Nuclear Safety
NEA/CSNI/R(2021)7
April 2025
www.oecd-nea.org

ICDE Project Report: Lessons Learnt from Common-Cause Failures of Motor-Operated Valves

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NEA/CSNI/R(2021)7

Unclassified **English text only**

4 April 2025

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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JT03563811

COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS (CSNI)

The Committee on the Safety of Nuclear Installations (CSNI) addresses Nuclear Energy Agency (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 in 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 Committee on the Safety of Nuclear Installations (CSNI) formally approved this project to be carried out within the NEA framework. Since then, the project has operated over seven consecutive terms (the current, eighth-term being 2019-2022).

The purpose of the ICDE project is to allow 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, are sufficient 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 that 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 the frequency of CCF events 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 these 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 members in the context of PSA/PRA reviews and application will use the data.

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

- NEA (1999), "Collection and Analysis of Common Cause Failure of Centrifugal Pumps", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_16434.
- NEA (2000), "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 (2002), “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 (2007), “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.
- NEA (2013), “Collection and Analysis of Common Cause Failure of Heat Exchangers”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19648.
- NEA (2015), “ICDE Workshop - Collection and Analysis of Common Cause Failures due to External Factors”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19670.
- NEA (2017), “ICDE Workshop - Collection and Analysis of Emergency Diesel Generator Common Cause Failures Impacting Entire Exposed Population”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19784.
- NEA (2018), “Lessons Learnt from Common Cause Failure of Emergency Diesel Generators in Nuclear Power Plants – A Report from the International Common Cause Failure Data Exchange (ICDE) Project”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19852.
- NEA (2019), “ICDE Project Report: Summary of Phase VII of the International Common Cause Data Exchange Project”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_19902.
- NEA (2019), “ICDE Topical report: Collection and Analysis of Common Cause Failures due to Plant Modifications”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_36527.
- NEA (2019), “ICDE Topical report: Provision against Common Cause Failures by Improving Testing”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_75196.
- NEA (2019), “ICDE Topical report: Collection and Analysis of Multi-Unit Common Cause Failure Events”, OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_75202.

This report was approved by the Committee on the Safety of Nuclear Installations on 8-9 December 2021 during its 70th session (NEA, 2021).

Acknowledgements

The following individuals have significantly contributed to the preparation of this report by their personal effort: Mattias Håkansson (ÅF) Gunnar Johanson (ÅF) and Joran de Jong (ANVS).

In addition, the ICDE working group and the colleagues with whom they liaised in the participating countries are thanked for contributing to the success of this study. Diego Escrig Forano was the administrative NEA officer and contributed to finalising the first version of the report.

Table of contents

List of tables

List of figures

List of abbreviations and acronyms

BWR	Boiling water reactor
CCF	Common cause failure
ECCS	Emergency core cooling system
EDG	Emergency diesel generator
EL	External leakage
FC	Failure to close
FO	Failure to open
I&C	Instrumentation and control
ICDE	International Common Cause Failure Data Exchange
IL	Internal leakage
LOCA	Loss of coolant accident
MOV	Motor operated valves
PRA	Probabilistic risk assessment
PSA	Probabilistic safety assessment
PWR	Pressurised water reactor

Note: The acronyms from the ICDE General Coding Guideline[1] are presented in Appendix C.

Organisations

ANVS	Autoriteit Nucleaire Veiligheid en Stralingsbescherming (Authority for Nuclear Safety and Radiation Protection, Netherlands)
CNSC	Canadian Nuclear Safety Commission (Canada)
CSNI	Committee on the Safety of Nuclear Installations (NEA)
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat (Federal Nuclear Safety Inspectorate, Switzerland)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
INL	Idaho National Laboratory (United States)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (Institute of Radiological Protection and Nuclear Safety, France)
NRA	Nuclear Regulatory Authority (Japan)
NEA	Nuclear Energy Agency (IO)

[1] NEA (2004), "ICDE General Coding Guidelines: Technical Note (Revision number: Issue 3)", OECD Publishing, Paris, www.oecd-nea.org/jcms/pl_17990.

NRC	Nuclear Regulatory Commission (United States)
OECD	Organisation for Economic Co-operation and Development
SSM	Swedish Radiation Safety Authority (Sweden)
STUK	Finnish Centre for Radiation and Nuclear Safety (Finland)
UJV	Nuclear Research Institute (Czechia)

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: 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**:** Encompasses the set of piece parts that are considered to form the component.

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: Describes the actions taken by the licensee to prevent the CCF event from re-occurring. 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: 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 represents 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 that 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 that 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 an 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 that are in some way "extraordinary" or provide "major" insights.

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.

Executive summary

This report presents a study performed on a set of common cause failure (CCF) events of motor operated valves (MOV) within the International Common Cause Failure Data Exchange (ICDE) project. In July 2001, the ICDE project published a report summarising the collection and analysis of 87 MOV CCF events. Since that time, the ICDE project has continued to collect MOV events, with the database now including 172 events, spanning a period from 1980 through 2017. It was therefore decided to update the report.

The report is mainly intended for designers, operators and regulators to provide insights into the types of failure mechanisms and causes of MOV events in the ICDE database. These insights can improve the understanding of failure mechanisms and phenomena involved and their relationship to the CCF root cause.

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

- The CCF root causes "solely or predominant design" and "solely or predominant procedures" were equally common, about 45% respectively. About 10% were due to deficiencies in human actions.
- Design deficiencies are slightly more common among the severe events (raising the share to 55%). The less severe events are more commonly caused by deficiencies in procedures (raising it to 57%).

An analysis of the events led to the following qualitative insights, lessons learnt and recommendations:

- Deficiencies in design tend to result in more severe events for MOVs and most problems are caused by electrical I&C design issues, with the most common issue involving set points exceeding the torque switch limit. Recurrent control of the set points and verification of these after test and maintenance can reduce the risk of CCF and should be implemented. Without such surveillance and control, these types of problems tend to develop into severe CCF events, as seen in the data set.
- The degradation of components until failure occurs slowly. Consequently, adequate operational procedures, ageing management and operational actions should be implemented as they can prevent events from happening or can help detect the degradation before complete failure of the component occurs.
- Operator performance errors result in severe events. To prevent such errors, it is vital to have adequate procedures, written work plans, training of personnel and a well-established safety culture. In addition, verification of operability after actions must be performed on a structured basis as it has an important role to minimise such failure causes.
- An appropriate ageing management programme, in combination with frequent inspections, to detect wear and the degradation of valve internals should be implemented as it can prevent leakage in valves.

Compared with the earlier MOV CCF report published in 2001 (NEA, 2001), one noteworthy difference is the rate of CCF event occurrence, which appears to have been decreasing in recent years. However, no significant difference in the event cause distribution was observed. It could be assumed that the decrease in event rate is due to global efforts to enhance nuclear safety. Further study of the event trends is planned as the ICDE project continues to expand the data collection for the years after 2010.

1. Introduction

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

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

Chapter 2 describes the MOV component, while Chapter 3 presents an overview of the contents of the MOV database and a summary of statistics. Chapter 4 contains high-level engineering insights into the MOV CCF events, supported by failure mechanisms and failure causes. Chapter 5 provides a summary and conclusions. References are found in Chapter 6.

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 and Appendix C present the definition of common cause failures as well as the ICDE event definitions from the ICDE General Coding Guideline (NEA, 1999). Appendix D presents the workshop form that was used in the event analysis. Appendix E presents the concluded failure mechanism descriptions according to the failure analysis assessment.

1.1. Background

The first ICDE component study of MOVs was published in 2001 (NEA, 2001). It examined 87 events in the ICDE database by tabulating the data and observing trends. Most events that were analysed in the report were from observation periods from 1995 and earlier. 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. The current report expands the event set to include more recent data covering observation periods through 2015. This report shows the similarities and differences in the examined events compared to the 2001 report.

The analysis approach in (NEA, 2001) especially focused on the CCF root cause. The examined events showed errors in the calculation during design that caused false stroke forces. Wearing was a widespread effect. The subcomponent "limit switch" caused also a substantial amount of CCF. Failures on locking out during maintenance actions were also conspicuous. There were further failure effects that caused CCF in not such a large and determinant scope. For example, selection of unsuited lubricant, improper materials, and assembly faults.

The full version of the ICDE report can be found on the NEA website.

Another CCF component study of MOVs was published by the NRC in 2003, based on the NRC CCF database (NRC, 2003). The report addresses and discusses engineering aspects of the included events. The used data for this report overlap, to some extent, with the dataset in the ICDE component report since the United States contributes with CCF data to the ICDE project. Several common parameters with the ICDE database were assessed and tabulated, such as the failure modes, event severity and method of discovery. In addition, sub-components were addressed in detail.

The analysis showed that the leading *proximate causes* were operational/human error, design/construction/installation/manufacture inadequacy, and internal to component. The operational/human errors contributed to about 45% of the complete CCFs. Operational/human errors involve accidental actions, failure to follow procedures, inadequate procedures for construction, modification, operation, maintenance, calibration and testing, and deficient training. The design/construction/installation/manufacture inadequacies involved events resulting from an error in equipment and system specifications, material specifications and calculations. The internal to component cause group was important for MOVs. Internal causes resulted from malfunctioning of hardware internal to the component. Specific observed deficiencies were erosion, corrosion, internal contamination, fatigue, wear-out and end-of-life.

A more recent study of MOVs was published in 2019 by the Idaho National Laboratory (INL) (Ma, 2019). This study was an enhanced component study of MOVs but for single failures from the ICES[2] database. Nevertheless, the MOV failure cause groups used are like the ICDE event parameter *event causes* (see Section 3.4). Thus, the engineering insights are of interest for this update of the ICDE component study of MOVs.

The insights show that the actuator is the largest contributor to the failures. The component cause group is the most likely cause category. The component cause group involved causes related to something internal to the component, mainly worn-out parts or drifting set points due to the normal internal environment. The human cause group was primarily influenced by maintenance and operating procedures and practices. The other cause group is used, when the cause is the result of another component state external to the one that failed. The other cause group showed increased importance for the spurious operation failure mode. The detection method for the failure mode failure to open was most likely a testing demand. Failure to close and spurious operation were heavily influenced by testing and non-test demands.

2. Institute of Nuclear Power Operations (INPO) Consolidated Events Database (not publicly accessible).

2. Component description

This section is extracted from the Motor operated valves coding guidelines, which is an appendix to the ICDE General Coding Guidelines (NEA, 2004).

2.1. General description of the component

This family of valves is comprised of those emergency system (e.g. ECCS) valves that are motor operated and are used for the purpose of establishing or isolating flow to or from the primary system. The main systems [3] for which MOV data are collected are (the corresponding IRS system coding is added in parentheses):

• Pressure control (includes primary safety and relief valves)	(3.ÅF)
• Reactor core isolation cooling (BWR)	(3.BA)
• Auxiliary and emergency feedwater	(3.BB)
• Emergency poisoning function (PWR mainly with the boron injection tank, chemical and volume control system participation)	(3.BC*)
• Residual heat removal (PWR and BWR except emergency core cooling functions)	(3.BE)
• Chemical and volume control (PWR with main pumps seal water, ...)	(3.BF*)
• Emergency core cooling	(3.BG)
• Component cooling water (including reactor building closed cooling water)	(3.CA)
• Essential raw cooling or service water	(3.CB)
• Borated or refuelling water storage (PWR)	(3.CD)
• Condensate storage	(3.CE*)
• Containment isolation (including penetrations and air lock door seals)	(3.DB*)
• Containment atmosphere clean-up/treatment systems (e.g. spray, iodine removal…)	(3.DD)
• Main steam and auxiliaries (including auxiliary steam)	(3.FA*)
• Feedwater and condensate (including pumps, heat exchangers, tanks, etc.)	(3.FG*)

*System types collected due to plant-specific design for some countries. Not explicitly given in the coding guideline as a system to collect data.

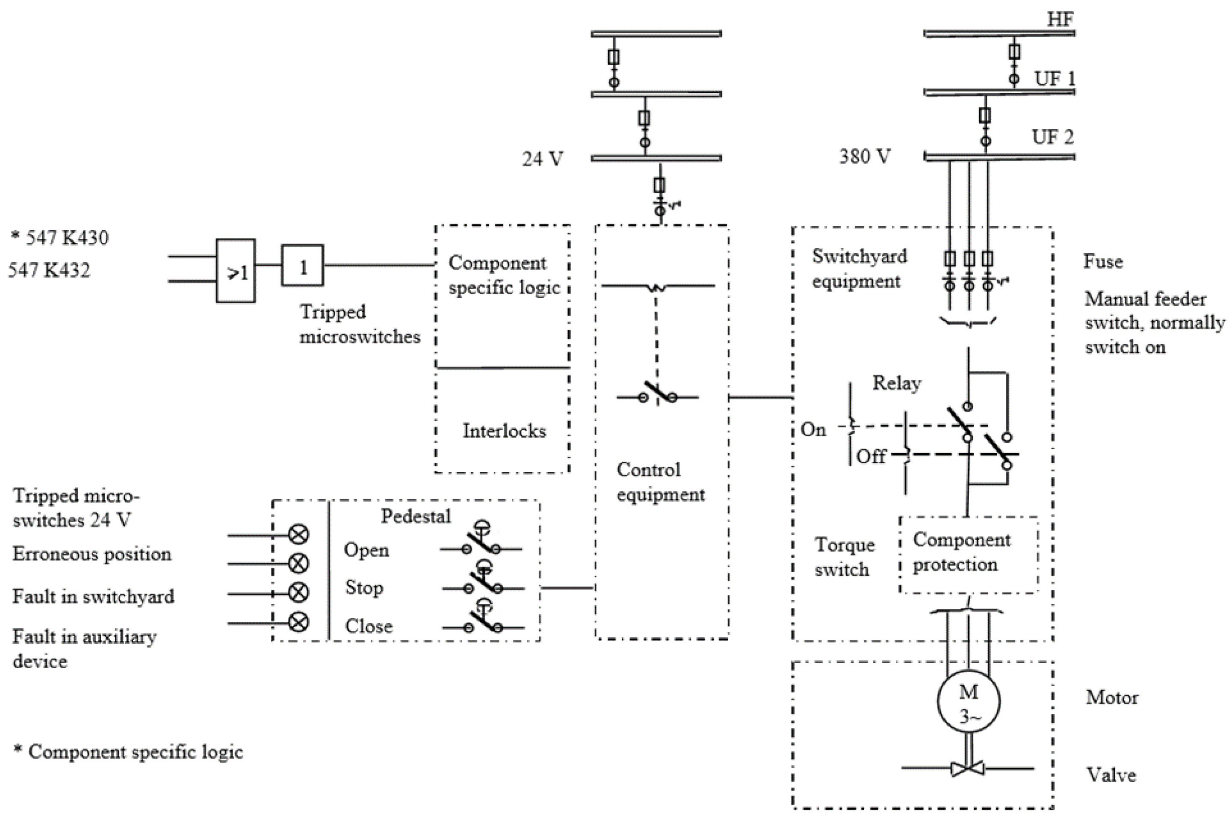
3. Main systems listed here include CCF group records in the ICDE database with more than ten records.

The distinguished component types are a motor-operated ball, gate, globe or butterfly valve, or an MOV of general type. The essential failure modes are failure to open (FO) and failure to close (FC). For some valves, only one of the two failure modes is relevant. Several countries also have the failure modes internal leakage (IL) and external leakage (EL).

2.2. Component boundary

The MOV is comprised of a valve with its internal piece part components and a motor operator. The operator includes the circuit breaker, power leads, local protective devices, open/close limit switches, torque switches, and the motor. The control circuit that induces a close or open signal to a MOV is not included within the MOV boundary if it also controls other component functions, such as other valve actions or pump starts. The MOV component boundary is illustrated in Figure 2.1.

Figure 2.1. The component boundaries for MOVs.



2.3. Event boundary

The mission for an MOV is to allow the flow of water into the primary system following a loss of coolant accident (LOCA) or to prevent water from leaving the primary containment system in the event of a LOCA. Some of the systems for which MOV data were reviewed serve dual purposes (low-pressure injection and residual heat removal), such that the flow paths are used during normal plant evolutions. The MOV fails to perform its PRA mission if a valve that is required to be open to allow injection or cooling flow does not open, or if a valve that is required to close to isolate secondary parts of the ECCS after a LOCA fails to close.

2.4. Coding rules and exceptions

In general, the definition of the ICDE event given in Section 2 of the general ICDE coding guidelines applies (NEA, 2004). Some reports discuss only one actual failure and do not consider that the same cause will affect other MOVs, but the licensee replaces the failed component on all MOVs as a precautionary measure. This type of event will be coded as incipient impairment (0.1) of the components that did not actually fail. Inoperability due to seismic criteria violations will not be included unless an actual failure has occurred. Administrative inoperability that does not cause the valve to fail to function will not be included as failures. An example is a surveillance test not performed within the required time frame. Failure of the electrical operator without coincident failure of the manual operator is considered an MOV failure. Failure of the MOV to cycle in the required time (as opposed to mission time) will not be considered a failure, either as a CCF or independently, if the MOV reached its intended state.

3. Overview of database content

This chapter presents an overview of the data set, which includes 172 events. Tables exhibiting the event count for each of the event parameters (failure mode, event cause, coupling factor, corrective action, CCF root cause, detection method, and event severity) are presented. The event parameters are defined in the ICDE General Coding Guidelines (NEA, 2004); see Appendix C.

To put the percentages in context, two values are given. "Percent" is the percentage in relation to the subset of events that was analysed in the workshop. "Relative occurrence" is the occurrence factor of the event parameter in relation to the complete ICDE database content.

It is worth noting that all relative occurrences need to be interpreted carefully since the statistical certainty is not always high. This is especially important for the event codes with only a few events reported since the relative occurrence can differ significantly if another event is added/removed with that specific event code.

3.1. Data collection overview

The data collection of MOV encompasses data of 201 reactor units from 11 countries and include a total of 1 366 CCF groups. The ICDE events have been observed in 139 unique CCF groups for 92 unique reactor units. Table 3.1 and Figure 3.1 show the observation time and the number of reported events per year. The data collection is ongoing in several countries and the observation time from 2010 is expected to increase to similar levels as observed in the 2005-2010 period.

The 172 collected events represent a significant expansion of the database since the first ICDE report on MOV CCF events (NEA, 2001). One notable difference in comparison to the events analysed in NEA (2001) is the apparent decrease in the ICDE event occurrence rate in more recent years. 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 appears to have been decreasing in recent years. However, caution should be used in interpreting this result without further statistical analysis. Also, incomplete data collection for portions of the observation period (e.g. prior to 1990 and after 2010) could influence the results. Additional study of the event trends is planned as the ICDE project continues to expand the data collection for the years after 2010.

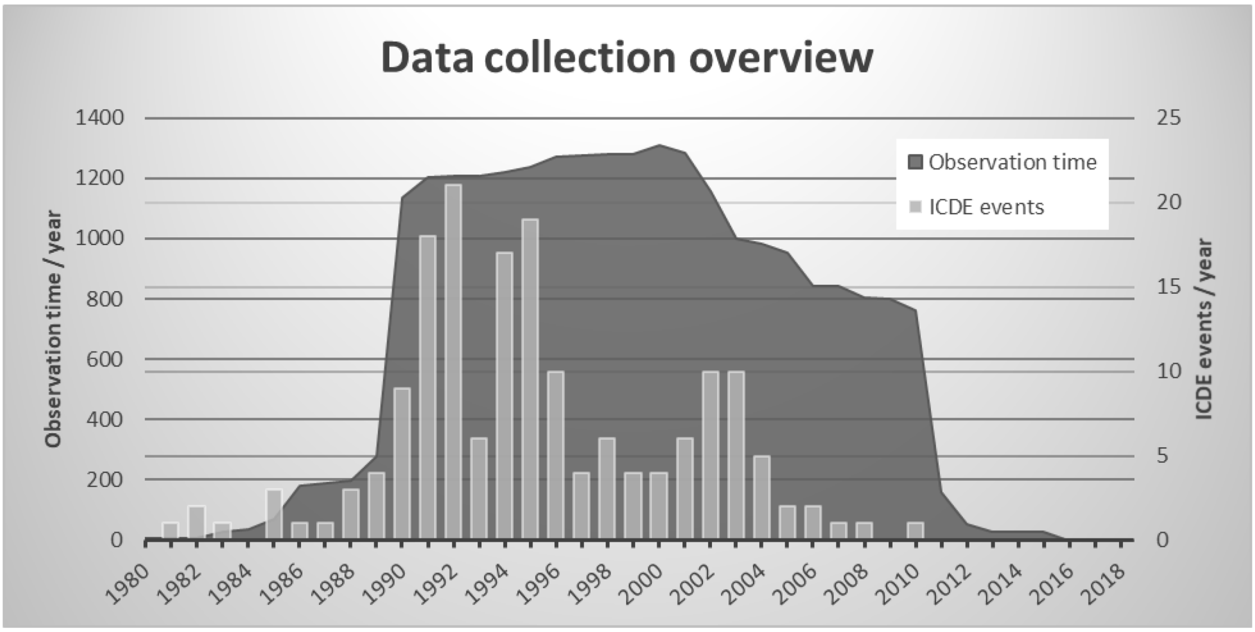
Table 3.1. Observation time and ICDE events per five-year period

Five-year period	Observation time [yrs]	ICDE events	ICDE event rate
1980-1985	83	4	4,8%
1985-1990	916	12	1,3%
1990-1995	5 969	71	1,2%
1995-2000	6 341	43	0,7%
2000-2005	5 728	35	0,6%
2005-2010	4 241	6	0,1%
2010-2015	1 038	1	0,1%

Table 3.1. Observation time and ICDE events per five-year period (Continued)

Five-year period	Observation time [yrs]	ICDE events	ICDE event rate
2015-2020	29	0	0,0%
Total	**24 345 (1 366 records)**	**172**	

Figure 3.1. Data collection overview observed populations and ICDE events



3.2. System types

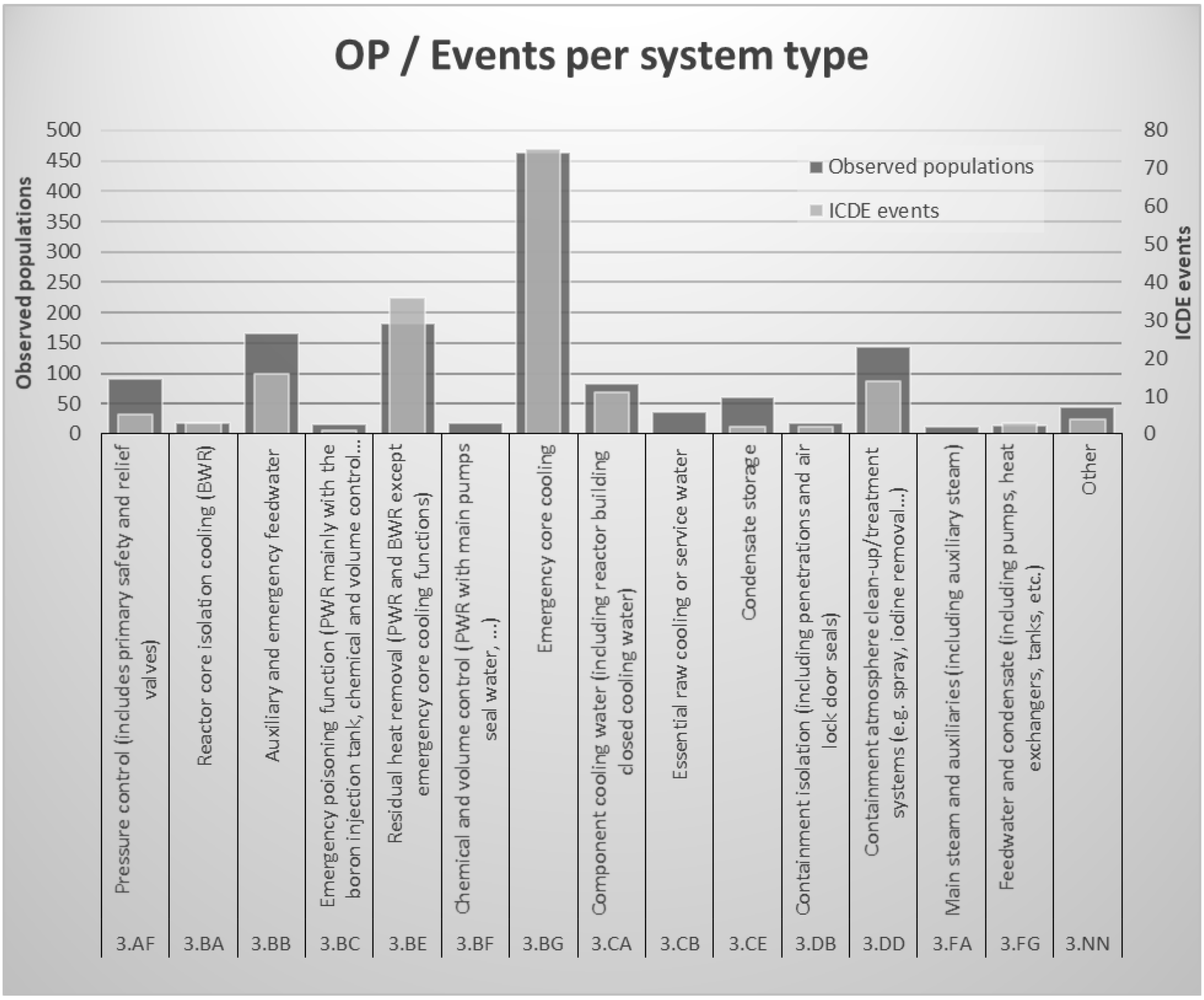
Table 3.2 and Figure 3.2 present the collected system types. The system types listed include at least ten CCF group records in the ICDE database. The system types marked with an asterisk (*) are not officially collected according to the component coding guideline but reported due to plant-specific design for some countries. Here it is seen that the most common system type is "emergency core cooling" (34%), which is also the most common system with observed events (44%). In terms of the number of events per system type, the system type "residual heat removal" has a higher portion of events. However, this does not consider the observation periods, which may differ between the system types.

Table 3.2. System types and ICDE events

IRS	IRS description	Observed populations	Percent	ICDE events	Percent
3.AF	Pressure control (includes primary safety and relief valves)	90	7%	5	3%
3.BA	Reactor core isolation cooling (BWR)	19	1%	3	2%
3.BB	Auxiliary and emergency feedwater	165	12%	16	9%
*3.BC**	Emergency poisoning function (PWR mainly with the boron injection tank, chemical and volume control system participation)	16	1%	1	1%
3.BE	Residual heat removal (PWR and BWR except emergency core cooling functions)	181	13%	36	21%
*3.BF**	Chemical and volume control (PWR with main pumps seal water, ...)	18	1%	0	0%
3.BG	Emergency core cooling	464	34%	75	44%
3.CA	Component cooling water (including reactor building closed cooling water)	82	6%	11	6%
3.CB	Essential raw cooling or service water	37	3%	0	0%
*3.CE**	Condensate storage	61	4%	2	1%
*3.DB**	Containment isolation (including penetrations and air lock door seals)	18	1%	2	1%
3.DD	Containment atmosphere clean-up/treatment systems (e.g. spray, iodine removal…)	144	11%	14	8%
*3.FA**	Main steam and auxiliaries (including auxiliary steam)	11	1%	0	0%
*3.FG**	Feedwater and condensate (including pumps, heat exchangers, tanks, etc.)	15	1%	3	2%
3.NN	Other[4]	45	3%	4	2%
Total		**1 366**	**100%**	**172**	**100%**

4. This category includes all other system types collected in the ICDE database with less than ten records.

Figure 3.2. System types and ICDE events



3.3. Failure mode and event severity

Table 3.3 and Figure 3.3 show the distribution of the events by failure mode and event severity. The failure mode most susceptible to failures is “failure to open” (52%). Leakage, internal or external, has only occurred for about 12% of the events. The most common event severity categories were “CCF impaired” and “incipient impairment”. The relative occurrence of partial CCFs is high, about a factor of 1.5 higher compared to the complete ICDE database, but the occurrence of complete CCF is lower. These severe events make-up about 25% of all MOV events.

Table 3.3. Distribution of failure modes and event severities

Failure mode	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent
Failure to open	6	26	30	10	17	1	**90**	52%
Failure to close	2	7	17	8	22	3	**59**	34%
Internal leakage			2	3	10		**15**	9%
External leakage	1			1	3		**5**	3%
No data			3				**3**	2%
Total	**9**	**33**	**52**	**22**	**52**	**4**	**172**	**100%**
Percent	**5%**	**19%**	**30%**	**13%**	**30%**	**2%**		
Relative occurrence	**60%**	**150%**	**130%**	**40%**	**130%**	**110%**		

Figure 3.3. Distribution of failure modes and event severities

3.4. Event cause

Table 3.4 and Figure 3.4 show the distribution of the events by event causes. The major observed event causes are “design, manufacture or construction inadequacy” (31%) and “internal to component, piece part” (28%). For the relative occurrence, no significant deviation is observed.

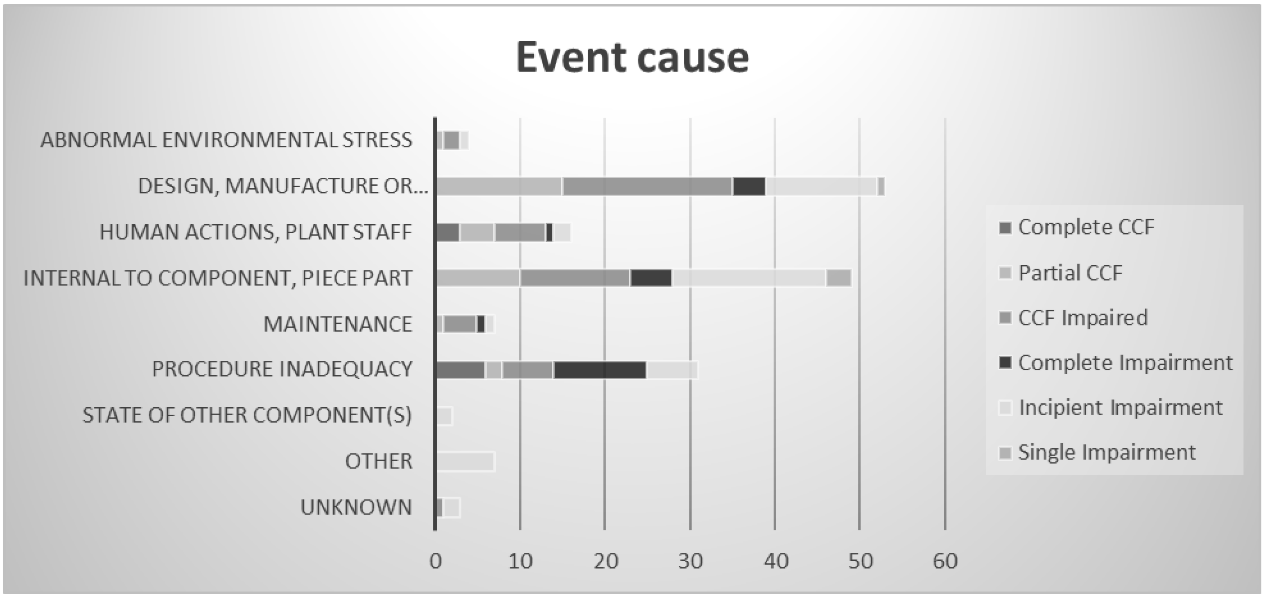
Table 3.4. Distribution of event causes

Event cause	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent	Relative occurrence
Abnormal environmental stress		1	2		1		**4**	2%	50%
Design, manufacture or construction inadequacy		15	20	4	13	1	**53**	31%	100%
Human actions, plant staff	3	4	6	1	2		**16**	9%	100%
Internal to component, piece part		10	13	5	18	3	**49**	28%	140%

Table 3.4. Distribution of event causes (Continued)

Event cause	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent	Relative occurrence
Maintenance		1	4	1	1		**7**	4%	80%
Procedure inadequacy	6	2	6	11	6		**31**	18%	140%
State of other component(s)					2		**2**	1%	20%
Other					7		**7**	4%	80%
Unknown			1		2		**3**	2%	40%
Total	**9**	**33**	**52**	**22**	**52**	**4**	**172**	**100%**	

Figure 3.4. Distribution of event causes



3.5. Coupling factor

Table 3.5 and Figure 3.5 show the distribution of the failure events by coupling factor. The most common coupling factors are "operational" (23%) and "hardware" (20%). The relative occurrence for coupling factors related to some "operational" aspects are over-represented by almost a factor of three compared to the complete database.

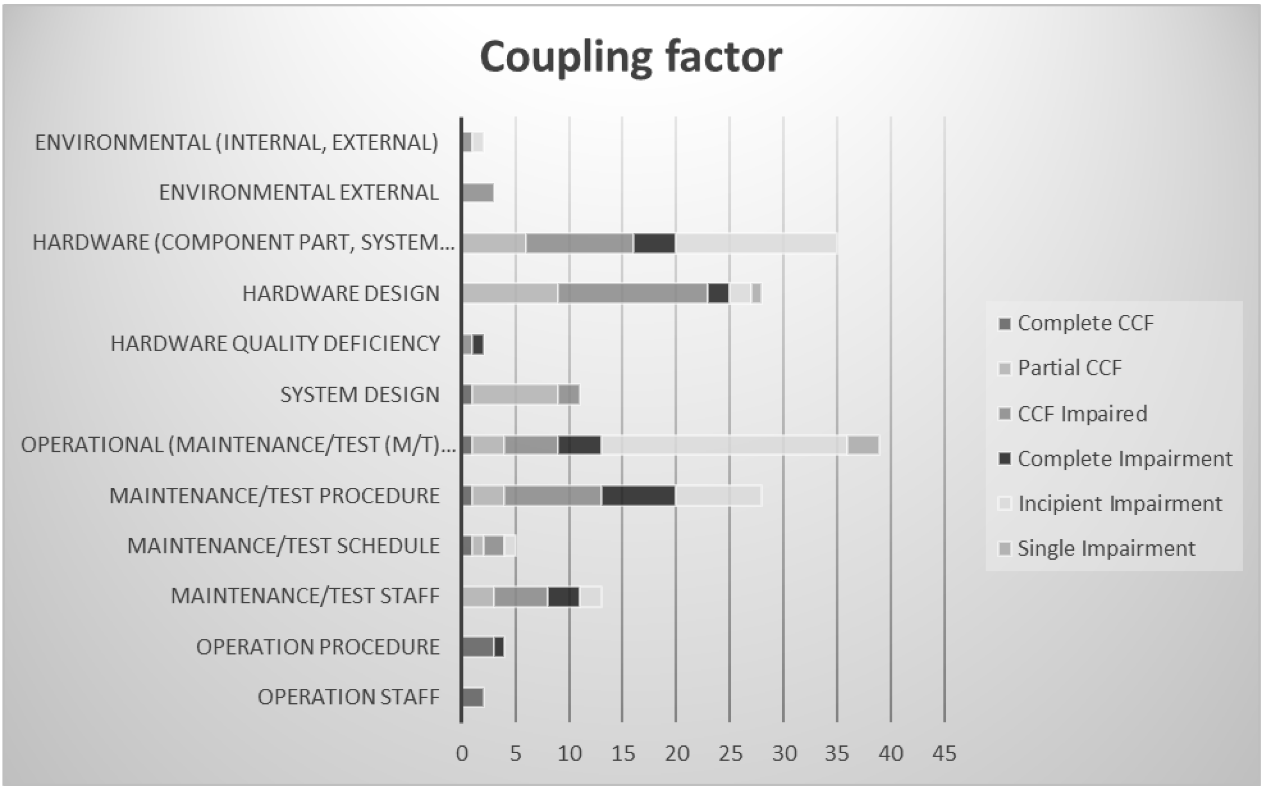
Table 3.5. Distribution of coupling factors

Coupling factor	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent	Relative occurrence
Environmental (internal, external)			1		1		**2**	1%	50%
Environmental External			3				**3**	2%	80%
Environmental Internal							**0**	0%	0%
Hardware (component part, system configuration, manufacturing quality, installation/configuration quality)		6	10	4	15		**35**	20%	110%

Table 3.5. Distribution of coupling factors (Continued)

Coupling factor	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent	Relative occurrence
Hardware design		9	14	2	2	1	**28**	16%	100%
Hardware Quality Deficiency			1	1			**2**	1%	30%
System Design	1	8	2				**11**	6%	90%
Operational (maintenance/test (M/T) schedule, M/T procedure, M/T staff, operation procedure, operation staff)	1	3	5	4	23	3	**39**	23%	270%
Maintenance/test procedure	1	3	9	7	8		**28**	16%	120%
Maintenance/test schedule	1	1	2		1		**5**	3%	30%
Maintenance/test staff		3	5	3	2		**13**	8%	160%
Operation procedure	3			1			**4**	2%	170%
Operation staff	2						**2**	1%	180%
Total	**9**	**33**	**52**	**22**	**52**	**4**	**172**	**100%**	

Figure 3.5. Distribution of coupling factors



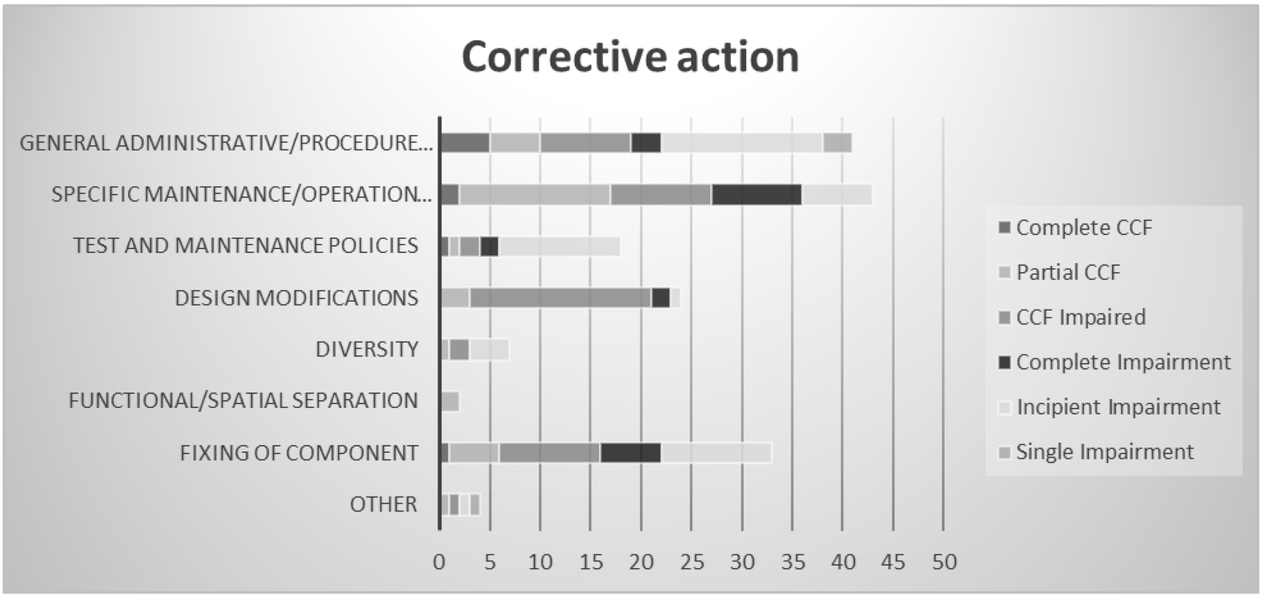
3.6. Corrective action

The distribution of the events for corrective actions is shown in Table 3.6 and Figure 3.6. A broad distribution of corrective actions is observed, but most common is "specific maintenance/operation practices", followed by "general administrative/procedure controls". As for the relative occurrence, no significant occurrence is seen.

Table 3.6. Distribution of corrective actions

Corrective action	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent	Relative occurrence
General administrative/procedure controls	5	5	9	3	16	3	**41**	24%	160%
Specific maintenance/operation practices	2	15	10	9	7		**43**	25%	100%
Test and maintenance policies	1	1	2	2	12		**18**	10%	100%
Design modifications		3	18	2	1		**24**	14%	60%
Diversity		1	2		4		**7**	4%	160%
Functional/spatial separation		2					**2**	1%	40%
Fixing of component	1	5	10	6	11		**33**	19%	140%
Other		1	1		1	1	**4**	2%	50%
Unknown							**0**	0%	140%
Total	**9**	**33**	**52**	**22**	**52**	**4**	**172**	**100%**	

Figure 3.6. Distribution of corrective actions



3.7. 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" (IAEA, 2015). 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).

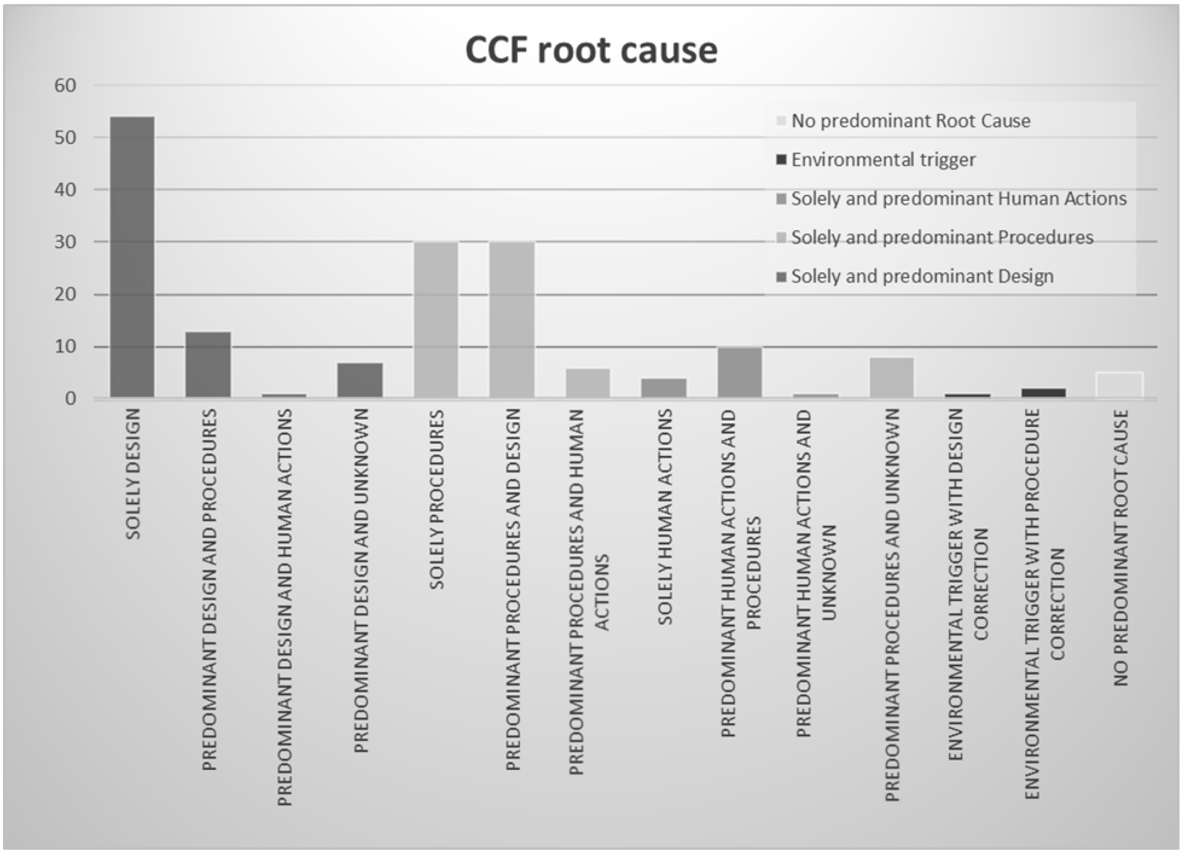
In addition to these three basic aspects, the supporting aspects "environmental" and "unknown" are used in case of events due to external factors or events, which are not completely coded. It is distinguished if all three aspects of an event are identical (e.g. 3 x Design) or if there is a predominant 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 Guideline (NEA, 2004). The results of the CCF root cause assignment are given in Table 3.7 and Figure 3.7.

The CCF root causes "solely and predominant design" and "solely and predominant procedures" were equally common. Only a few events had an environmental trigger and about 10% of the events had a CCF root cause related to deficiencies in human actions.

Table 3.7. Distribution of CCF root causes

CCF root cause	Total	Percent
Solely and Predominant Design	**75**	**44%**
Solely Design	54	31%
Predominant Design and Procedures	13	8%
Predominant Design and Human Actions	1	1%
Predominant Design and Unknown	7	4%
Solely and predominant Procedures	**74**	**43%**
Solely Procedures	30	17%
Predominant Procedures and Design	30	17%
Predominant Procedures and Human Actions	6	3%
Predominant Procedures and Unknown	8	5%
Solely and predominant Human Actions	**15**	**9%**
Solely Human Actions	4	2%
Predominant Human Actions and Procedures	10	6%
Predominant Human Actions and Unknown	1	1%
Environmental trigger	**3**	**2%**
Environmental Trigger with design correction	1	1%
Environmental Trigger with procedure correction	2	1%
No predominant Root Cause	**5**	**3%**
Total	**172**	**100%**

Figure 3.7. Distribution of CCF root causes



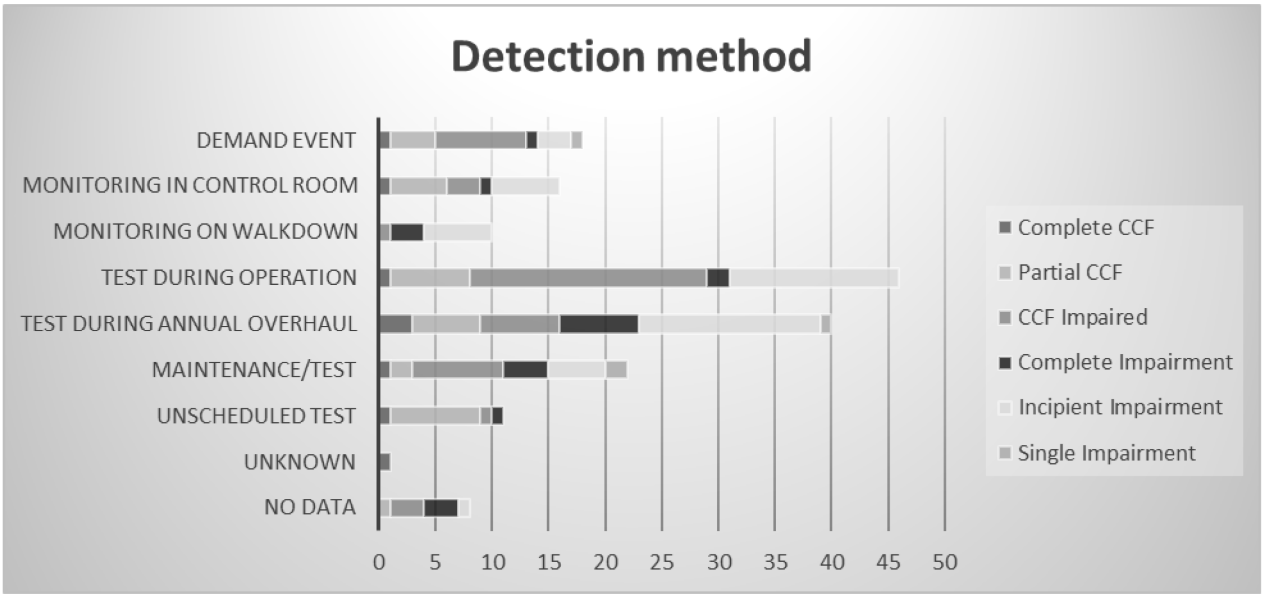
3.8. Detection method

Table 3.8 and Figure 3.8 contain the distribution of the events by detection method. The most common detection methods were “test during operation” and “test during annual overhaul”. These two detection methods include about 50% of the events and can be seen as detected by normal tests. The other 50% of the events were non-test demand events, where some were monitored and some were real demand events (i.e. the system safety function was needed).

Table 3.8. Distribution of detection methods

Detection method	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent
Demand event	1	4	8	1	3	1	**18**	10%
Monitoring in control room	1	5	3	1	6		**16**	9%
Monitoring on walkdown			1	3	6		**10**	6%
Test during operation	1	7	21	2	15		**46**	27%
Test during annual overhaul	3	6	7	7	16	1	**40**	23%
Maintenance/test	1	2	8	4	5	2	**22**	13%
Unscheduled test	1	8	1	1			**11**	6%
Unknown	1						**1**	1%
No data		1	3	3	1		**8**	2%
Total	**9**	**33**	**52**	**22**	**52**	**4**	**172**	**100%**

Figure 3.8. Distribution of detection methods



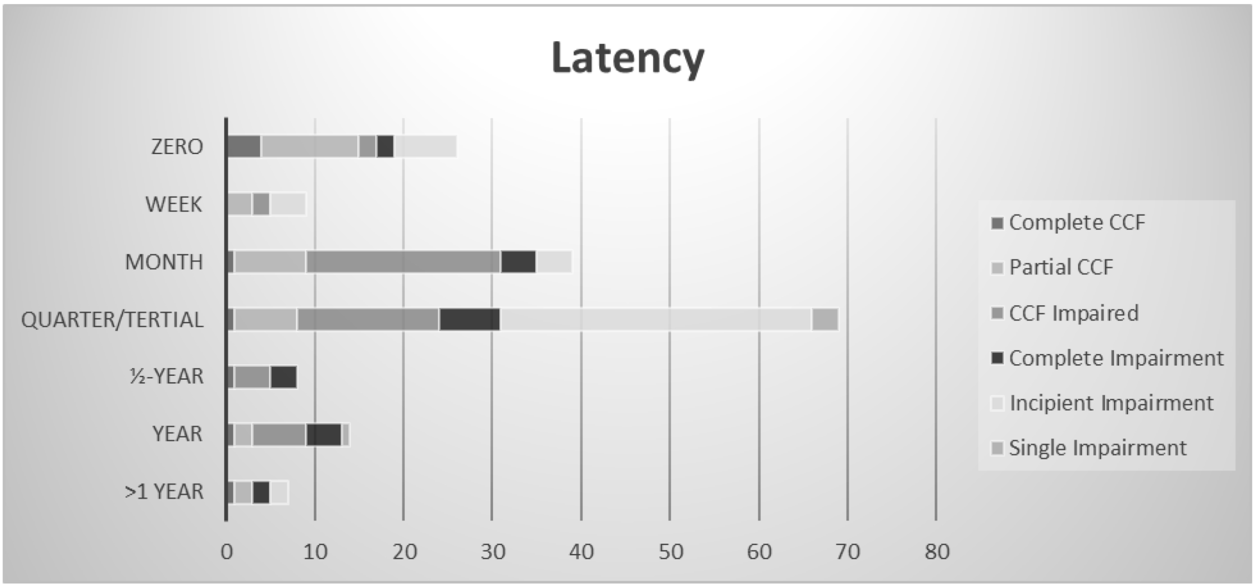
3.9. Latency

Table 3.9 and Figure 3.9 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 within a quarter/tertial year. About 17% of the events had a latent time factor of more than half a year, which may indicate an overlong test interval of the components or inadequate test procedures. If the detection method is taken into consideration, about 60% of the severe events are detected outside normal test (i.e. not via test during operation or annually). For the less severe events about 53% of the events are detected by normal test.

Table 3.9. Distribution of latencies

Latency factor	Complete CCF	Partial CCF	CCF impaired	Complete impairment	Incipient impairment	Single impairment	Total	Percent
Zero	4	11	2	2	7		**26**	15%
Week		3	2		4		**9**	5%
Month	1	8	22	4	4		**39**	23%
Quarter/Tertial	1	7	16	7	35	3	**69**	40%
½-year	1		4	3			**8**	5%
Year	1	2	6	4		1	**14**	8%
>1 year	1	2		2	2		**7**	4%
Total	**9**	**33**	**52**	**22**	**52**	**4**	**172**	**100%**

Figure 3.9. Distribution of latencies



4. Engineering aspects of the collected events

This chapter contains an engineering review of the MOV events. The analysis was based on questions listed in the workshop form; see Appendix D. 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, are expressed by a human error-related event cause, or involve 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 which 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. Engineering analysis of all component-type-specific events and appropriate binning of similar failure mechanisms identify the failure mechanism sub-categories. The result of this engineering analysis is summarised in ICDE component-specific reports such as the present report.

The following failure mechanism categories and sub-categories were concluded for the MOV events; see Table 4.1.

Table 4.1. Failure mechanism categories and sub-categories

Failure mechanism		Description
Movement of the main valve impeded by mechanical problems		
A1	Insufficient quantity/quality of lubricant	Valve internals with lack of or unsuited lubricant, which impedes the valve to fully open or close.
A2	Bonding	Bonding or sticking of the valve, which impedes the valve to fully open or close.
A3	Loose/broken/degraded piece parts	Loose/broken/degraded internal piece parts, which impede the valve to fully open or close.
A4	Mechanical misalignments	Mechanical misalignments, which impede the valve to fully open or close.
Electrical and I&C failures		
B1	Loss or degradation of the power supply	Degradation of the MOVs power supply excluding failures of the MOVs circuit breakers (see MOV-b2). Examples for such failures are degraded power cables, triggered fuses or incorrect installation of power cables.
B2	Failure of the circuit breaker	Failures directly related to the circuit breaker of the MOV. Events were a breaker acted erroneously due to a faulty or missing I&C command are not assigned to that sub-category but to MOV-b3.
B3	I&C related failures	Failures related to the I&C of the MOV excluding failures, which directly related to limiting switches (see MOV-b5 and MOV-b6).
B4	Motor drive failures	Failures related to the drive of the MOV including the complete power train (motor, gear, breaks, etc.).
B5	Failures or misadjustments of limit switches (torque, way, overcurrent…)	Failures related to the limit switches of the MOV including hardware failures as well as misadjustment due to human or organisational issues.
B6	Wrong setpoints or drift of limit switches	Misadjustment of setpoints due to human or organisational issues or issues to uphold calibration settings of limit switches
Main valve leaking		
C1	Seat/disk/o-ring surface degradation	Degradation of valve internals, which results in leaking of the main valve.
Other		
D1	Other/Unknown	Other or unknown mechanisms.

<u>Interesting event categories</u>

The marking of interesting events in the ICDE database consists of pointing out interesting and extraordinary CCF event records such as subtle dependencies with specific codes and descriptions. These records are important dependency events that are useful for the overall operating experience and can be used as input for the stakeholders to develop defences against CCF. Several areas may be relevant for a single event.

4.2. Failure analysis assessment matrix

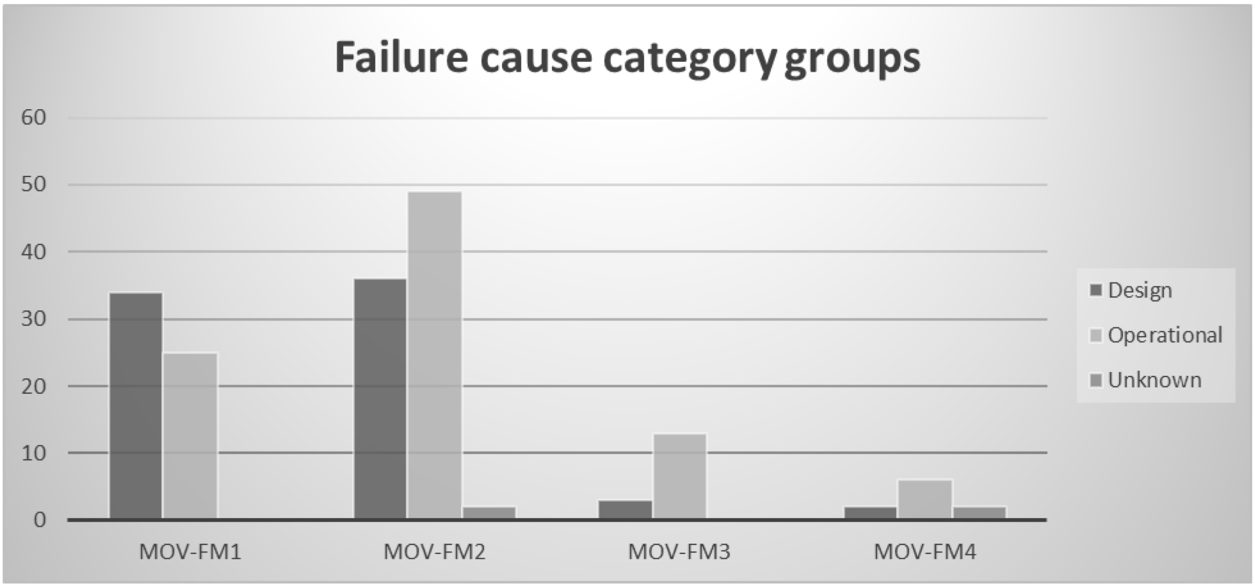
Table 4.2 presents the failure mechanism categories and their sub-categories, the failure cause categories[5]. In Figure 4.2, the failure mechanism categories are presented with respect to the failure cause category groups. The most common failure mechanism category is "electrical and I&C failures", which was assigned to about half of the events. The main sub-category of these events was "wrong setpoints or drift of limit switches" with a slight over-representation of operational failure cause. Failure mechanisms that caused an impeded movement of the valve due to mechanical problems involved about one-third of the events and these failures were mainly due to "loose/broken/degraded piece parts". About 10% of the events involved leakage of the main valve, mainly due to an operational failure cause and often due to ageing.

Table 4.2. Failure analysis assessment matrix

	Failure cause category								
	Design			**Operational**			**Unknown**		
Failure mechanism	**C/M**	**D**	**D-MOD**	**O1**	**O2**	**O3**	**U**	**Total**	**Percent**
MOV-FM1 Movement of the main valve impeded by mechanical problems	**14**	**20**		**12**	**4**	**9**		**59**	**34%**
MOV-a1 Insufficient quantity/quality of lubricant		2		2	1	1		**6**	3%
MOV-a2 Bonding	5	5		2		1		**13**	8%
MOV-a3 Loose/broken/degraded piece parts	9	11		8	3	3		**34**	20%
MOV-a4 Mechanical misalignments		2				4		**6**	3%
MOV-FM2 Electrical and I&C failures	**3**	**32**	**1**	**31**	**5**	**13**	**2**	**87**	**51%**
MOV-b1 Loss of power supply		1		2		6		**9**	5%
MOV-b2 Failures of breakers	1	2		1	2			**6**	3%
MOV-b3 Failures of the MOVs I&C		5		1	1	2		**9**	5%
MOV-b4 Failure of the motor drive		5					1	**6**	3%
MOV-b5 Failure of limit switches (torque, way, overcurrent…)		5		8	1	2		**16**	9%
MOV-b6 Wrong setpoints or drift of limit switches	2	14	1	19	1	3	1	**41**	24%
MOV-FM3 Main valve leaking		**3**		**6**	**6**	**1**		**16**	**9%**
MOV-c1 Seat/disk/o-ring surface degradation		3		6	6	1		**16**	9%
MOV-FM4 Other		**1**	**1**	**3**		**3**	**2**	**10**	**6%**
MOV-d1 Other/Unknown		1	1	3		3	2	**10**	6%
Total	**17**	**56**	**2**	**52**	**15**	**26**	**4**	**172**	**100%**
Percent	**10%**	**33%**	**1%**	**30%**	**9%**	**15%**	**2%**	**100%**	

5. 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.

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



In Table 4.3, the failure analysis assessment matrix is presented with consideration of the degree of the severity of the events.

Section 4.3 discusses the severe events. The engineering analysis of the less severe events is divided into two sections, Section 4.4 and 4.5, and presents the insights based on the failure cause categories.

Table 4.3. Failure analysis assessment matrix with the degree of severity

	Failure cause category groups[6] (severe[7] | less severe[8])				
Failure mechanism category	**Design**	**Operational**	**Unknown**	**Total**	**Percent**
Movement of the main valve impeded by mechanical problems	7 | 27	6 | 19	0 | 0	**13 | 46**	**31% | 35%**
Electrical and I&C failures	16 | 20	9 | 40	0 | 2	**25 | 62**	**60% | 48%**
Main valve leaking	0 | 3	1 | 12	0 | 0	**1 | 15**	**2% | 12%**
Other	0 | 2	3 | 3	0 | 2	**3 | 7**	**7% | 5%**
Total	**23 | 52**	**19 | 74**	**0 | 4**	**42 | 130**	**100% | 100%**
Percent	**55% | 40%**	**45% | 57%**	**0% | 3%**	**100% | 100%**	

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. In case of a single event in a category, the failure mechanism description is given in full. The severe events, i.e. complete and partial CCFs, were almost entirely observed with a failure

6. Design = C/M, D and D-MOD, Operational = O1, O2 and O3

7. Severe = Complete and Partial CCF

8. Less severe = All other event severities

mechanism related to mechanical and electrical-related problems. Only a single severe event was caused by leakage and no events had a failure cause related to design modifications. In addition, construction manufacturing deficiencies and ageing problems were only observed for a few events.

The main problem of the severe events was related to electrical design issues, more specifically due to setpoints exceeding the torque switch limit. I&C failures appear more likely than other types of failure mechanisms to result in severe CCF events that completely fail multiple components in a group. Another noteworthy insight is that about 52% of the events with an operational failure cause were caused by operator performance errors, such as incorrect adjustments and tightening, inadequate back-fitting (wiring) and modifications, and improper installation.

Table 4.4. Failure analysis assessment matrix for complete and partial CCF events

Failure cause category	**Movement of the main valve impeded by mechanical problems**	**Electrical and I&C failures**	**Main valve leaking**	**Other**	**Total**
Deficiencies in design, construction, manufacturing	**7**	**16**	**0**	**0**	**23**
C/M Deficiency in construction or manufacturing of hardware	Problems related to failed piece parts (a3) and the events involve improper material and fatigue of piece parts. (3)				**3**
D Deficiency in design of hardware	Problems related to categories a1-a3. Failures involved friction, fatigue and wear. (4)	11 of 16 events with wrong setpoints (b6), exceeding torque switch limit. Other problems with fuse fault (b1), faulty control card (b3), loss of automatic control (b3), breaker failure (b4), compression springs to torque switch (b5). (16)			**20**
D-MOD Design modification					**0**
Deficiencies in operation	**6**	**9**	**1**	**3**	**19**
O1 Deficient procedures for maintenance and/or testing	Dried grease led to insufficient opening torque of the MOVs (a1). (1)	Different problems across the failure mechanism sub-categories. (5)		Deficiency in the interpretation of safety rules and procedures regarding the four isolation MOVs of the boron accumulator. Fuses were removed and not replaced which led to failure to open the MOVs for containment isolation. (2)	**8**
O2 Insufficient attention to ageing of piece parts	Ageing of the stuffing box packing led to failure to close two MOVs (a3). (1)				**1**
O3 Insufficient qualification and/or work control after or during maintenance/test or operation	Problems caused by operational errors, such as incorrect adjustments and tightening. (4)	Problems related to inadequate back-fitting (wiring) and modifications. (4)	Improper installation of the retaining ring led to leakage of two safety injection MOVs. (1)	Isolation MOVs of boron accumulators were locked out in closed position prematurely during plant shutdown. (1)	**10**

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

Deficiencies in the design of hardware involve about 40% of the less severe events. The failure mechanism categories related to mechanical and electrical problems are almost equally common, with a slightly higher percentage of mechanical issues. The main failure cause category is deficiencies in the design.

In general, failures are occurring slowly after several cycles of the valve. It is unlikely that all valves would fail at the same time. Regular monitoring during outages could prevent failure.

For events with construction and manufacturing deficiencies, mechanical problems that impede the valve movement have a much higher percentage of failure compared to the electrical I&C problems. For events with design deficiencies, the mechanical and electrical I&C problems are equally common. The failures involve issues with different piece parts, but also bonding and mechanical misalignments. Only two events were due to a design modification and only three events resulted in leakage due to problems related to the wear and degradation of seals.

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 matrix findings for deficiencies in design, construction or manufacturing

Failure cause category	Movement of the main valve impeded by mechanical problems	Electrical and I&C failures	Main valve leaking	Other	Total
Deficiencies in design, construction, manufacturing	**27**	**20**	**3**	**2**	**52**
C/M Deficiency in construction or manufacturing of hardware	Problems relate to bonding (a2) and loose/broken/degraded piece parts (a3). The bonding issues involved higher friction factor, higher packing load and lack of gap width. (5) Other problems relate to the motor pinion keys, such as cracks and shearing. In addition, issues with dimensioning, such as too short bolts and manufacturer design error. (6)	Surface degradation on contactors (b2). Two events with problems related to MOV-b6. A low setting of actuator torque release led to failure of one MOV (the other MOV's actuator was replaced). The second event involved a fabrication deficiency, which led to the MOVs being not sufficiently close to design basis system conditions. (3)			**14**
D Deficiency in design of hardware	Problems with piece parts (a5) relate to some kind of wear, fatigue, or vibration issues, and involve unique type of failures. Design deficiencies did not properly account for these conditions. Failures are occurring slowly after several cycles of the valve. It is unlikely that all valves would fail at the same time. Regular monitoring during outages could prevent failure. Four events involved bonding (a2) with, ageing, friction and sticky coating as main cause. Two events were mechanical misalignments (a4). (16)	Problems relate to all sub-categories (breakers, I&C, motor drive, limit switch, setpoints) except b1. The failures of the breaker affected the switch and coupling contactors. I&C failures due to affected cards and wiring error. Different unique mechanisms led to failure of the actuator and limit switches. Setpoint drift was the main cause in category b6. (16)	Problems related to wear and degradation of seals. (3)	Defect in the electronic control of the component led to failure of two out of three MOVs. (1)	**36**
D-MOD Design modification		After a modification of the MOVs inside containment, wrong settings of torque limit switches were used (b6). (1)		Design modification error of MOVs resulted in ice plug in backwash line. (1)	**2**

4.5. Failure analysis assessment of deficiencies in operation

Deficient procedures are the most common cause of failure among the less severe events assigned to deficiencies in operation and involve about 57% of the less severe events. Deficiencies due to ageing and operator errors are about equally common. A total of 12 events were due to leakage of the main valve. Observed causes were deficient procedures and insufficient attention to ageing.

The failure mechanism category related to electrical I&C problems is most common. Again, as observed among the severe events, failures related to wrong, or drift of, setpoints are very common. Thus, there is evidence of such failures sometimes being detected in time; if not detected, they often progress to severe events.

Failure mechanisms across all categories are observed with deficient procedures for maintenance and/or testing, but mainly for electrical I&C. The observed events attributed to the failure cause of "insufficient attention to the ageing of piece parts" mainly involved wear. These events tend to evolve slowly over time and can be prevented by an effective ageing management programme. Events due to operator performance errors involve mainly mechanical and I&C problems.

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 matrix findings for deficiencies in operation

Failure cause category	Movement of the main valve impeded by mechanical problems	Electrical and I&C failures	Main valve leaking	Other	Total
Deficiencies in operation	**19**	**40**	**12**	**3**	**74**
O1 Deficient procedures for maintenance and/or testing	Problems mainly due to looseness and wear of piece parts (8). Other problems with bonding which caused failure to open the MOVs. In addition, one event involved unsuited lubricant. (11)	18 of the 26 events were related to wrong/drift of setpoints. Issues were caused by incorrect setting and insufficient control. Other problems relate to the limit switch (7) that was out of adjustment due to procedures or other reasons. (26)	The leaking problems involved cyclic fatigue, insufficient packing material with improper maintenance, and steam cutting that caused degraded seals. (6)	High overpressure led to high torque to overcome the increased frictional force and multiple operations of the valves resulted in heated and damaged MOVs. (1)	**44**
O2 Insufficient attention to ageing of piece parts	Two events with ageing effect, one due to grease and the other event involved ageing of O-rings and seals. (2)	The ageing problems involved mainly wear that affected the limit switch and contacts. (5)	All leakage events attributed to ageing was caused by wear. (6)		**14**
O3 Insufficient qualification and/or work control after or during maintenance/test or operation	Problems related to deficient mounting of internal component parts. For example, use of wrong grease, missing screws, too low tightening force, erroneous mounting of discs, seats and wedges. (5)	Problems related to the power supply (b1) and involved faulty cabling and re-assembly. Other problems related to improper maintenance, such as incorrect adjustments of the limit switch (b5). Two events involved calculation and calibration errors (b6). (9)		The wrong type of lamp replacement for indications led to a miniature circuit breaker to release resulting in failure to open/close one MOV. (2)	**16**

4.6. Interesting event categories

Table 4.7 presents the statistics per interesting event code, which are defined in the ICDE General Coding Guidelines. An event can be assigned to more than one code. About 78% of the events were marked as “no code applicable”, meaning that the event is not of any special interest.

Table 4.7. Applied interesting event codes

Interesting event codes	No. of events	Percent
Complete CCF	9	5%
CCF Outside planned test	9	5%
Component not capable	14	8%
Multiple defences failed	1	1%
Sequence of multiple CCF failure mechanisms	0	0%
Multiple systems affected	4	2%
Common cause initiator	0	0%
Safety culture	6	3%
Multi-Unit CCF	17	10%
No code applicable	134	78%
Total codes	194	

The insights from the applied interesting event codes are:

- Multi-unit CCF: A total of 17 events (10%) were marked as multi-unit CCFs. One interesting example is an event where the D2O isolation MOVs may not open in case of a large LOCA due to high differential pressure (exceeding the torque limit switch). This event was reported as eight partial CCF events and affected four units. Most of the multi-unit events share some organisation factor or design but are not sharing components between units. A detailed analysis of multi-unit aspects is addressed in another ICDE topical report, see (NEA, 2019a).
- Complete CCF: This event code sums up all the complete CCFs. It is worth noting that the share of complete CCFs is relatively low compared to the complete ICDE database.
- CCF outside planned testing: Nine events were marked as interesting due to the fact that they occurred outside planned testing. In one such event, the manufacturer staff used unsuited grease when making a modification of MOVs, leading to a potential CCF failure of valves during an accident situation when the temperatures at the valves are much higher than during normal operation and testing. A detailed analysis of testing inadequacies is addressed in another ICDE topical report; see (NEA, 2019b).
- Component not capable: 14 events revealed deficiencies in performing the component’s function over a long period of time. One example is an event where a higher-than-expected (valve disc) friction factor led to failure of an MOV and the potential for other valves to be affected.
- Safety culture: Six events were marked as interesting from a safety culture perspective. One event showed evidence of deficiency in the interpretation of safety rules and procedures regarding the four isolation MOVs of the boron accumulator. In another event, fuses were removed and not replaced, which led to failure to open the MOVs for containment isolation.

5. Summary and conclusions

Organisations from Canada, Finland, France, Germany, Japan, Korea, the Netherlands, Spain, Sweden, Switzerland and the United States contributed CCF data of MOV to this data exchange. A total of 172 ICDE events were analysed from nuclear power plants in these countries.

These reported ICDE events were reviewed in Chapters 3 and 4 of this report with respect to the degree of failure, failure cause and failure mechanism. Several conclusions can be drawn from this data review, as listed below.

- The number of analysed ICDE events has significantly expanded since the publication of the ICDE report on MOV CCF data in 2001 (NEA, 2001). The current data show no noticeable differences in the distribution of event causes, coupling factors, and other CCF coding compared to the previous report. One noteworthy difference from the 2001 report is that the rate of CCF event occurrence appears to have decreased in recent years.
- The data collection is ongoing in several countries and the observations for 2010 onward are expected to increase to similar levels as observed in the 1995-2010 period. Trend analysis of the number and impact of reported events per year is a topic for continued work.
- The relative occurrence of partial CCFs is about a factor 1.5 higher compared to the complete ICDE database, but the occurrence of complete CCF is about a factor 0.5 lower.
- The CCF root causes "solely or predominant design" and "solely or predominant procedures" were equally common, at about 45%.
- Design deficiencies are more common among the severe events (55%). The less severe events are more commonly caused by deficiencies in operation (57%).
- The main problem of the severe events was related to electrical I&C design issues, more specifically due to setpoints exceeding the torque switch limit. I&C failures appear more likely than other types of failure mechanisms to result in severe CCF events that completely fail multiple components in a group.
- Failures or component degradations related to wrong, or drift of, setpoints are very common, both for severe and less severe events. Failures are sometimes detected in time; if not detected, they often progress to severe events.
- About 52% of the severe events (ten events) with an operational failure cause were caused by operator performance errors.
- About 10% of the events involved leakage of the main valve, mainly due to an operational failure and often due to an insufficient ageing management programme.
- About 17% of the events had a latent time factor of more than half a year, which may indicate an overly long test interval of the components or inadequate test procedures.

The lessons learnt for the engineering aspects are as follows:

- Deficiencies in design tend to result in more severe events for MOVs and most problems are caused by electrical I&C design issues, with the most common issue involving setpoints exceeding the torque switch limit. Recurrent control of setpoint and verification of these after test and maintenance have the possibility to reduce the risk of CCF. Without such surveillance and control, these types of problems tend to develop into severe CCF events, as seen in the data set.

- Degradation of components until failure occurs slowly. Consequently, adequate operational procedures, ageing management and operational actions can keep events from happening or detect the degradation before complete failure of the component occurs.
- Operator performance errors result in severe events. To prevent such errors, it is vital to have adequate procedures, written work plans, training of personnel and in general a well-established safety culture. In addition, the verification of operability after actions is important to minimise such failure causes.
- A sufficient ageing management programme, in combination with frequent inspections, to detect wear and degradation of valve internals can prevent leakage in valves.

6. References

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Appendix A. Overview of 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, with the project 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 NEA´s website: www.oecd-nea.org/jcms/pl_25090.

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 requirements 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 co-ordinators 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. 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[9]. 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, the ICDE project is

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

interested in collecting complete CCF events as well as partial CCF events. The 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.

Appendix C. 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 re-occurring. 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 item 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:

a) 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, even though they were operated and maintained as 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.

b) 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.

c) 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:

- 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.)
- 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.)
- 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 (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. No CCF event.

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 defense-in-depth level 2.*
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.*

Interesting CCF event codes	**Description** ***Purpose***
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.*
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 the 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.

Interesting CCF event codes	**Description** ***Purpose***
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 that 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 D. Workshop form

Study the events in your assigned failure analysis assessment matrix cell. What can you observe and conclude?

The objective is to form summarising texts in your assigned cells of the matrix. The summarising texts should be documented in a PowerPoint-file and presented during the round table discussion. Aspects to consider could be:

- Common failure mechanism issue or aspect? Type of failures within the failure mechanism sub-category?
- Common event triggers (initiators)?
- Common degree of event severity? Can anything be concluded for the most severe (complete/partial CCF) events?
- Common event causes, CCF root causes, or other coding?
- Can any type of general improvement or defence be identified to prevent your events from happening again?

- *Design of system or site, Design of component, Surveillance of component or Maintenance procedure for component, Testing procedure, Operation procedure for component, Management system of plant (QA of vendor, spare parts management, training of personnel, sufficient resources/staff, etc.)*

- Is any event of specific interest, including a topical aspect or a good example to be explicitly presented in the report?

Also, if you have time,

- Study the whole matrix and see if more general/high-level conclusions can be drawn based on the distribution of events across failure mechanisms and failure causes.

Do you have any comments on the defined failure mechanism categories or sub-categories?

Appendix E. Failure mechanism descriptions

Severe events (complete and partial CCFs)

Failure cause category [10]	Failure mechanism category [11]	Failure mechanism sub-category [12]	Total	Failure mechanism description
C/M	MOV-FM1	MOV-a3	**1**	Improper material caused shearing of the MOVs motor pinion keys.
C/M	MOV-FM1	MOV-a3	**2**	Nucleation and growth of fatigue type cracks on Bakelite pinions of MOVs.
D	MOV-FM1	MOV-a1	**1**	Combination of under-dimensioning (design) of actuator/torque limits and at the same time valve stiffness (lubricant drying/packing friction) led to failure to open two MOVs.
D	MOV-FM1	MOV-a2	**1**	Pressure locking of the valve resulted in too high friction forces, which led to two inoperable MOVs.
D	MOV-FM1	MOV-a3	**1**	A broken anti-rotation device (key) due to low cycle fatigue or sudden brittle failure prevented two MOVs to close.
D	MOV-FM1	MOV-a3	**1**	Abnormal wear of the brake surface led to insufficient brake force of the motor brakes, which caused rupture of the cardan joint of the remote drive of two MOVs.
D	MOV-FM2	MOV-b1	**1**	Fuse faults in circuits led to failure of two MOVs.
D	MOV-FM2	MOV-b3	**1**	Faulty control card, which was detected in the main control room, prevented two MOVs from opening.
D	MOV-FM2	MOV-b3	**1**	Loose sliding link (piece part for switching between automatic and local control) led to disabled automatic control of three MOVs.
D	MOV-FM2	MOV-b4	**1**	The electrical brakes of the motors to the two MOVs remained closed.
D	MOV-FM2	MOV-b5	**1**	Compression springs in the torque switch assembly were weakened by vibration, which led to failure of two MOVs.
D	MOV-FM2	MOV-b6	**1**	Design deficiency (matching of the valve operator with the spring pack) coupled with instrument errors caused an overlap between the normal closed torque switch and the overload heater trip set point resulting in tripping the thermal overload heater of two MOVs.
D	MOV-FM2	MOV-b6	**8**	The D2O isolation MOVs may not open in case of a large LOCA due to high differential pressure (exceeding torque limit switch).
D	MOV-FM2	MOV-b6	**1**	The torque switch limits were adjusted (calculated) incorrectly which prevented the full operation of the MOVs.
D	MOV-FM2	MOV-b6	**1**	Too low torque limit led to failure to close two MOVs.
O1	MOV-FM1	MOV-a1	**1**	Dried grease led to insufficient opening torque of the MOVs.
O1	MOV-FM2	MOV-b1	**2**	MOVs were left locked out electrically in a closed position (need to be open) during the test due to inadequate test procedure.
O1	MOV-FM2	MOV-b2	**1**	Dirty contacts and a broken terminal block led to deficient component protections and failure of two MOVs.
O1	MOV-FM2	MOV-b5	**1**	Torque switch malfunction during manoeuvring test of both MOVs.
O1	MOV-FM2	MOV-b6	**1**	Normal wear led to failure of limit switches resulting in failure of three MOVs.
O1	MOV-FM4	MOV-d1	**1**	Deficiency in interpretation of safety rules and procedures regarding the four isolation MOVs of the boron accumulator.
O1	MOV-FM4	MOV-d1	**1**	Fuses were removed and not replaced which led to failure to open the MOVs for containment isolation.
O2	MOV-FM1	MOV-a3	**1**	Ageing of the stuffing box packing led to failure to close two MOVs.
O3	MOV-FM1	MOV-a2	**1**	Thermal expansion led to increased friction, which prevented the opening of both MOVs.
O3	MOV-FM1	MOV-a3	**1**	The stuffing box was incorrectly tightened which prevented two MOVs to fully open.

10. The definitions of the Failure cause category acronyms are found in Section 4.1.

11. The definitions of the Failure mechanism category acronyms are found in Section 4.1.

12; The definitions of the Failure mechanism sub-category acronyms are found in Section 4.1.

Failure cause category [10]	Failure mechanism category [11]	Failure mechanism sub-category [12]	Total	Failure mechanism description
O3	MOV-FM1	MOV-a4	**1**	False adjustment during valve installation led to jamming of both MOVs.
O3	MOV-FM1	MOV-a4	**1**	Operating personnel over-torqued MOVs in the open direction resulting in a failure to close with the motor operator.
O3	MOV-FM2	MOV-b1	**1**	During rewiring of MOVs, open circuited fuses were installed which prevented the operation of six MOVs.
O3	MOV-FM2	MOV-b1	**1**	Fuses were removed and not replaced which led to failure to open both MOVs.
O3	MOV-FM2	MOV-b3	**1**	Design modifications at the logic of the containment isolations were erroneously not applied for MOVs in the residual heat removal (RHR) system, which prevented containment isolation during the plant shutdown phase.
O3	MOV-FM2	MOV-b6	**1**	Two MOVs had mispositioned wire leads, which caused failure to open the MOVs. One was attributed to personnel error and one was attributed to management deficiency.
O3	MOV-FM3	MOV-c1	**1**	Improper installation of the retaining ring led to leakage of two safety injection MOVs.
O3	MOV-FM4	MOV-d1	**1**	Isolation MOVs of boron accumulators were locked out in closed position prematurely during plant shutdown.

Less severe events (CCF impaired and complete/incipient/single impairment)

Failure cause category [13]	Failure mechanism category [14]	Failure mechanism sub-category [15]	Total	Failure mechanism description
C/M	MOV-FM1	MOV-a2	**1**	High packing load caused mechanical binding preventing the operator from fully closing the MOV.
C/M	MOV-FM1	MOV-a2	**3**	Higher (valve disc) friction factor than expected led to the failure of a MOV and the potential for other valves to be affected.
C/M	MOV-FM1	MOV-a2	**1**	Lack of gap width of the valve led to sluggishness and tripping of the torque switch of two MOVs.
C/M	MOV-FM1	MOV-a3	**1**	Design error by the manufacturer of the MOV plug (wrong dimensions due to error in vendor drawing).
C/M	MOV-FM1	MOV-a3	**2**	Improper material caused shearing of the MOVs motor pinion keys.
C/M	MOV-FM1	MOV-a3	**1**	Multiple causes involved - procedure and design deficiencies and operating experience review programme inadequacies. Original construction design error resulted in pump minimum flow valves not being installed with the valve stem in the vertical, pointing upward orientation. Since these MOVs do not have wedge springs they have potential to prematurely seat failing to fully close.
C/M	MOV-FM1	MOV-a3	**1**	Nucleation and growth of fatigue type cracks on Bakelite pinions of MOVs.
C/M	MOV-FM1	MOV-a3	**1**	The MOVs motor was mounted with bolts, which were too short to properly attach the motor to the valve, which resulted in the motor to come off, and the power cable was stretched and a short circuit occurred.
C/M	MOV-FM2	MOV-b2	**1**	Surface degradation on contactors led to failure to open two MOVs.
C/M	MOV-FM2	MOV-b6	**1**	A low setting of actuator torque release led to failure of one MOV (the other MOV's actuator was replaced).
C/M	MOV-FM2	MOV-b6	**1**	Fabrication deficiency led to MOVs would not sufficiently close against design basis system conditions.
D	MOV-FM1	MOV-a1	**1**	Harsh environmental operating conditions led to dried grease causing high friction of the limit switch, which led to failure to close one MOV and the other valve in a degraded state.
D	MOV-FM1	MOV-a2	**1**	A missing hole in the valve housing resulted in no depressurisation and the gate valve disc was pushed too tight to the side of the seat, which led to a failed and a degraded state of the two MOVs.
D	MOV-FM1	MOV-a2	**1**	Ageing and wearing led to mechanical binding of two MOVs.
D	MOV-FM1	MOV-a2	**1**	Friction related problems caused failed the MOVs to seat tightly.
D	MOV-FM1	MOV-a2	**1**	Sticky coating on the gear wheel of the time delay relay led to failure of the control unit to the MOV (others were incipient impaired).
D	MOV-FM1	MOV-a3	**1**	Broken gear of the MOV.
D	MOV-FM1	MOV-a3	**1**	Cracks in valve yolk of the MOVs.

13. The definitions of the Failure cause category acronyms are found in Section 4.1.

14. The definitions of the Failure mechanism category acronyms are found in Section 4.1.

15 The definitions of the Failure mechanism sub-category acronyms are found in Section 4.1.

Failure cause category [13]	Failure mechanism category [14]	Failure mechanism sub-category [15]	Total	Failure mechanism description
D	MOV-FM1	MOV-a3	**1**	Incorrect configuration or assembly of the MOV actuator (one valve with motor gear contacting the trip finger, and the other valve had an improperly installed washer with the spring which led to the close torque to operate erratically).
D	MOV-FM1	MOV-a3	**1**	Mechanical wearing (loss of self-locking between a screw and a nut) caused the MOV to re-bounce after closure.
D	MOV-FM1	MOV-a3	**1**	The wedge between the spindle and the spindle nut on the actuator had fallen off (probably vibrated off) which led to failure of one MOV (the other valve was locked with Loctite).
D	MOV-FM1	MOV-a3	**1**	Two MOVs failed to open. Stern and spindle nut was replaced (cause not clear).
D	MOV-FM1	MOV-a3	**1**	Weak dimensioning of locking pins at several MOVs led to failures.
D	MOV-FM1	MOV-a3	**1**	Wear of the steam nut of the MOVs.
D	MOV-FM1	MOV-a3	**1**	Vibration caused cyclic fatigue, accelerated by mechanical overload caused by high differential pressure across two MOVs, which led to valve stem nut wear-out and break.
D	MOV-FM1	MOV-a4	**1**	A gate valve was used in globe valve application, which led to misalignment of the gate valve seat over time resulting in failure to close two MOVs.
D	MOV-FM1	MOV-a4	**1**	Too small mechanical tolerances in the MOV design led to high friction in the bearings, which resulted in all four valves to be in a degraded state.
D	MOV-FM2	MOV-b2	**1**	A deformation of the cover of the switch prevented the opening of the MOV.
D	MOV-FM2	MOV-b2	**1**	Design error concerning the materials composition of a certain coupling contactor housing led to phosphate deposits in the coupling contactors, resulting in one complete failure and one incipient failure of the two MOVs.
D	MOV-FM2	MOV-b3	**1**	Contact faults of the interposing logic system cards of the hand switches to two MOVs.
D	MOV-FM2	MOV-b3	**1**	Oxide formation of the controller card prevented manoeuvre of one MOV.
D	MOV-FM2	MOV-b3	**1**	Wiring error (missing and faulty connections) led to failure to open of two MOVs.
D	MOV-FM2	MOV-b4	**1**	Actuator problem led to not being able to supply enough thrust to the MOVs.
D	MOV-FM2	MOV-b4	**1**	Hydraulic locking of the valve bonnet led to sustained operation at locked-rotor current, which caused failed actuator motor and failure to open the MOVs.
D	MOV-FM2	MOV-b4	**1**	The valve actuator has a great closing torque, which causes a hard closing of the valve and shaking affecting the switch to open the valve, which stops the valve, resulting in failure to open the MOV.
D	MOV-FM2	MOV-b4	**1**	Water ingress through actuator led to failure of two MOVs.
D	MOV-FM2	MOV-b5	**1**	Binding in the torque switch led to degradation of one MOV.
D	MOV-FM2	MOV-b5	**1**	Due to the original valve operator selection criteria using less conservative factors, the outboard primary containment spray isolation MOVs had an inadequate torque and thrust capability.
D	MOV-FM2	MOV-b5	**1**	High differential pressure in the system led to insufficient torque protection of MOVs.
D	MOV-FM2	MOV-b5	**1**	Limited design margins associated with the valve operators (adjustment of the limit switches is very sensitive) led to two MOVs to "over-travel" in the open direction (excessive flow had no safety impact).
D	MOV-FM2	MOV-b6	**1**	Set point for limiting valve stroke switches drifted low for one MOV and later high for another MOV.
D	MOV-FM2	MOV-b6	**1**	The torque setting had dropped resulting in failure to open one MOV (the other two valve's settings were adjusted as precautionary measure).
D	MOV-FM2	MOV-b6	**1**	Torque switch set point too high which led to failure of two MOVs.
D	MOV-FM3	MOV-c1	**1**	Internal leakage due to degraded seals of two MOVs.
D	MOV-FM3	MOV-c1	**1**	Normal wear of isolation valves led to leakage and degraded state of all MOVs.
D	MOV-FM3	MOV-c1	**1**	Unknown cause, but MOVs were leaking.
D	MOV-FM4	MOV-d1	**1**	Defect in the electronic control of the component led to failure of two out of three MOVs.
D-MOD	MOV-FM2	MOV-b6	**1**	After a modification of the MOVs inside containment, wrong settings of torque limit switches was used.
D-MOD	MOV-FM4	MOV-d1	**1**	Design modification error of MOVs resulted in ice plug in backwash line.
O1	MOV-FM1	MOV-a1	**1**	The MOV's stem-to-stem nut nickel-based lubricant led to degraded output thrust of the valve operator.
O1	MOV-FM1	MOV-a2	**1**	Coating on the MOVs spindle led to insufficient opening torque.
O1	MOV-FM1	MOV-a2	**1**	Mechanical binding caused increased opening force, which led to failure to open one MOV (other degraded).
O1	MOV-FM1	MOV-a3	**1**	Excessive wear on the internal stern nut led to failure of both MOVs.
O1	MOV-FM1	MOV-a3	**1**	Improper material caused shearing of the MOVs motor pinion keys.
O1	MOV-FM1	MOV-a3	**1**	Loose bolts of actuators to MOVs.

Failure cause category [13]	Failure mechanism category [14]	Failure mechanism sub-category [15]	Total	Failure mechanism description
O1	MOV-FM1	MOV-a3	**1**	Loose/missing actuator bolts caused impairments of the four MOVs.
O1	MOV-FM1	MOV-a3	**1**	Loose/missing actuator bolts caused impairments of two MOVs.
O1	MOV-FM1	MOV-a3	**1**	Metal Swarfs inside the valve, which were inserted due to a design engineering improvement of the locking pin in the past, led to failure close the MOVs.
O1	MOV-FM1	MOV-a3	**1**	Normal wear of MOVs prevented the valves to fully close.
O1	MOV-FM1	MOV-a3	**1**	Two MOVs were found with loose bolts.
O1	MOV-FM2	MOV-b3	**1**	Erroneous setting of a limit switch led to degradation (leakage) of two MOVs.
O1	MOV-FM2	MOV-b5	**1**	A limit switch fuse failed due to ageing causing loss of power to the first MOV. The second MOV failed due to loose washers, which grounded the motor. CCF event with low shared cause and time factor.
O1	MOV-FM2	MOV-b5	**1**	Grease on torque switch contacts prevented contacts from closing circuit, which prevented closure of the MOV.
O1	MOV-FM2	MOV-b5	**1**	Inadequate procedures for testing and checking led to faulty contactors preventing the MOVs to properly close.
O1	MOV-FM2	MOV-b5	**2**	Oxidation on the open torque switch contacts causing the motor to stop the valve movement before the valve was fully open (Oxidation is an expected occurrence over time in this atmosphere).
O1	MOV-FM2	MOV-b5	**2**	The valve operators limit switch was out of adjustment, which caused failure of the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Faulty contactors led to valve operations exceeding time limits to open MOVs.
O1	MOV-FM2	MOV-b6	**1**	High torque settings cause relaxation of springs, which led to actuator outside limits for all four MOVs.
O1	MOV-FM2	MOV-b6	**1**	Inadequate torque switch setting led to tripping on overload while closing two MOVs.
O1	MOV-FM2	MOV-b6	**1**	Inappropriate limits of the torque switches led to failure to fully open the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Incorrect setting (too low) of the torque switch led to tripping of the circuit breaker to the MOV (the other valve was adjusted as precaution).
O1	MOV-FM2	MOV-b6	**1**	Incorrect setting of torque led to no closing indication of the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Insufficient control of set points of torque switch to the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Insufficient thrust of the actuator close torque switch to close the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Insufficient valve operator closing thrust led to two degraded MOVs.
O1	MOV-FM2	MOV-b6	**1**	Limit switch was out of adjustment, which led to excessive opening travel of the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Limit switches being out of adjustment resulted in leakage of two MOVs.
O1	MOV-FM2	MOV-b6	**1**	Preventive maintenance increased the closing torque, which led to the MOVs to trip on the torque limiter on opening.
O1	MOV-FM2	MOV-b6	**1**	Set point drift (assumed) led to degraded overcurrent protection, which could have caused damage to the valve actuator motor of the MOVs.
O1	MOV-FM2	MOV-b6	**2**	Set point drift or a cyclic loading of the torque switch setting led to degraded operability to open the MOVs.
O1	MOV-FM2	MOV-b6	**1**	Too high closing torque led to failure to open one MOV.
O1	MOV-FM2	MOV-b6	**2**	Too low torque limit led to degraded function to close both MOVs.
O1	MOV-FM3	MOV-c1	**1**	Cyclic fatigue resulted in wear on all seating surfaces, which caused leaking MOVs.
O1	MOV-FM3	MOV-c1	**4**	Insufficient packing material and improper maintenance led to leaking MOVs.
O1	MOV-FM3	MOV-c1	**1**	Steam cutting probably caused minor indications on the wedge and in-body seats of the MOVs, which led to degraded valve seal and leakage.
O1	MOV-FM4	MOV-d1	**1**	High overpressure led to high torque to overcome the increased frictional force and multiple operations of the valves resulted in heated and damaged MOVs.
O2	MOV-FM1	MOV-a1	**1**	Two perhaps related and similar failure causes, ageing grease for one MOV and micro switch problems for another, led to excessive friction in valve operation.
O2	MOV-FM1	MOV-a3	**1**	Ageing of O-rings and seals in motor operated butterfly valves allowed penetration of water into corrodible areas of the valves which led to corrosion product build-up and consequently, to sluggishness of the MOVs.
O2	MOV-FM1	MOV-a3	**1**	Excessive leakage past MOVs was attributed to wear and ageing.
O2	MOV-FM2	MOV-b2	**1**	Dust (in particular sulphur compounds) on the surface of the contactors led to high resistance values in the contactors resulting in failure of two MOVs.
O2	MOV-FM2	MOV-b2	**1**	Failure of breaker is unknown but attributed to normal wear and ageing of breaker components to the MOVs.
O2	MOV-FM2	MOV-b3	**1**	Wear-out/ageing caused the close contacts to hang-up, which prevented MOVs from closing.

Failure cause category [13]	Failure mechanism category [14]	Failure mechanism sub-category [15]	Total	Failure mechanism description
O2	MOV-FM2	MOV-b5	**1**	Faster than expected ageing led to a defective torque switch and the rotor on limit switch (piece part) to not be turning fully to proper position of a single MOV. Event reoccurred days later where excessive grease had accumulated on torque switch contacts.
O2	MOV-FM2	MOV-b6	**1**	Wear-out caused a defective torque switch, which led to two degraded MOVs.
O2	MOV-FM3	MOV-c1	**1**	Both MOVs failed local leak rate test (LLRT) due to normal wear.
O2	MOV-FM3	MOV-c1	**1**	Normal wear caused leakage of MOVs.
O2	MOV-FM3	MOV-c1	**2**	Normal wear of MOVs led to leakage.
O2	MOV-FM3	MOV-c1	**1**	Normal wear of valve seat and disc led to leakage of MOVs.
O2	MOV-FM3	MOV-c1	**1**	Wear-out of valve internals led to leakage of MOVs.
O3	MOV-FM1	MOV-a1	**1**	Manufacturer staff used unsuited grease when making a modification of MOVs leading to a potential CCF failure of valves during an accident situation when the temperatures at the valves are much higher than during normal operation and testing.
O3	MOV-FM1	MOV-a3	**1**	5 of 8 cap screws securing the actuator body to the valve yoke were missing and the other three were loose, which led to failure to open the MOV. For the other valve, the actuator key was not working which prevented the valve to open.
O3	MOV-FM1	MOV-a3	**1**	Too low tightening force of a nut caused the locking pins to only partially engage resulting in degraded state of the MOVs.
O3	MOV-FM1	MOV-a4	**1**	Erroneous mounting of the discs and seats of the two redundant MOVs led to leakage.
O3	MOV-FM1	MOV-a4	**1**	Two discs and the corresponding wedges of the gate valve of one MOV had been mounted inversely.
O3	MOV-FM2	MOV-b1	**2**	Human error led to faulty cabling connection, which prevented one MOV to close.
O3	MOV-FM2	MOV-b1	**1**	Human error led to faulty cabling connection, which prevented one MOV to open.
O3	MOV-FM2	MOV-b1	**1**	Wrong re-assembly caused a connection problem in the adapter of the actuator, which led to failure of one MOV (the others were incipient impaired).
O3	MOV-FM2	MOV-b3	**1**	Inappropriate use of cleaning product to clean relay, which caused it to become sticky causing failure to open MOVs.
O3	MOV-FM2	MOV-b5	**1**	Improper maintenance of MOVs. First case was a torque switch out of adjustment. Second case was a mispositioned motor wire lead holding a torque switch open.
O3	MOV-FM2	MOV-b5	**1**	Incorrect adjustment of the torque limiter caused a failure while attempting to open the MOV.
O3	MOV-FM2	MOV-b6	**1**	Incorrect calculation of torque switch set point led to degraded state during a demand of the MOVs.
O3	MOV-FM2	MOV-b6	**1**	Wrong calibration led to incorrect limit value of the actuator of the MOVs.
O3	MOV-FM4	MOV-d1	**1**	Wrong type of lamp replacement for indications led to a miniature circuit breaker to release resulting in failure to close one MOV.
O3	MOV-FM4	MOV-d1	**1**	Wrong type of lamp replacement for indications led to a miniature circuit breaker to release resulting in failure to open one MOV.
U	MOV-FM2	MOV-b4	**1**	Unknown cause, for the second MOV the actuator and contacts were replaced.
U	MOV-FM2	MOV-b6	**1**	Unknown cause, internal leakage of MOVs.
U	MOV-FM4	MOV-d1	**1**	Unknown cause, but MOVs failed their leak test.
U	MOV-FM4	MOV-d1	**1**	Unknown cause, MOVs exceeded closing times.