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Collection and Analysis of Common-cause Failures of Heat Exchangers

International Common-cause Failure Data Exchange (ICDE) Project Report

April 2013

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Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development

English text only

NUCLEAR ENERGY AGENCY
COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

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ICDE Project Report

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ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

The OECD is a unique forum where the governments of 34 democracies work together to address the economic, social and environmental challenges of globalisation. The OECD is also at the forefront of efforts to understand and to help governments respond to new developments and concerns, such as corporate governance, the information economy and the challenges of an ageing population. The Organisation provides a setting where governments can compare policy experiences, seek answers to common problems, identify good practice and work to co-ordinate domestic and international policies.

The OECD member countries are: Australia, Austria, Belgium, Canada, Chile, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, the Republic of Korea, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission takes part in the work of the OECD.

OECD Publishing disseminates widely the results of the Organisation's statistics gathering and research on economic, social and environmental issues, as well as the conventions, guidelines and standards agreed by its members.

NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1 February 1958. Current NEA membership consists of 31 countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Poland, Portugal, the Republic of Korea, the Russian Federation, the Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The European Commission also takes part in the work of the Agency.

The mission of the NEA is:

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

Specific areas of competence of the NEA include the safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information.

The NEA Data Bank provides nuclear data and computer program services for participating countries. In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

THE COMMITTEE ON THE SAFETY OF NUCLEAR INSTALLATIONS

The NEA Committee on the Safety of Nuclear Installations (CSNI) is an international committee made up of senior scientists and engineers with broad responsibilities for safety technology and research programmes, as well as representatives from regulatory authorities. It was created in 1973 to develop and co-ordinate the activities of the NEA concerning the technical aspects of the design, construction and operation of nuclear installations insofar as they affect the safety of such installations.

The committee's purpose is to foster international co-operation in nuclear safety among NEA member countries. The main tasks of the CSNI are to exchange technical information and to promote collaboration between research, development, engineering and regulatory organisations; to review operating experience and the state of knowledge on selected topics of nuclear safety technology and safety assessment; to initiate and conduct programmes to overcome discrepancies, develop improvements and reach consensus on technical issues; and to promote the co-ordination of work that serves to maintain competence in nuclear safety matters, including the establishment of joint undertakings.

The priority of the committee is on the safety of nuclear installations and the design and construction of new reactors and installations. For advanced reactor designs, the committee provides a forum for improving safety-related knowledge and a vehicle for joint research.

In implementing its programme, the CSNI establishes co-operative mechanisms with the NEA's Committee on Nuclear Regulatory Activities (CNRA), which is responsible for the Agency's programme concerning the regulation, licensing and inspection of nuclear installations with regard to safety. It also co-operates with the other NEA Standing Technical Committees as well as with key international organisations such as the International Atomic Energy Agency (IAEA) on matters of common interest.

PREFACE

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

The objectives of the ICDE Project are to:

a) Collect and analyse Common-cause failure (CCF) events over the long term so as to better understand such events, their causes, and their prevention;

b) Generate qualitative insights into the root causes of CCF events which can then be used to derive approaches or mechanisms for their prevention or for mitigating their consequences;

c) 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;

d) Generate quantitative insights and record event attributes to facilitate quantification of CCF frequencies in member countries; and

e) 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 openly. It is not the aim of those reports to provide direct access to the CCF raw data recorded in the ICDE data bank. The confidentiality of the data is a prerequisite of operating the project. The ICDE database is accessible only to those members of the ICDE Project Working Group who have actually contributed data to the data bank.

Database requirements are specified by the members of the ICDE Steering Group and are fixed in the ICDE coding guidelines. It is assumed that the data will be used by the members in the context of PSA/PRA reviews and application.

ACKNOWLEDGEMENTS

The following people have significantly contributed to the preparation of this report by their personal effort: Gunnar Johansson (ES-Konsult), Wolfgang Werner (SAC), Albert Kreuser (GRS), and in addition, the ICDE Steering Group and the people with whom they liaise in all participating countries are recognised as important contributors to the success of this study. Axel Breest has been the administrative NEA officer and contributed to finalising the report.

LIST OF ABBREVIATIONS AND ACRONYMS

BWR	Boiling Water Reactor
CCCG	Common Cause Component Group
CCF	Common Cause Failure
GCR	Gas Cooled Reactor (graphite or heavy water moderated), includes Magnox AGR, HTGR and HWGCR
HE	Heat Exchanger
HT-	General Failure mode - Failure of heat transfer
ICDE	International Common Cause Failure Data Exchange
I&C	Instrumentation and Control
NPP	Nuclear Power Plant
OA	Operating Agent
OP	Observed Population
NPP	Nuclear Power Plant
PHWR	Heavy Water moderated, Pressure tube Reactor
PRA	Probabilistic Risk Assessment
PSA	Probabilistic Safety Assessment
PWR	Pressurised Water Reactor
TS	Technical Specifications

ORGANISATIONS

AECB	Atomic Energy Control Board (Canada)
CNSC	Canadian Nuclear Safety Commission (Canada)
CSN	Consejo de Seguridad Nuclear (Spain)
CSNI	Committee on the Safety of Nuclear Installations
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit (Germany)
HSK	Hauptabteilung für die Sicherheit der Kernanlagen (Switzerland)
ENSI	Eidgenössisches Nuklearsicherheitsinspektorat / Swiss Federal Nuclear Safety Inspectorate (Switzerland)
IRSN	Institut de Radioprotection et de Sûreté Nucléaire (France)
JNES	Japan Nuclear Energy Safety Organisation (Japan)

KAERI	Korea Atomic Energy Research Institute (Republic of Korea)
NEA	Nuclear Energy Agency
NII	Nuclear Installations Inspectorate (UK)
NRC	Nuclear Regulatory Commission (USA)
OECD	Organisation for Economic Co-operation and Development
SKI	Sweden Nuclear Inspectorate (Sweden), see SSM
SSM	Swedish Radiation Safety Authority
STUK	Finish Centre for Radiation and Nuclear Safety (Finland)

GLOSSARY

- **Common Cause Event**: A dependent failure in which two or more component fault states exist simultaneously, or within a short time interval, and are a direct result of a shared cause.
- **Complete failure**. The component has completely failed and will not perform its function. For example, if the cause prevented a pump from starting, the pump has completely failed and impairment would be complete. If the description is vague this code is assigned in order to be conservative.
- **Component**: An element of plant hardware designed to provide a particular function.
- **Component Boundary:** The component boundary encompasses the set of piece parts that are considered to form the component.
- **Coupling Factor/Mechanism**: 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.
- **Defence**: Any operational, maintenance, and design measures taken to diminish the probability and/or consequences of common-cause failures.
- **Exposed Population (EP)**: A set of similar or identical components actually having been exposed to the specific common causal mechanism in an actually observed CCF event.
- **Failure**: The component is not capable of performing its specified operation according to a success criterion.
- **Failure Cause Categories**: List of potential deficiencies in operation and in design, construction and manufacturing which rendered possible a CCF event to occur.
- **Failure Mechanism**: The history describing the events and influences leading to a given failure.
- **Failure Mode**: The failure mode describes the function the components failed to perform.
- **Failure Symptom**: An observed deviation from the normal condition or state of a component, indicating degradation or loss of the ability to perform its mission.
- **Failure Symptom Aspects**: Are component-type-specific observed faults or deviant conditions which have led to the CCF event. They are derived from the event description
- **Failure Symptom Categories**: Are component-type-specific groupings of similar failure symptom aspects.
- **Degraded**: The component is capable of performing the major portion of the safety function, but parts of it are degraded. For example, high bearing temperatures on a pump will not completely disable a pump, but it increases the potential for failing within the duration of its mission.
- **ICDE Event**: Impairment 1) of two or more components (with respect to performing a specific function) that exists over a relevant time interval 2) and is the direct result of a shared cause.

- **Incipient**: The component is capable of performing the safety function, but parts of it are in a state that - if not corrected — would lead to a degraded state. For example, a pump-packing leak, that does not prevent the pump from performing its function, but could develop to a significant leak.

- **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.

- **Root Cause**: The most basic reason for a component failure, which, if corrected, could prevent recurrence. The identified root cause may vary depending on the particular defensive strategy adopted against the failure mechanism.

- **Shared-Cause Factor**: The shared cause factor allows the analyst to express his degree of confidence about the multiple impairments resulting from the same cause.

- **Timing Factor**: This is a measure of the “simultaneity” of multiple impairments. This can be viewed as an indication of the strength-of-coupling in synchronising failure times.

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EXECUTIVE SUMMARY

Common-cause failure (CCF) events can significantly impact the availability of safety systems of nuclear power plants. For this reason, the International Common Cause Failure Data Exchange (ICDE) project was initiated by several countries in 1994. In 1997, CSNI formally approved the carrying out of this project within the NEA framework. The project has successfully operated six consecutive terms, with the current term being 2011-2014.

The objectives of the ICDE are to a) collect and analyse CCF events over the long term so as to better understand such events, their causes, and their prevention; b) to generate qualitative insights into the root causes of CCF events which can then be used to derive approaches or mechanisms for their prevention or for mitigating their consequences; c) to 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; d) to generate quantitative insights and record event attributes to facilitate quantification of CCF frequencies in member countries; and e) to use the ICDE data to estimate CCF parameters. The ICDE Project aims to include all possible events of interest, comprising complete, partial, and incipient CCF events, called “ICDE events”. The ICDE events are defined as “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.”

The ICDE Project has furthermore established a principle that it shares the engineering insights of its analyses through the NEA Committee on Safety of Nuclear Installations (CSNI) by writing public reports of the analysis results of each component.

This report documents a study performed on a set of ICDE events related to heat exchangers. The events studied here had been collected in the ICDE database. Organisations from Canada, Germany, Japan, Spain, Sweden and the United States contributed to the exchange. The ICDE Project is the only international effort where large amounts of data from different countries are collected and analysed to draw conclusions about common cause failures.

Forty-six (46) ICDE events, exhibiting at least some degree of dependency, and spanning a period from 1987 through 2007, were examined in the study. The database contains general statistical information about event attributes like impairment of the components in the observed populations, root cause, coupling factor, detection methods and corrective actions taken. The events contained in the ICDE database were analysed with respect to failure modes, degree of impairment, failure symptoms, failure causes, and technical fault aspects.

The top failure mode relevant from a PSA point of perspective is the failure mode HT-General (Failure of heat transfer) representing 100% of the events.

Degree of impairment: 4 of the events (8,7%) are complete CCFs (all redundant components had failed in a short time interval and for the same cause) while 1 event is defined as partial CCF (at least two, but not all completely failed components). The majority of the events (78%) have low impairment vectors, i.e. less than two components that have completely failed. Because of the small number of complete CCFs, the statistical significance of any result concerning complete CCFs should be handled carefully.

Dominant **root causes** were “abnormal environmental stress”, “procedure inadequacy” and “design, manufacture or construction inadequacy”, accounting for in total 37 events (83% of the events) with 1/3 in each of these root cause classes.

The **coupling factors** are strongly dominated by “environmental internal” (28%). However, if coupling factors are combined into top-level categories of environmental, hardware and operational, there is no dominant group.

Detection modes: 26 events (57%) were detected during test and maintenance activities, i.e. the equipment failure was discovered during the performance of a scheduled test or during maintenance activities. Only 7 events (15%) were revealed by demand events. Furthermore, 3 of the 4 complete CCFs were revealed by “test during operation”. These results imply that the employed procedures and practices for detecting common-cause failures have been effective.

Concerning **corrective actions**, design related actions make up only 23% of the corrective actions, although “deficiencies in design, hardware and manufacturing” were involved in 65% of the events.

The identification of the relationship of **failure symptom categories** and **failure cause categories** was based on the verbal event descriptions and further engineering analysis for all of the ICDE events.

Heat exchangers are passive components operated in different systems and environmental conditions. In the majority of the events, dependencies occur in systems with an aggressive environment affecting heat exchanger internals as tubes, plates, chambers in multiple trains and components. Observed failures have also lead to leaks and impeded flow due to corrosions (corrosion, erosion) and dirt accumulation (pitting, fouling). There are also direct human/operator related faults causing dependencies of heat exchanger trains, e.g. by faulty alignment of valve configuration and wrong maintenance procedures and/or –practices.

The dominating failure symptom category is failure of heat transfer due to “clogging or blockage (no or reduced flow)”, accounting for 54% of the events, followed by ”internal leakage” accounting for 41% of the events.

The **failure symptom aspect analysis** reveals that there are two strong manifestations: “Foreign objects impede flow” and “Dirt accumulation or fouling impedes flow”, which represents 72 % of the events in failure symptom category “clogging or blockage”.

Deficiencies in design, construction and manufacturing contribute 65% of the failure causes, the majority due to failure cause category "Deficiency in design of hardware". The other 35% of failure causes are deficiency in operation, mainly due to failure cause category “Deficient procedures for maintenance and/or testing”. Among the four complete CCFs, 3 of 4 were due to deficiencies in design, construction and manufacturing.

The study shows that there are several test interval lengths practiced in the member countries.

A more frequent testing and –maintenance practice would be a powerful approach to reduce events with high severity, e.g. as shorter test intervals, more frequent cleaning, faster change of degraded heat exchangers, improved instrumentation of in/out flows and water temperatures, improved maintenance and/or testing instructions.

1. INTRODUCTION

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

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

The ICDE Project was organised to exchange CCF data among countries. A brief description of the project, its objectives, and the participating countries, is given in Section 2. Section 3 presents the definition of common cause failure and the ICDE event definitions. Section 4 presents a description of the component, and Section 5 summarises the coding guidelines for this component. Sections 6 and 7 contain the results of the study. Section 8 contains the summary and conclusions of the study.

2. ICDE PROJECT

2.1 Background

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

To overcome these obstacles, the preparation for the international common-cause data exchange (ICDE) project was initiated in August of 1994. Since April 1998, the NEA has formally operated the project. The Phase II had an agreement period covered years 2000-2002, phase III covered the period 2002-2005, phase IV 2005-2008 and phase V 2008 -2011. Member countries under the current Phase VI Agreement of NEA and the organisations representing them in the project are: Canada (CNSC), Finland (STUK), France (IRSN), Germany (GRS), Japan (JNES), Korea (KAERI), Spain (CSN), Sweden (SSM former SKI), Switzerland (ENSI former HSK), United Kingdom (NII), and United States (NRC).

2.2 Objectives of the ICDE Project

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

a) collect and analyse common-cause failure (CCF) events over the long term so as to better understand such events, their causes, and their prevention

b) generate qualitative insights into the root causes of CCF events which can then be used to derive approaches or mechanisms for their prevention or for mitigating their consequences

c) 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

d) generate quantitative insights and record event attributes to facilitate quantification of CCF frequencies in member countries

e) use the ICDE data to estimate CCF parameters, and

The multinational co-operation generates new insights for further development of CCF data collection and methods development. The ICDE Project has furthermore established a principle that it disseminates the engineering insights of its analyses through the NEA Committee on Safety of Nuclear Installations (CSNI) by writing public reports of the analysis results of each component.

2.3 Scope of the ICDE Project

The ICDE Project aims to include all possible events of interest, comprising complete, partial, and incipient CCF events, called “ICDE events” in this report.

So far the project covers the key components of the main safety systems, including centrifugal pumps, diesel generators, motor operated valves, power operated relief valves, safety relief valves, check valves, batteries, control rod drive mechanisms (CRDA), circuit breakers, level measurement, heat exchangers, etc.

2.4 Reporting and documentation

The ICDE project has produced the following reports, which can be accessed through the OECD/NEA CSNI web site for CSNI reports [1]:

- Collection and analysis of common-cause failure of centrifugal pumps [NEA/CSNI/R(99)2]. Issued September 1999.
- Collection and analysis of common-cause failure of emergency diesel generators [NEA/CSNI/R(2000)20]. Issued May 2000.
- Collection and analysis of common-cause failure of motor-operated valves [NEA/CSNI/R(2001)10]. Issued February 2001.
- Collection and analysis of common-cause failure of safety valves and relief valves [NEA/CSNI/R(2002)19]. Issued October 2002.
- Collection and analysis of common-cause failure of check valves [NEA/CSNI/R(2003)15]. Issued February 2003.
- Collection and analysis of common-cause failure of batteries [NEA/CSNI/R(2003)19]. Issued September 2003.
- Collection and analysis of common-cause failure of switching devices and circuit breakers [NEA/CSNI/R(2008)1]. Issued October 2007.
- ICDE General Coding Guidelines [NEA/CSNI/R(2004)4]. Issued January 2004.
- Proceedings of ICDE Workshop on the qualitative and quantitative use of ICDE Data [NEA/CSNI/R(2001)8. Issued November 2002.
- Collection and analysis of common-cause failure of level measurement components [NEA/CSNI/R(2008)8]. Issued March 2008.

2.5 Database management

Heat exchanger data is stored and processed in a Microsoft.NET based database implemented and maintained at ES-Konsult, Sweden, the appointed ICDE Operating Agent (OA). The database name is the ICDE Tools. The database is regularly updated. It is operated by the OA following the decisions of the ICDE Steering Group.

2.6 ICDE coding format and coding guidelines

Data collection guidelines have been developed during the project and are continually revised. They describe the methods and documentation requirements necessary for the development of the ICDE databases and reports. The format for data collection is described in the general coding guideline and in the component specific guidelines. Component specific guidelines are developed for all analysed component types as the ICDE plans evolve [2].

A specific heat exchanger coding guideline exists for this particular study [Ref. 4].

2.7 Protection of proprietary rights

Procedures for protecting confidential information have been developed and are documented in the Terms and Conditions of the ICDE project [6].

The co-ordinators in the participating countries are responsible for maintaining proprietary rights according to the stipulations in the ICDE Terms and Conditions for the project operation 2008-2011, [6].

The data collected in the database are password protected and are only available to ICDE participants who have provided data.

3. DEFINITION OF COMMON-CAUSE EVENTS AND ICDE EVENTS

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

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

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

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

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

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

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

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

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

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1. Possible attributes of impairment are the following:

- Complete failure of the component to perform its function
- Degraded ability of the component to perform its function
- Incipient failure of the component

Default is component working according to specifications

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

4. COMPONENT DESCRIPTION

The coding guideline for heat exchangers [4] is applied in the following description.

4.1 General description of the component heat exchanger

A heat exchanger is a device built for efficient heat transfer from one fluid to another, where the fluids are separated by a solid wall so that they never mix, or are directly contacted. They are widely used in refrigeration, air conditioning, space heating, power production, chemical processing. Hence, typical functions of heat exchangers are to heat or to cool.

There are two types of heat exchangers considered in this study, “shell and tube” and “plate”.

Shell and tube heat exchangers

As its name implies, this type of heat exchanger consists of a shell (a large tube) surrounding a bundle of tubes. Two fluids, of different inlet temperatures, flow through the exchanger. One fluid flows through the tubes and the other flow through the shell. Heat is transferred from one fluid to the other.

There can be many variations of the shell and tube design. Most heat exchangers are of either 1, 2, or 4 passage designs. This refers to the number of times the fluid in the tubes passes through the fluid in the shell.

Plate heat exchangers

This type of heat exchanger uses metal plates to transfer heat between two liquids. The liquids spread out over the plate.

The medium that carries the transferred heat (the cold side) in a heat exchanger is called the refrigerant. The cooling capacity (the heat transfer capacity, is also called the *k-value*) of a heat exchanger, is usually expressed in kW/m^2 °C. The k-value is very dependent on how clean the tube/plate surfaces are, and on how the heat exchangers are operated.

In most of the cases, the redundant trains are equipped with similar type of heat exchangers.

There are also plants that have mixed (plate and tube) type of heat exchangers. In some systems and in redundant trains, there are HE:s installed in series in one train and in parallel in another train. There are also heat exchangers that are shared by multiple plants at a site area.

Heat exchanger data are collected for the following systems (the corresponding IRS system coding is added in parenthesis and for some systems, also the type of nuclear power plant):

- Component cooling water system (including closed cooling water) (salt / sea water / river / well / lake water) (3.CA)
- Essential raw cooling or service water (3.CB)
- Core cooling system
  - High pressure systems (3.BG)

   – Low pressure systems including residual heat removal systems (3.BE, 3.BG)

- Chemical and Volume Control System (Let-down system) [3](3.BF)
- Auxiliary or emergency feed water (3.BB)
- Fuel pool cooling system (3.DA)
- Containment spray system (3.DD)
- Containment cooling water system (sump cooling) (3.DE)
- Reactor water clean-up (BWR, PHWR, LWGR,...) (3.WK)

These systems may be either safety- or operational systems. Further systems can be included in the data exchange if considered as appropriate by a participating country. In this study some countries have also collected data from the following systems:

- Moderator and auxiliaries (PHWR, ...) (3.AD)
- Stand-by liquid control (BWR) (3.BD)

Data is collected from the following types of nuclear power plants;

- **BWR** (Boiling Water Reactor)
- **PWR** (Pressurised Water Reactor)
- **PHWR** (Heavy Water moderated, Pressure tube Reactor)
- **GCR** (Gas Cooled Reactor (graphite or heavy water moderated); includes Magnox AGR, HTGR and HWGCR)

4.2 Component boundaries

The component boundary includes the following:

- The heat exchanger itself consisting of inlet- and outlet chambers, shell and tubes/plates
- Piping system between the heat exchanger shell and inside of closest valve
- Local valves

Control equipment belonging to heat exchanger is judged not to be a part of the data collection if malfunction of such equipment has no influence on the function of the heat exchanger.

The component boundary is illustrated in figure 4.2-1 below. The figure is from the Reliability data of components in Nordic NPPs, the T-book [5].

3. CVCS is both a safety and operational system in Swedish Westinghouse PWR plants, and CS system is part of the PWR PSAs

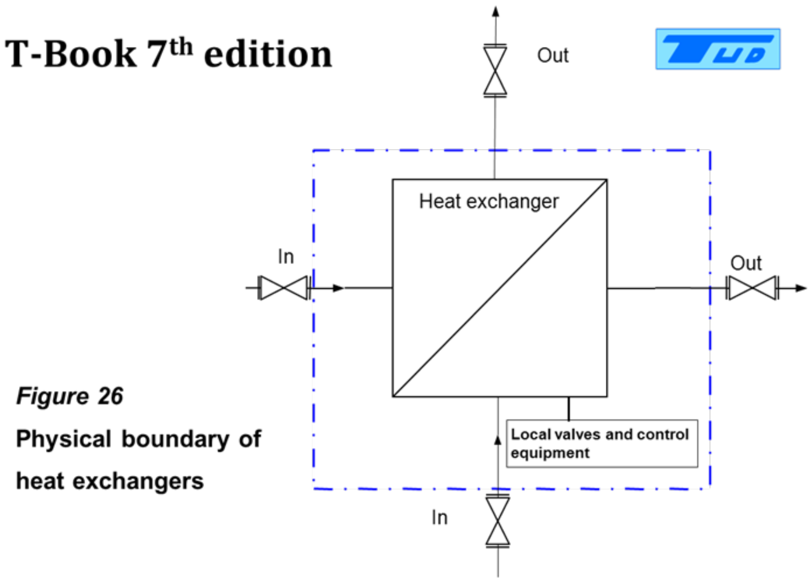

Figure 4.2-1. Physical boundary of heat exchanger

4.3 Event boundary

If there is no indication of component wear out, mechanical degradation or malfunction and there is a sufficient cooling capacity at normal flow, operation of the heat exchanger is judged successful.

4.4 Basic unit for ICDE event collection

The basic set for heat exchanger data collection is the observed population (OP) and is the total of all redundant heat exchangers components in the systems of interest. The OP sise typically varies from two to four, with the bulk of two OPs. There are also a few OP sises more than four. The system on the primary side of the heat exchangers is identified in the OP records.

4.5 Time frame for ICDE event exchange

The minimum period of exchange should cover a period of 5 years. It is suggested that data is collected for the time period 2000-2005.

5. HEAT EXCHANGER EVENT COLLECTION AND CODING GUIDELINES

5.1 Coding rules and exceptions

1. In general, the definition of the ICDE event is given in Section 2 of the General ICDE Coding Guidelines [2].

2. Some reports may discuss only one actual failure, and do not consider that the same cause will affect other heat exchangers, but the licensee replaces the failed component in all heat exchanger trains as a precautionary measure. This event will be coded as incipient impairment of the components that did not actually fail.

3. Administrative in-operability that does not cause the heat exchanger to fail to function is not included as failure. An example is a surveillance test not performed within the required time frame

4. In-operability due to external event situations (blockage of salt / sea / river water flow) shall be included.

5.2 Functional failure modes

In the ICDE data collection the functional heat exchanger failure mode “failure of heat transfer” (FT) should be considered, as defined in the heat exchanger coding guideline [4].

The impairment vector gives information on the impairment status of each heat exchanger of the exposed population, i.e. information about the impairment of the heat transfer function.

Example of complete failure of heat transfer.

Plugging or internal leakage is so important that no significant heat transfer is possible

Example of degraded failure of heat transfer:

Plugging or internal leakage is important enough to reduce heat transfer capacity significantly but the safety function "heat transfer" is not compromised yet.

Example on incipient failure of heat transfer:

Plugging or internal leakage is small and has no safety significance, e.g. only few tubes out of the large number of tubes in a tube heat exchanger are plugged or have leakages and there are much more tubes in the heat exchanger than are necessary to fulfil the safety function "heat transfer".

6. OVERVIEW OF DATABASE CONTENT

CCF data have been collected for heat exchangers (HE). Organisations from Canada, Germany, Japan, Sweden and the United States have contributed to this data exchange. Forty-six (46) ICDE events were reported from nuclear power plants (pressurised water reactors, boiling water reactors, heavy water moderated pressure tube reactors, magnox and advanced gas reactors). The data span a period from 1987 through 2007. The data are not necessarily complete for each country throughout this period.

Collecting these events has included both top-down work by identifying events on basis of licensee event reports and bottom-up work by going through events in plant maintenance databases. Although most CCF events are identified through the former mechanism, the latter has led to ICDE events that were not identified otherwise. This bottom-up work is rather resource intensive.

The distributions of events in the following section are strictly based on the classes given in the ICDE coding guidelines [2]. In Section 7, a deeper engineering analysis of the events is presented.

6.1 Failure mode and impact of failure

For each event in the ICDE database, the **impairment** of each component in the OP has been defined according to the categorisation in the general coding guidelines [2], and are summarised here.

- **C** denotes complete failure. The component has completely failed and will not perform its function. For example, internal leakage is so extensive that no significant heat transfer is possible.

- **D** denotes degraded. The component is capable of performing the major portion of the safety function, but parts of it are degraded. For example, internal leakage is extensive enough to reduce the heat transfer capacity significantly but the safety function "heat transfer" is not compromised.

- **I** denotes incipient. The component is capable of performing the safety function, but parts of it are in a state that - if not corrected - would lead to a degraded state. This coding is selected when slight damage is evident. If an event report discusses only one actual failure, and does not consider that the same cause will affect other Heat exchangers, but the licensee replaces the failed part on parallel components, this code is used for the components that didn’t actually experience a failure. This also applies if it was decided to implement said replacement at a later time. For example, internal leakage is small and has no safety significance, e.g. only few tubes out of the large number of tubes in a tube heat exchanger are plugged or have leakages and there are lot of fault free tubes in the heat exchanger that can fulfil the safety function "heat transfer".

- **W** denotes working, i.e. component has suffered no damage. The component is working according to specifications.

The impairments of each component in the exposed population (or observed population respectively) result in an impairment vector, which can be used as a measure of the impact of failure. Complete CCF events are ICDE events in which all components of the exposed population (or observed population respectively) fail completely and where these fault states exist simultaneously and are the direct result of a shared cause. A further subclass of ICDE events are partial CCF events having at least two components, but not all of them completely failed and where these fault states exist simultaneously and are the direct result of a shared cause.

Table 6.1-1 summarises the reported ICDE events by impact of failure. 46 ICDE events have been collected in the ICDE database, 4 of them were complete CCF events.

Table 6.1-1. Impact of failure distribution

FAILURE MODE	**No. of ICDE events**	**Impact of failure [1)]**	
		Complete CCF events	**Partial CCF events**
HT – Failure of heat transfer	46	4	1
TOTAL	46	4	1

[1] Only events with time factor and shared cause factor "high" are included.

Complete CCF makes up 9% of the HE events and partial CCF makes up for 2%.

6.2 Root cause, coupling factor, corrective action and detection method

6.2.1 Root Cause

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

- **C** – State of other component(s) (if not modelled in PSA). The cause of the state of the component under consideration is due to state of another component. Examples are loss of power and loss of cooling.

- **D** – Design, manufacture or construction inadequacy. This category encompasses actions and decisions taken during design, manufacture, or installation of components, both before and after the plant is operational. 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. 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 (sprays, floods, etc.) radiation, abnormally high or low temperature, vibration load, and severe natural events.

- **H** – Human actions. Represents causes related to errors of omission or commission on the part of plant staff or contractor staff. An example is a failure to follow the correct procedure. 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, piece part. Deals with malfunctioning of parts internal to the component. Internal causes result from phenomena such as normal wear or other intrinsic failure mechanisms. It includes the influence of the environment of the component. Specific mechanisms include erosion/corrosion, internal contamination, fatigue, and wear out/end of life.
- **P** – Procedure inadequacy. 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 of procedures, such as change control.
- **O** – Other. The cause of events is known, but does not fit in one of the other categories.
- **U** – Unknown. This cause category is used when the cause of the component state cannot be identified.

Figure 6.2.1-1 summaries the root causes of the analysed events as coded in the ICDE database.

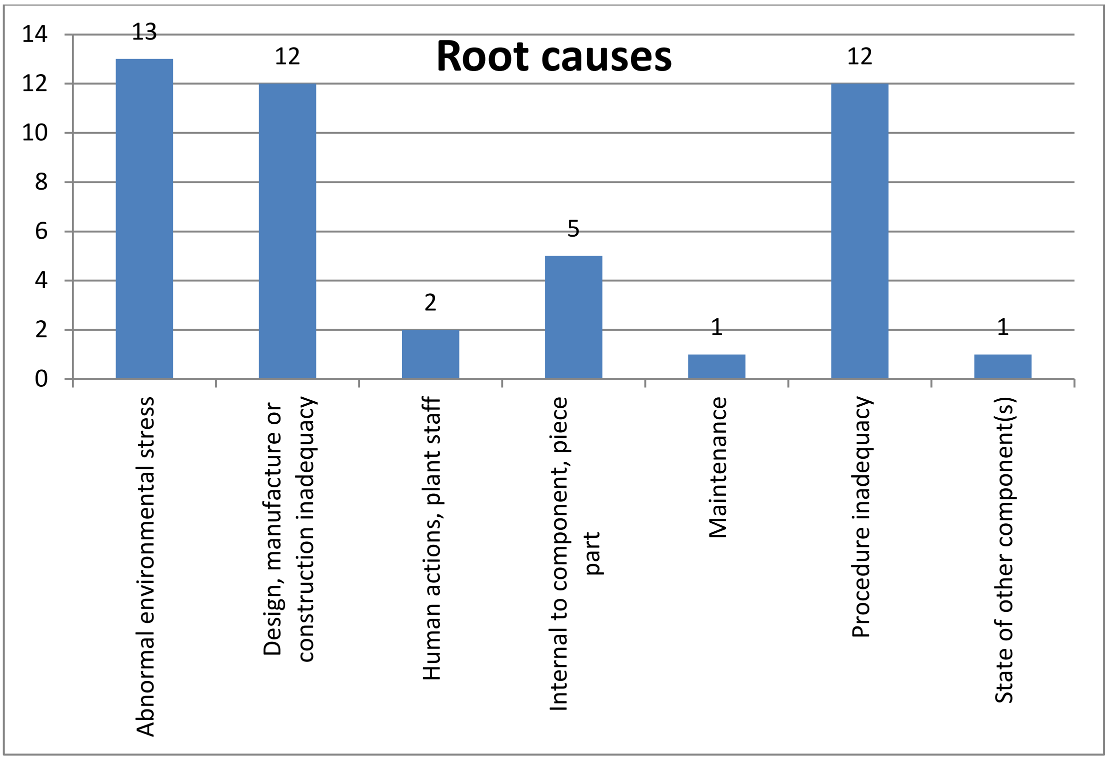

Figure 6.2.1-1. Root cause distribution

The dominant root causes based on ICDE codes is "**A -** Abnormal environmental stress" accounting for 28% of the events, followed by "**D -** Design, manufacture or construction inadequacy" and "**P -** Internal to component, piece part" accounting for 26% of the events each. ICDE codes A, D and P represent in total 80% of all heat exchanger root causes.

The complete heat exchanger CCFs are caused by root cause D - design, manufacture or construction inadequacy (one event), H - human action (one event) and I - internal to component (two events).

6.2.2 Coupling factor

The general coding guidelines [2] define **coupling factor** as follows. The coupling factor field describes the mechanism that ties multiple impairments together and identifies the influences that created the conditions for multiple components to be affected. For some events, the root 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 of 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** – Maintenance/test (M/T) schedule. Components share maintenance and test schedules. For example, the component failed because maintenance was delayed until failure.

- **OMP** – M/T procedure. Components are affected by the same inadequate maintenance or test procedure. For example, the component failed because the maintenance procedure was incorrect or a calibration set point was incorrectly specified.

- **OMF** – M/T staff. Components are affected by a maintenance staff error.

- **OP** – Operation procedure. Components are affected by an inadequate operations procedure.

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

- **EI** – Environmental internal. Components share the same internal environment. For example, the process fluid flowing through the component was too hot.

- **EE** – Environmental external. Components share the same external environment. 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.

Some of the ICDE events have been classified using the top-level categories only (e.g. H), whereas for others also sub-categories (e.g. HC) have been used.

Figure 6.2.2-1 shows the coupling factors of the analysed events as coded in the ICDE database.

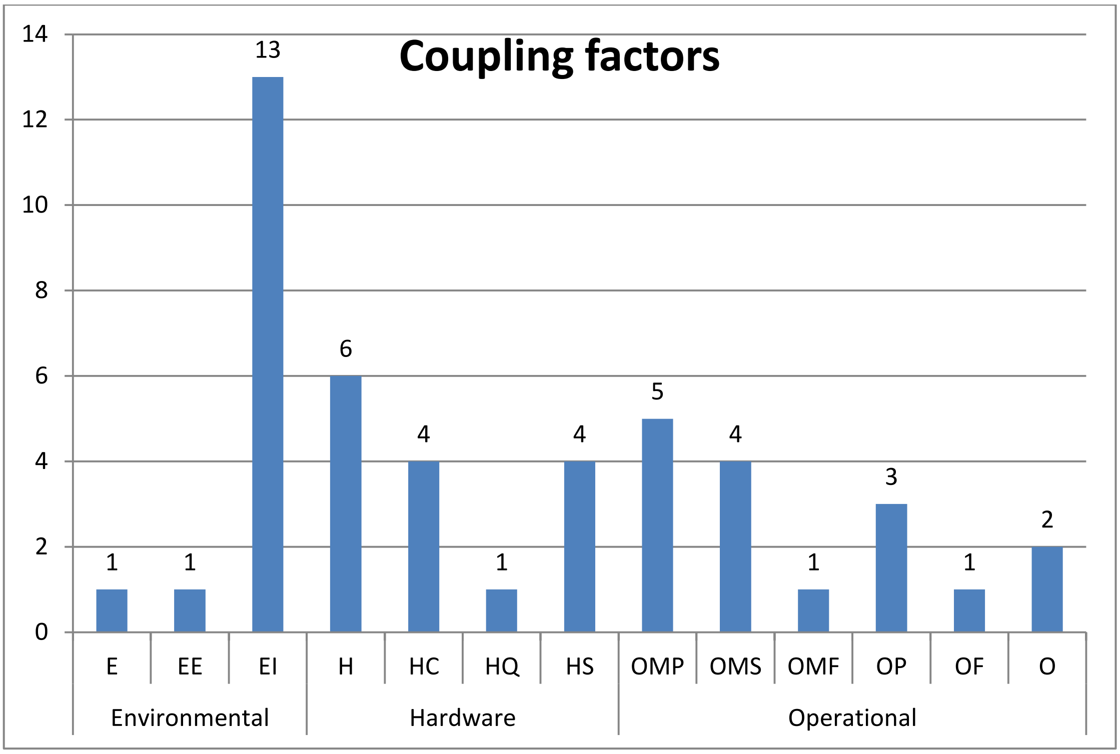

Figure 6.2.2-1. Coupling factor distribution

In figure 6.2.2-1 it can be seen that the dominant coupling factor is "**EI** - environmental internal", accounting for 28% of the events. However, if considering the top-level categories of coupling factors, environmental, hardware and operational, there are no dominant group since the shares are 32%, 32% respectively 35%.

The 4 complete CCFs are represented in all the three coupling factor groups.

Most often affected component impairment for **EI** in this study is DD, DI, IIII and IIWW.

6.2.3 Corrective actions

The ICDE general coding guidelines [2] 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 root cause and/or coupling factor between the 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 program modification. The modification includes items such as staggered testing and maintenance/operation staff diversity.
- **G** – Fixing of component.
- **O** – Other. The corrective action is not included in the classification scheme.
- **U** – Unknown. Adequate detail is not provided to make adequate corrective action identification.

Figure 6.2.3-1 summarises the corrective actions of the analysed events as coded in the ICDE database.

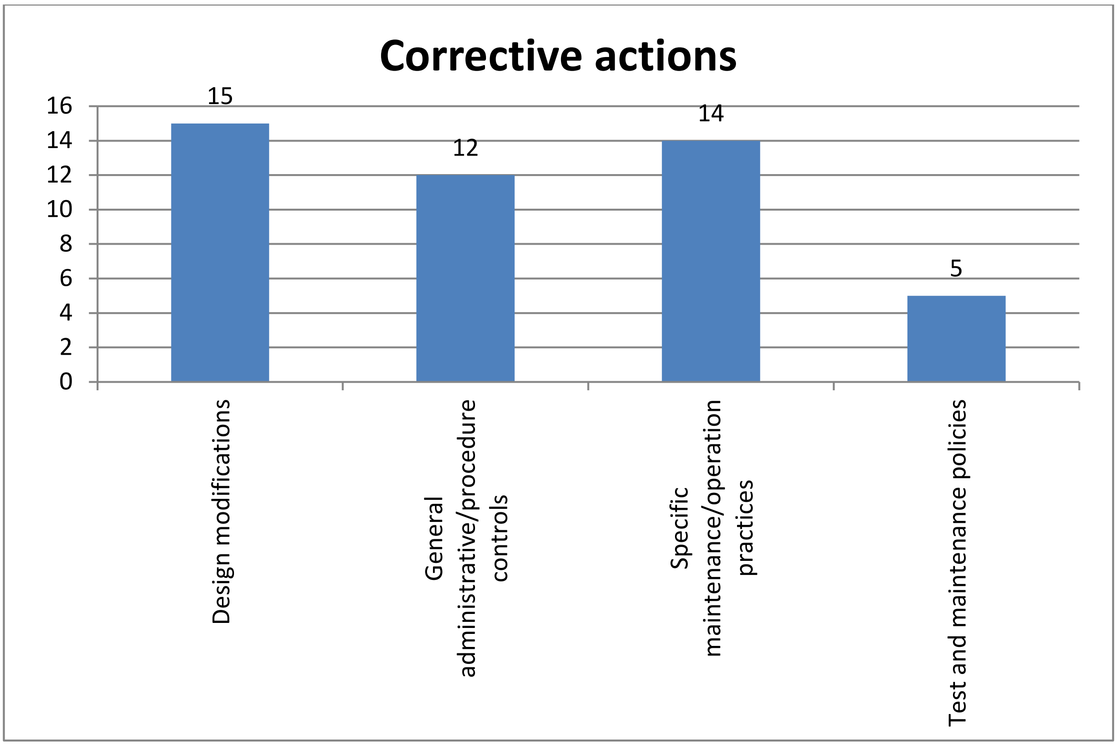

Figure 6.2.3-1. Corrective actions distribution

Improvement of maintenance and test procedures (the corrective action codes **B** – specific maintenance/operation practices and **F -** test and maintenance policies) makes up 41% of the corrective actions taken, while actions related to **C** – design modifications make up 32% of the corrective actions. Corrective action **A -** general administrative/procedure controls was undertaken in all 4 complete CCFs in this study.

6.2.4 Detection methods

Figure 6.2.4-1summarises how the failures were detected. The whole list of the detection codes used in the ICDE data collections are found in the General Coding Guidelines (Ref. 2]. In cases where the detection method for at least one component was unknown and the rest in the observed population had the same code, the coding of the event was changed from “several detection methods” to the specified detection method. This did only concern one event which was changed to detection method “monitoring in control room”.

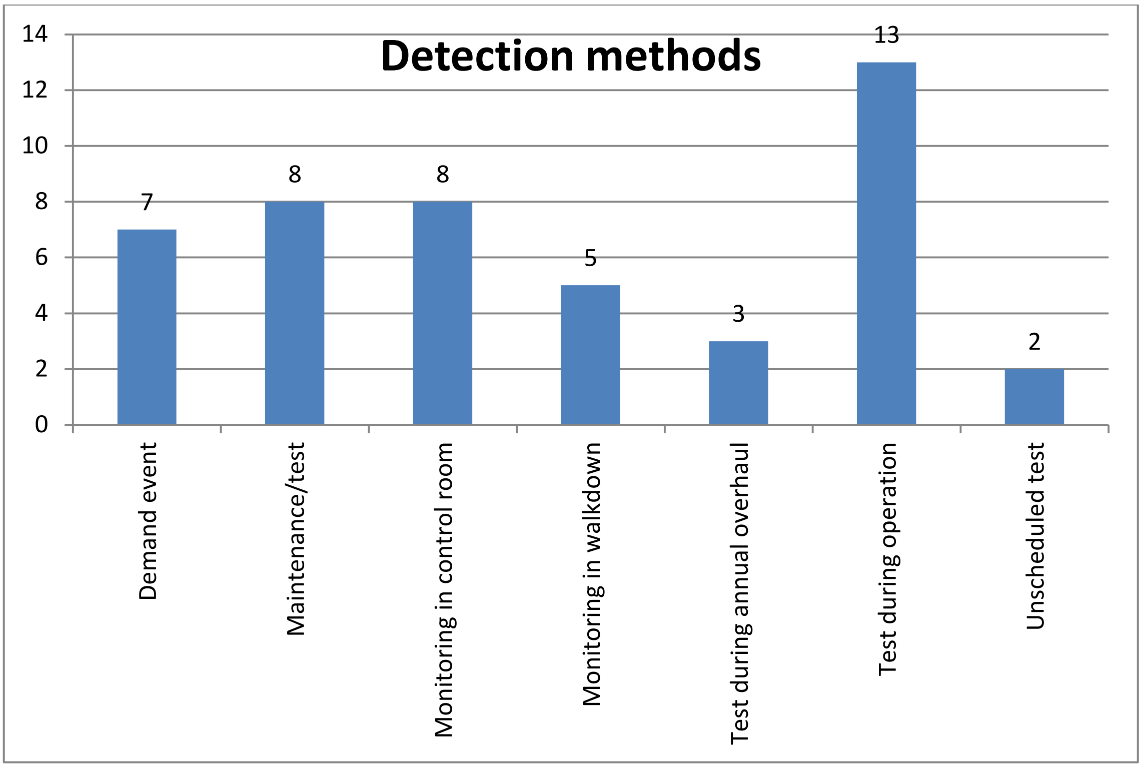

Figure 6.2.4-1. Detection methods distribution

26 ICDE events (57%) were discovered during test and maintenance activities (**TA** - test during annual overhaul, **TI** - test during operation, **TU** - unscheduled test and **MA** - maintenance/test), i.e. the equipment failure was discovered during the performance of a scheduled test or during maintenance activities, usually during preventive activities. 13 events (28%) were discovered by monitoring, either by walkdown or in the control room.

7 events (15%) were revealed by demand events. Among the events revealed by a demand, none of them were complete CCFs.

3 of the 4 complete CCFs were revealed by "test during operation" which implies that the employed procedures and practices for detecting common-cause failures have been effective.

6.3 Component impairment vectors

The severity of heat exchanger CCF events is presented in the next table 6.3-1.

Possible attributes of impairments are the following (see definitions in chapter 6.1):

- C - Complete
- D - Degraded
- I - Incipient
- W - Working

The ICDE project defines the following classes of events, depending on the severity of observed impairments:

Complete CCF: 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.

Partial CCF: is a complete failure of at least two components, but not all of the exposed population, where these fault states exist simultaneously and are the direct result of a shared cause.

CCF impaired: ICDE events with at least one C and at least one additional impairment, but not partial CCF or complete CCF. This counts the number of events with multiple impairments where failure mechanisms surely may lead to complete failure. It includes the events with multiple complete failures but shared cause and/or time factor not high.

Complete impairment (all D or I): No complete failures but complete impairment, all components in the exposed population are affected (all degraded or incipient failures) - This counts the number of events where all components in the affected component group are impaired. This count does not include any events from “CCF impaired”, “Partial CCF” and “Complete CCF”.

Incipient impairment: Multiple impairments but at least one component working. No complete failure. Incomplete but multiple impairments with no C.

The severity of heat exchanger CCF events is presented in the next table 6.3-1.

Table 6.3-1. Distribution of event impairments

Impairments	Number of events
Complete CCF	4
Partial CCF	1
CCF impaired	2
Complete impairment	29
Incipient impairment	10
Total	**46**

In total, 19 different impairment combinations have been found among the 46 approved heat exchanger CCF event records. The 5 most common impairments are DD, DI, IIWW, II and IIII, representing in total 39 CCF event records or 85% of all events.

- Among the 4 complete CCFs (all C:s) three occurred in a 2-train system and one in a 4-train system
- The partial CCF is an event with 2 completely failed components in a 4-train system
- The majority of the CCF events are reported from 2-train and 4-train systems, 22 events and 21 events in each of the group sises respectively

Because of the small number of complete CCFs, the statistical significance of any result concerning complete CCFs should be handled carefully.

7. ENGINEERING ASPECTS OF THE COLLECTED EVENTS

7.1 Scope

The intention of this section is to provide the reader with a deeper qualitative insight in the database content beyond that obtained from using the database coding only (as performed in Section 6 of this report). In the subsequent paragraphs a detailed analysis of failure symptoms and failure causes is presented.

7.2 Assessment basis

In the following sections the events are analysed with respect to failure symptom categories, failure symptom aspects and failure causes categories. The following definitions are applied:

Failure Symptom is an observed deviation from the normal condition or state of a component, indicating degradation or loss of the ability to perform its mission.

Failure Symptom Aspects are component-type specific observed faults or deviant conditions which have led to the CCF event. They are derived from the event descriptions.

Failure Symptom Categories are component-type-specific groupings of similar failure symptom aspects.

Failure Cause Categories are a list of potential deficiencies in operation and in design, construction and manufacturing which rendered possible CCF event to occur.

Appropriate failure symptom categories and failure symptom aspects are identified by engineering binning derived from the verbal event descriptions.

For the identification of the failure cause categories, root causes are combined with coupling factors, because, by definition, it is the coupling factor that identifies the mechanism that ties together multiple failures and the influences that created the conditions for multiple components to be affected. The root cause alone does not provide the information required for identifying failure cause categories.

Finally, the mapping of failure symptom categories onto failure cause categories is shown by the assessment matrix; see Figure 7.6-1 for details. This matrix provides the basis for deriving insights and conclusions. Furthermore, matrices presenting test intervals and test procedures are also relevant for the final conclusions.

7.3 Failure symptom categories

The first step in the failure analysis procedure chain is to examine the failure symptoms. Failure symptom aspects are derived from the event descriptions. Up to five similar failure symptom aspects are grouped to one failure symptom category. The following failure symptom categories and corresponding failure symptom aspects were identified as being important to the analysis:

- Internal leakage (HE-IL) due to erosion/corrosion and wear
  - Corrosion/erosion of tubes due to intrusion of foreign material (HE-a1)

   - Corrosion due to vibration (HE-a2)
   - Corrosion/erosion of tubes (not caused by foreign material or vibration) (HE-a3)
   - Cracks of dividing plates (HE-a4)
- Clogging or blocking (no or reduced flow) (HE-CB)
   - Foreign material passed through degraded screens (HE-b1)
   - Foreign material clogs the screens (HE-b2)
   - Dirt accumulation or fouling impedes flow (HE-b3)
   - Closed flow path due to faulty alignment (HE-b4)
   - Foreign objects impede flow (HE-b5)
- Bypass (faulty alignment) of the heat exchanger (HE-FA)
   - Bypass of the heat exchanger due to faulty alignment (HE-c1)
- Others (HE-OT)
   - Problems to perform test, inspections (HE-d1)

Table 7.3-1. Heat exchanger event severities (see definitions in chapter 6.3) vs. Failure symptom categories

Event severity	**Failure Symptom Categories**			
	HE-IL	HE-CB	HE-FA	**Total**
Complete CCF	1	2	1	4
Partial CCF	0	1	0	1
CCF impaired	0	1	1	2
Complete impairment	10	19	0	29
Incipient impairment	8	2	0	10
Total	**19**	**25**	**2**	**46**

The most often observed failure symptom category is HE-CB in total 54% events followed by the category HE-IL in total 41% of the event reports.

Each of the identified failure symptom categories were affected in the heat exchanger events leading to a complete CCFs.

Causes of the complete failures are;

- Erosion/corrosion twice leading to internal leaks
- Faulty alignment of heat exchanger once due to by-pass

- Clogging/blockage of heat exchanger once due to fouling/foreign material

The severity group "Complete impairment" and failure symptom category HE-CB dominates strongly in 19 events (41%) followed by HE-IL in 10 events (22%).

The severity group "Complete impairment" dominates strongly, with 63% of the events and second largest severity group is "Incipient impairment" in about 22% of the events.

- Failure symptom category HE-CB and failure symptom aspects fouling (HE-b3) and foreign objects impede flow (HE-b5) dominate strongly in this symptom category, followed by failure symptom category HE-IL with different failure symptom aspects of erosion/corrosion.
  - HE are often affected by corrosion of any kind (bad environment) e.g., of fouling
  - Absence of capacity testing on Containment Spray System HE:s have in one case been the major cause to failing HE:s.
  - One Initiating event found among all HE events - Residual Heat Removal System and Diesel generator cooling HE:s affected during the refueling plant mode, by degraded cooling system.
  - Leaking tubes due to cracks, corrosion attacks (of any kind) and testing problems are often the cause to HE failures.

There is just one event in total belonging to severity group "Partial CCF" and this event is found among the failure symptom category HE-CB with the symptom aspect HE-b5 "foreign objects impede flow".

The failure symptom category HE-CB - Clogging or blockage (no or reduced flow) is very often detected and observed by the detection method **TI -** test during operation/annual overhaul/ laboratory. Some examples are;

- Mesh seals before heat exchangers have in several CCF events created dependencies between heat exchanger trains. Strainers ought to be tested more frequently and/or ought to be cleaned more often than today. Filters in the strainers should be changed more often e.g., as a preventive maintenance measure.

7.4 Failure cause categories

The second step in the failure analysis chain is to examine the failure cause categories. This is an additional analyst code which classifies the identified causes in hardware and operator errors. It allows fast comparison, e.g. with the failure symptom aspects and failure symptoms category coding. Two principal categories of failure causes are introduced:

7.4.1 Deficiencies in operation

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

- The root cause is human error related or
- The root 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 root 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 aging of piece parts
O3 Operator performance error during maintenance/test activities

7.4.2 Deficiencies in design, construction, manufacturing

This group comprises all events with hardware related root cause and hardware related coupling factor. Thus, an event is only included, for example, in category D (design deficiency) if the root 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 root 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

Table 7.4.2-1 summarises the identified failure cause categories vs. severity of events.

Table 7.4.2-1. Heat exchanger events severities (see definitions in chapter 6.3) vs. Failure cause categories.

	Failure cause categories **O codes** = Deficiencies in operation (root cause or coupling factors are human error related) ***D codes*** = Design, construction, manufacturing deficiencies (root cause and coupling factor are hardware related)						
Comp Imp Vector	**Hardware related**			**Operator related**			
	D	**C/M**	**D-MOD**	**O1**	**O2**	**O3**	**Total**
Complete	3	-	-	-	-	1	**4**
Partial CCF	1	-	-	-	-	-	**1**
CCF impaired	1			1	-	-	**2**
Complete impairment	16	1	-	12	-	-	**29**
Incipient impairment	8	-	-	1	-	1	**10**
TOTAL	**29**	**1**	**0**	**14**	**0**	**2**	**46**

The most dominant failure cause category is hardware related, with 63% accounting for “D - deficiencies in design of hardware”, followed by the operator related failure cause category “O1- deficient maintenance/test procedures” accounting for 30%.

It is noted that 3 of 4 complete CCFs are hardware related “D” (Deficiencies in design of hardware)”. This category of failure cause also contains one partial CCF. The fourth complete HE CCF is operator related, “O3” (Insufficient re-qualification and/or work control, after maintenance).

74% of the events have occurred in tube heat exchangers. Also, all complete CCFs concerns tube heat exchangers. 2 of 4 complete CCFs are due to failure in a flow dividing plate and an alignment error.

CCF events on plate heat exchangers are only reported from one country.

7.5 Assessment matrices

Table 7.5.1 summarises the dominating causes and symptoms in heat exchanger CCF events according to the failure analysis performed. The failure symptom categories as defined in Section 7.3 are assigned to the columns of the matrix, and the failure cause categories as defined in Section 7.4 are assigned to the rows of the matrix.

Table 7.5-1. Relationship of Failure Symptom Categories and Failure Cause Categories for the failure of heat transfer.

	Failure Symptom Categories			
Failure Cause Categories	HE-IL Internal leakage due to erosion/corrosion and wear	HE-CB Clogging or blocking (no or reduced flow)	HE-FA Bypass (faulty alignment) of the HE	**Total**
Deficiencies in operation Root cause or coupling factor are human error related	**3**	**11**	**2**	**16**
O1 Deficient maintenance / test procedures	**2**	**11**	**1**	**14**
O2 Insufficient attention to aging of piece parts	**-**	**-**	**-**	**0**
O3 Operator performance error during maintenance / test activities	**1**	**-**	**1**	**2**
Design, construction, manufacturing deficiencies Root cause and coupling factor are hardware related	**16**	**14**	**2**	**30**
D Deficiencies in design of hardware	**15**	**14**	**-**	**29**
C/M Deficiencies in construction / manufacturing of hardware	**1**	**-**	**-**	**1**
D-MOD Deficient design modifications	**-**	**-**	**-**	**0**
Total Unknown failure cause category	**19**	**25**	**2**	**46** **0**

The most dominant failure cause category is hardware related, accounting for 65% followed by the operator related “Deficiencies in operation (root cause or coupling factors are human error related)”, accounting for 35%.

The combination of failure cause category D = *design* and failure symptom category HE-IL = *Internal leakage*, is the dominating contributor to hardware related dependent failures on heat exchangers – 33% of all events. The second largest group is the combination D and HE-CB = *Clogging or blocking (no or reduced flow)* – 30% of all events. The third largest group is the combination operator related failure O1 = *deficient procedures for maintenance and/or testing* and failure symptom category HE-CB – in 24% of all events.

One of the two HT-FA = *Bypass (faulty alignment) of the HE* is a complete CCF. Both faulty alignments have occurred in 2-train systems. The heat exchanger study also points out that there is high probability that the few faulty alignments documented will end up in a complete CCF.

Heat exchangers are passive components operated in different systems and environmental conditions. Heat exchangers are also components that are operated for very long time and are therefore affected by the flows through them. In majority of the heat exchanger CCF event records, dependencies occur in systems with an aggressive environment affecting heat exchanger internals as tubes, plates, chambers. At long surveillance intervals this can lead to leaks and impeded flow due to corrosions (corrosion, erosion) and dirt accumulation (pitting, fouling). There are also direct human/operator related faults causing dependencies on heat exchanger train, e.g. by faulty alignment of valve configuration and by wrong maintenance procedures and/or –practices.

A good defence against serious dependent failures is to have good control of the causes of impairments with low impacts.

Better requalification of Eddy current testing method and –probe use, could reduce harm to heat exchanger tubes.

7.6 Test procedures and test intervals

Due to the relatively large share of events (57%) discovered during test and maintenance activities see section 6.2.4, it is of interest to look into the test procedures and test intervals of the reported events. In table 7.6-1 information is given about the test procedures which were applied in those observed populations of components that showed an ICDE event.

Table 7.6-1. Heat exchangers events vs. test procedures

	Test procedures			
	No data	**Sequential**	**Staggered**	**Total**
Total	1	20	25	**46**

All complete heat exchanger CCFs were observed during staggered testing. No obvious trend can be observed from this table.

In table 7.6-2 the variety of test intervals used in comparison with test procedures is presented for the 46 ICDE events. Please note that the test intervals coded in the Tools database are reduced from 8 to 3 test interval groups in this report to get more homogenous interval groups. The test intervals shown are the intervals for the recurrent functional tests.

The test intervals are modified as follows;

Table 7.6-2. Heat exchanger test intervals vs. test procedures

	Test interval length			
Test procedures	**<12m**	**12m**	**>12m**	**Total**
No data	0	0	1	**1**
Sequential	1	13	6	**20**
Staggered	15	1	9	**25**
Total	**16**	**14**	**16**	**46**

Remark: Reduced numbers of test interval groups are shown in this table. The database contains 8 different test interval lengths. In this table these have been collapsed to 3 (also in other tables where test intervals are compared).

In the previous table 7.6-2 it can be seen that the test interval <12 months in combination with staggered testing is the most frequently used test interval, in 35% of all the events. The second largest test interval group is sequential testing at 12 month represented in 28% of all the CCF events. Test interval group >12 months are found in 35% of the event reports.

12 months test intervals and longer are present in 65% of all CCF events.

Table 7.6-3. Test interval lengths vs. failure symptom categories

Severity groups and test intervals	**Failure symptom categories**			
	HE-IL	**HE-CB**	**HE-FA**	**Total**
Complete CCF	1	2	1	**4**
<12m	0	0	0	0
>12m	1	2	1	4
Partial CCF	0	1	0	**1**
<12m	0	0	0	0
>12m	0	1	0	1
CCF impaired	0	1	1	**2**
<12m	0	1	1	2
>12m	0	0	0	0
Complete impairment	10	19	0	**29**
<12m	3	16	0	19
>12m	7	3	0	10
Incipient impairment	8	2	0	**10**
<12m	8	1	0	9
>12m	0	1	0	1
Total	**19**	**25**	**2**	**46**

In table 7.6-3 the observed test intervals in the ICDE database are presented and re-grouped into 2 distinct test interval lengths, <12 months, and longer than 12 months. The table gives the amount of events observed per the two test interval length.

The failure symptom category “HE-CB” (Clogging or blocking (no or reduced flow)) can be found in 18 events with test intervals up to 12 months.

All (4) of the complete CCFs have occurred in heat exchangers with a test interval of 18 months. A defence against CCFs according to this observation is to practice shorter test intervals.

In next table 7.6- the relationship of failure symptom categories to test intervals is examined.

Table 7.6-4. Failure symptom categories vs. test intervals

Failure Symptom Category	<12M	12M	>12M	Total
HE-IL, Internal leakage	8	3	8	**19**
HE-CB, Clogging or blocking (no or reduced flow)	8	10	7	**25**
HE-FA, Bypass (faulty alignment) of the HE	0	1	1	**2**
HE-OT, Others				
Total	**16**	**14**	**16**	**46**

From table 7.6-4 no strong correlation is found – however 65% of all occurred failure symptom categories are discovered by test intervals ranging from 12 month or above.

8. SUMMARY AND CONCLUSIONS

Organisations from Canada, Germany, Japan, Sweden and the United States contributed with CCF data of heat exchangers to this data exchange. Forty-six (46) ICDE events were reported from Nuclear Power Plants in these countries.

All of the events were reviewed in more detail in Section 7.3, 7.4, 7.5 and 7.6 of this report with respect to impact of — failure symptom categories, failure cause categories, test procedures and test intervals.

The objective was to look beyond the CCF parameter estimates that can be obtained from the ICDE CCF data, to gain further understanding of why CCF events have occurred and what measures may be taken to prevent, or at least to mitigate the effects of heat exchanger CCF events.

4 of the events (9%) are complete CCFs while 1 event is defined as partial CCF (2%). All complete CCFs concern tube heat exchangers.

The most dominating failure cause category obtained is hardware related, with 63% accounting for "D — deficiencies in design of hardware", followed by the operator related failure cause category "O1— deficient maintenance/test procedures" accounting for 30%.

Heat exchangers are passive components operated in different systems and environmental conditions. In the majority of the events, dependencies occur in systems with an aggressive environment affecting heat exchanger internals as tubes, plates, chambers in multiple trains and components. In some cases leading to leaks and impeded flow due to corrosions (corrosion, erosion) and dirt accumulation (pitting, fouling). There are also direct human/operator related faults causing dependencies of heat exchanger trains, e.g. by faulty alignment of valve configuration and wrong maintenance procedures and/or –practices.

The dominant root causes based on ICDE codes is "A — Abnormal environmental stress" accounting for 28% of the events. The complete heat exchanger CCFs are caused by root cause D - Design, H — human action (one event each) and I — internal to component (two events).

The dominant coupling factor is "EI - environmental internal", accounting for 28% of the CCF events. The 4 complete CCFs are represented in the three coupling factor groups environment, hardware and operational.

Dominating corrective actions are - improvement of maintenance and test procedures (the corrective action codes B — specific maintenance/operation practices together with F — test and maintenance policies), these make up 41% of the corrective actions taken. Concerning corrective actions - design related actions make up only 33% of the corrective actions, although "deficiencies in design, hardware and manufacturing" were involved in 65% of the events.

26 events (57%) were detected during test and maintenance activities, i.e. the equipment failure was discovered during the performance of a scheduled test or during maintenance activities. Only 7 events (15%) were revealed by demand events. Among the events revealed by a demand, none of them were complete CCFs. Furthermore, 3 of 4 of the complete CCFs were revealed by "test during operation". These results imply that the employed procedures and practices for detecting common-cause failures have been effective.

Furthermore, the study shows that there are several test interval lengths practiced in the member countries. A more frequent testing and maintenance practice would be a powerful approach to reduce failures on less important failures.

Each of the identified failure symptom categories were affected in the heat exchanger events leading to a complete CCF.

The severity group “Complete impairment” and failure symptom category HE-CB (clogging or blocking (no or reduced flow)) dominates strongly in 19 events (41%) followed by HE-IL (Internal leakage) in 10 events (22%). HE are often affected by corrosion of any kind (bad environment) e.g., of fouling.

The failure symptom category HE-CB Clogging or blocking (no or reduced flow) is very often detected and observed by the detection method TI - test during operation/annual overhaul/ laboratory.

A good defence against serious dependent failures is to have good control of the causes of impairments with low impacts.

Better requalification of Eddy current testing method and –probe use, could reduce harm to heat exchanger tubes.

9. REFERENCES

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