	I	Broken battery lid and internal leakage.	16539
			Incipient Impairment	I	Degraded battery capacity.	16541
			Incipient Impairment	I	External leakage of accumulator.	16537
			Incipient Impairment	I	Oxidised battery poles.	16540
	FM2	b4	Complete Impairment	D	Low voltage in cells- particle migration.	16
		b6	Complete Impairment	D	Increased chloride concentration in electrolyte.	33
			Complete Impairment	D	Increased chloride concentration in electrolyte.	22
			Incipient Impairment	D	Increased chloride concentration in electrolyte.	27
			Incipient Impairment	D	Increased chloride concentration in electrolyte.	45
			Incipient Impairment	D	Increased chloride concentration in electrolyte.	48

Appendix E – Definition of common-cause events

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

- 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. They 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 events in other PSAs (for example, CCF of auxiliary feedwater pumps due to steam binding, resulting from leaking check valves).

Several definitions of CCF events can be found in the literature, for example, in NUREG/CR-6268, Revision 1 "Common-Cause Failure Data Collection and Analysis System: Event Data Collection, Classification, and Coding":

Common-Cause Failure 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.

A CCF event consists of component failures that meet four criteria: (1) two or more individual components fail, are degraded (including failures during demand or in-service testing), or have deficiencies that would result in component failures if a demand signal had been received, (2) components fail within a selected period of time such that success of the probabilistic risk assessment (PRA) mission would be uncertain, (3) components fail because of a single shared cause and coupling mechanism, and (4) components fail within the established component boundary.

In the context of the data collection part of the ICDE project, the focus will be on CCF events with total as well as partial component failures that exist over a relevant time interval[4]. To aid in this effort the following attributes are chosen for the component fault states, also called impairments or degradations:

- Complete failure of the component to perform its function
- Degraded ability of the component to perform its function
- Incipient failure of the component
- Default: component is working according to specification

Complete CCF events are of particular interest. A "complete CCF event" is defined as a dependent failure of all components of an exposed population where the fault state of each of its components is "complete failure to perform its function" and where these fault states exist simultaneously and are the direct result of a shared cause. Thus, in the ICDE project, we are interested in collecting complete CCF events as well as partial CCF events. The

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

ICDE data analysts may add interesting events that fall outside the CCF event definition but are examples of recurrent – eventually non-random – failures. With a growing understanding of CCF events, the relative share of events that can only be modelled as "residual" CCF events is expected to decrease.