European Commission

JRC TECHNICAL REPORTS

European Clearinghouse: Report on Events of the Cooling Chain of Nuclear Power Plants

Summary Report of an European Clearinghouse Topical Study

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2016

EUR 27691 EN

Joint Research Centre

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JRC Science Hub
https://ec.europa.eu/jrc

JRC98304

EUR 27691 EN

ISBN 978-92-79-54551-1 (PDF)
ISBN 978-92-79-54552-8 (print)

ISSN 1831-9424 (online)
ISSN 1018-5593 (print)

doi: 10.2790/067759 (online)
doi: 10.2790/943433 (print)

How to cite: R.M. Sanda, B. Zerger; European Clearinghouse: Report on Events of the Cooling Chain of Nuclear Power Plants; EUR 27691 EN; DOI 10.2790/943433

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Acknowledgements

This document summarizes a topical report prepared by the European Clearinghouse on NPP Operating Experience Feedback at the Institute for Energy and Transport of the Joint Research Centre (JRC/IET) with the support of the Institut de Radioprotection et de Sûreté Nucléaire (IRSN), France, and Gesellschaft für Anlagen und Reaktorsicherheit mbH (GRS), Germany.

The authors would like to thank MM. Miguel Peinador-Veira and Matthias Heitsch who helped in reviewing this summary report.

Abstract

This summary report presents the main results of an extensive review of operating experience related to deficiencies of the reactor cooling chain. The cooling systems included in the review are the Essential Service Water System (ESWS); the Component Cooling Water System (CCWS) and the Residual Heat Removal System (RHRS). More than 1000 events from the International Reporting System (IRS) database, the United States Nuclear Regulatory Commission (US NRC) licensee event report database and the French and German national databases were analysed.

Root cause analyses carried out allowed identifying Human and Organizational Factors (HOF) to represent a significant share in the spectrum of root causes. This finding is reflected in the long list of lessons learned from the events.

Recommendations how to avoid or mitigate similar events in future are included in the report. The lessons learned are presented separately in the Annex to this Summary Report. All recommendations made focus on enhancing nuclear safety whenever it might be affected.

1. Introduction

The centralized office of the European Clearinghouse operated by the Joint Research Centre (JRC) of the European Commission performs regularly in-depth studies on operating experience feedback of safety relevant equipment in NPPs. The topics to be covered by studies are identified by the European Clearinghouse Member States during their yearly Steering Committee meeting.

This Summary Report presents the major results of a comprehensive study [1] performed by the centralised office of the European Clearinghouse on operating experience from events related to the reactor cooling chain of nuclear power plants.

The report was prepared in cooperation with *Institut de Sûreté Nucléaire et de Radioprotection* (IRSN) and *Gesellschaft für Anlagen und Reaktorsicherheit mbH* (GRS).

This in-depth analysis of unusual events at nuclear power plants related to deficiencies of the reactor cooling chain was performed to extract lessons learned and provide recommendations to the international community to further improve nuclear safety and operational reliability. The systems considered and analysed are: Essential Service Water System (ESWS), Component Cooling Water System (CCWS) and Residual Heat Removal System (RHRS).

Failures of supporting systems which affect a large number of connected components and systems and which are not specific to the reactor cooling chain have not been included in the study. In addition, the study does not address the impairment of ESWS due to external hazards (blockage of heat sink, icing, external flooding…) as this was already covered by another topical study on external events [2].

2. Methodology

Operating experience from events related to the reactor cooling chain was gathered from four databases. IRSN and GRS analysed information from their respective databases, i.e. France and Germany while JRC processed information from the *International Atomic Energy Agency's International Reporting System* (IAEA IRS) and *United States Nuclear Regulatory Commission Licensee Event Reports* (US NRC LER). At the latest stage, JRC combined and further processed available results in the present study.

The databases were searched using specific searching tools (keywords and/or guidewords combined with logical operators) suitable for each database, yielding the first list of potentially relevant events. The reports contained into this first list were reviewed individually to determine their pertinence for the study, thus obtaining a screened list of relevant events.

The events relevant to the topic were classified into categories depending on:

- Plant status;
- Impact on safety;
- Affected system;
- Affected components;
- Direct cause of the event;
- Causal factor and root causes and
- Occasion and detection of the event.

For further analyses, the categories were divided into families and, if necessary, into sub-families. To achieve this goal, two consecutive steps were defined:

- Screening of databases and identification of events relevant for the reactor cooling chain;
- In depth analysis of the causes, root causes, contributing factors, consequences and lessons learned, and classification of them into families, in order to identify recommendations helping to avoid recurrence of similar events.

The present summary report focuses on the recommendations which can be drawn from the operating experience through analysing events affecting the RHRS, CCWS and ESWS cooling systems. System-oriented and situation-oriented lessons learned are presented separately within the annex of this summary report. It should further be noted that the full report of the study [1] presents all of them in detail.

3. Main Findings

This chapter describes the main statistical results of the study. No attempt to combine the statistics from the different databases was made as their reporting criteria are not consistent.

IAEA IRS search resulted in initially 206 events. Manual screening was followed by reading and analysing each event. For this study 142 events were selected.

Regarding US NRC LERs database, the search yielded 262 LERs. Following the screening stage, 208 LERs were found applicable for this study.

Screening the French national database revealed 381 events being relevant for this study. It has to be noted that a few events (24) of them were reported to IRS too.

The German database revealed 442 events relevant for the purpose of this report. Here, five events were double counted as they were reported to the IAEA IRS database too.

3.1. Affected System

Fig. 1 through Fig. 4 provide the statistical distribution of events for the three cooling systems. For RHRS the screening method used allowed to further split up the events to events concerning the main role of RHRS (i.e. heat removal, RHR) and the events concerning the secondary functions of RHRS (i.e. emergency core cooling and fuel building pools cooling, ECC/FPCS).

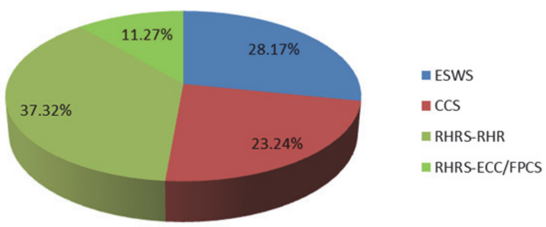


Fig. 1: Affected system in IRS reports

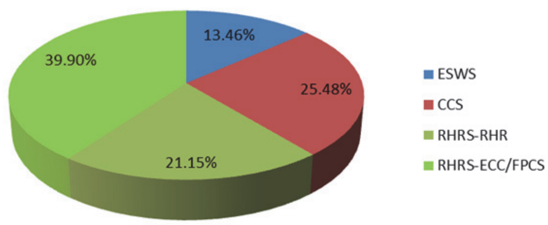


Fig. 2: Affected system in US NPPs

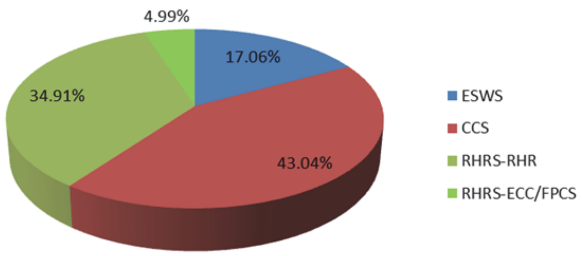


Fig. 3: Affected system in French NPPs

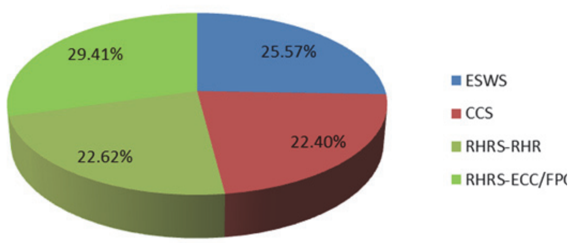


Fig. 4: Affected system in German NPPs

A high rate of events was recorded during either power operation or cold shutdown because these two states are the most common and many tests or maintenance operations can be carried out only during cold shutdown. It was observed that the number of events is quite similar for "On power" and "Cold shutdown" as operating technical specifications allow carrying out periodic tests or maintenance while the reactor is on power.

The events reporting a problem with RHRS were around 50% from the IRS and by about 60% from the US NRC database; while the number of the component cooling system and ESWS affecting events are significantly lower.

Regarding the French database, 43% of the reported events affect the component cooling system while 40% are related to the residual heat removal system. The residual heat removal function can be carried out by both, the residual heat removal (RHR) and the fuel pool cooling system, in case of total loss of the RHR. As the fuel pool cooling is only used as a backup for the residual heat removal when the reactor coolant system is totally depressurized, the number of events affecting this system is low (5%). The ESWS is responsible for 17% of the events. Note that one third of the events affecting the RHR are generic events.

As for the German distribution, 50 % of events affected the RHRS. Although the distribution of events between systems seems to be similar, events have a different impact on safety.

3.2. Casual Factors and Root Causes

The analysis of the causal factors and root causes for events from the four databases is presented in Fig. 5 to Fig. 8.

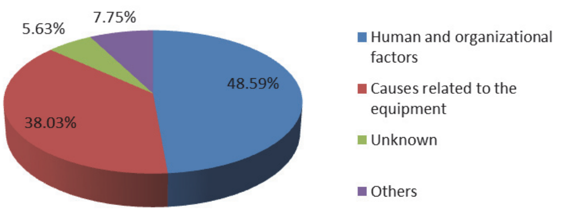


Fig. 5: Root causes in IRS reports

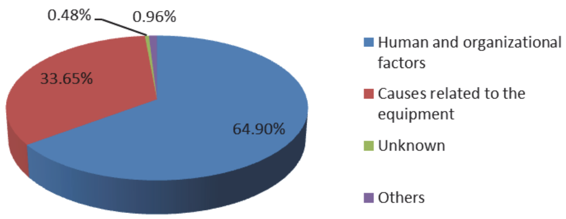


Fig. 6: Root causes in US NRC reports

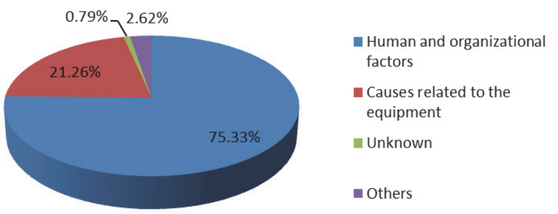


Fig. 7: Root causes in French events

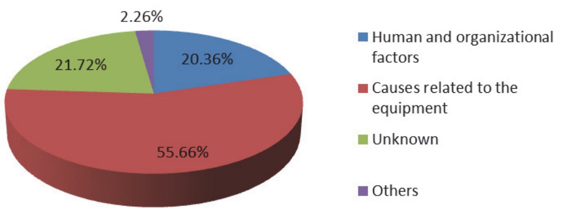


Fig. 8: Root causes in German events

The main causal factor or root cause is "Human and Organisational Factor" (HOF). The different distribution in the German database is not a surprise as in the German reporting system small leaks, non-trough wall cracks etc. have to be reported too (regarding mechanical failures). As for electrical failures these were classified according to equipment since a high percentage of the causal factors and root causes could not be identified during the investigations carried out. A probable reason for that is the fact that the investigation of the root causes of electrical failures is more complex and sometimes the components were destroyed during the event.

Fig. 9 to Fig. 12 present the detailed root causes of the family "Human and Organizational Factors". Errors during tests or maintenance activities followed by misalignment of systems or components and procedural deficiencies are the dominating causes consistently identified from all four databases.

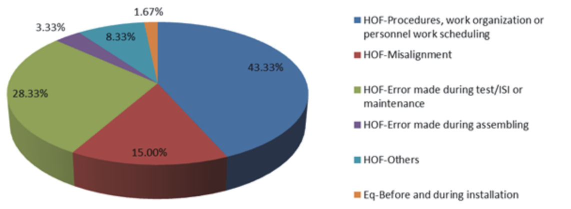


Fig. 9: HOF root causes in IRS reports

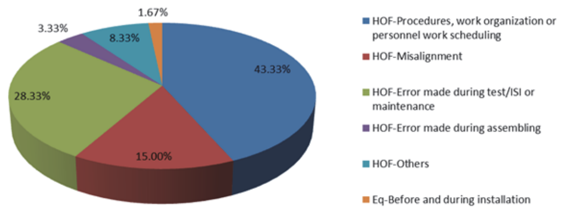


Fig. 10: HOF root causes in US NRC LERs

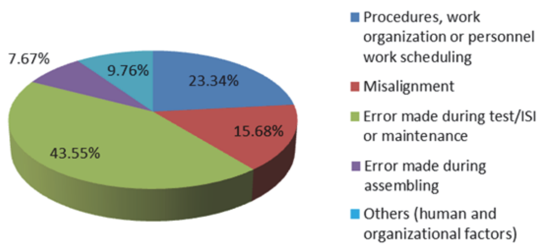


Fig. 11: HOF root causes in French events

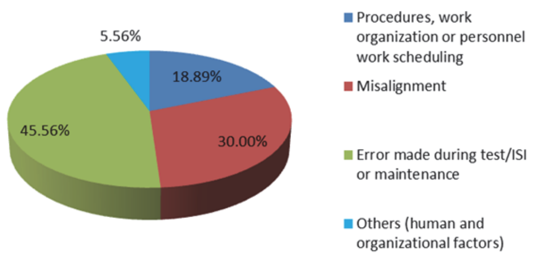


Fig. 12: HOF root causes in German events

The second largest contributor to root causes was found to be "Equipment" (see Fig. 5 to Fig. 8). Fig. 13 to Fig. 16 illustrate the statistical analysis performed for the detailed root causes related to equipment.

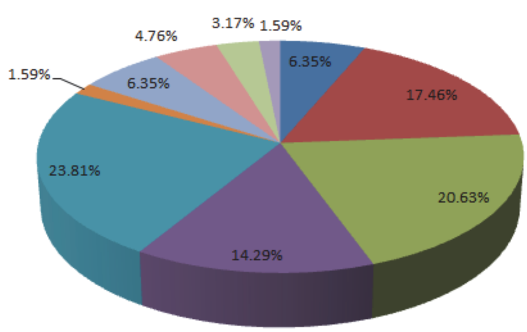


Fig. 13: Equipment-related root causes in IRS reports

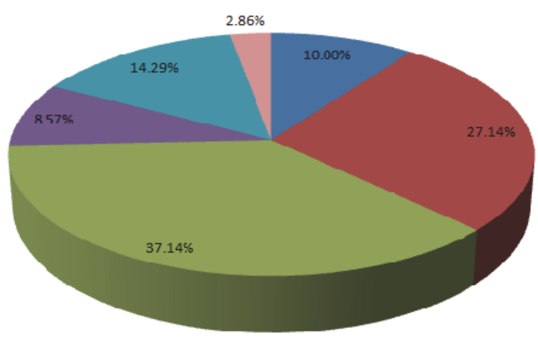
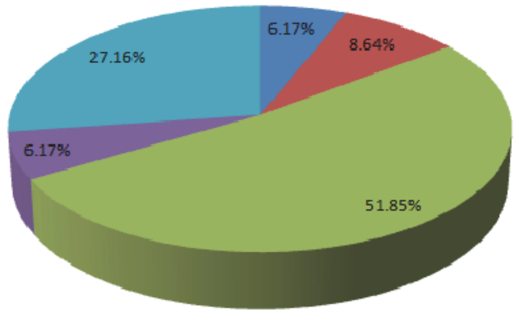


Fig. 14: Equipment-related root causes in US NRC LERs



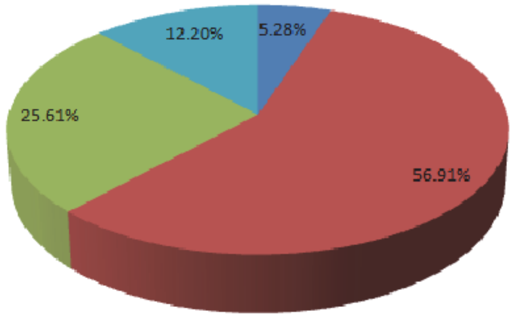


Fig. 15: Equipment-related root causes in France

Fig. 16: Equipment-related root causes in Germany

Among events of the sub-families of "Causes related to equipment", events due to fault before/during installation and after installation and those caused by ageing are quite equally distributed. Events in the sub-family "Others" are quite numerous and include detection of foreign objects, faulty internal coating, deficiencies caused by environmental conditions, oscillations, etc.

The statistics in the figures above show different structures in the distribution of events. This is due to the different reporting criteria applied in USA, France and Germany; while no well-defined reporting criteria exist for IRS and causes are more evenly distributed.

In the French SAPIDE database the non-compliance criterion with the technical specifications corresponds to about 50 % of the reported events. The technical specifications effectively authorize a specified time of unavailability for safety equipment. If the unavailability time of system/component of the reactor cooling chain exceeds the authorized time, the reactor shall be passed at shutdown. In other cases, notably if the unavailability time is less than the time allowed by the TS, failures are declared in another database called SAPHIRE managed by the licensee and accessible to the French safety organisations.

In Germany every failure or unavailability has to be reported. For example, if a pump does not start, it is immediately declared as unavailable, even if the damage can be repaired within the time frame specified in the technical specification (in most cases: unavailability of one out of four redundancies allowed for 14 days). Thus, in Germany the requirement to report and the unavailability period are not coupled.

4. Recommendations

In this section event related, specific recommendations are listed and discussed. The recommendations shall help to learn from events to avoid their recurrence and to improve the safety of NPPs.

4.1. RHRS Vibration and thermal fatigue

The positioning and condition of the supports have a strong effect on pipe vibration phenomenon. For systems particularly sensitive to vibration, special surveillance should be carried out. It is important to **remove nozzles that are unnecessary and sensitive to vibrations** in safety-related systems and to perform a vibration analysis whenever modifying the design of the system (including determination of vibration natural frequency).

As the residual heat removal system includes by nature fluids of different temperatures, special attention should be paid to **design and surveillance of mixing areas** as well to operation modes of RHRS to avoid excessive thermal fatigue which could lead to crack initiation and propagation. Some examples of preventive measures are:

- Limitation of time during which the RHRS operates when the temperature in the primary system is higher than 90°C;
- **Surveillance tests of mixing areas using ultrasonic techniques** after 450 hours of operation where the temperature in the primary system is higher than 90°C, or five years at the most, after the sections involved have been replaced.

4.2. Configuration errors (addresses both RHRS and CCWS)

The study has highlighted a number of occurrences where the RHRS cooling function was lost or RCS unexpectedly drained due to configuration error caused by:

- Improper communication between the Main Control Room and the local operators or between plant departments;
- Insufficient administrative controls;
- Improper tasks sequencing;
- Insufficient control of work.

This shows the need for:

- **Reinforcement of the work control process** (as regards: work permit release and the importance to plan works, which should not be performed simultaneously, in separate stages of the outage planning; the control of adequate timing of physical tagging of equipment; the need to keep operational control in the MCR of ongoing work).
- Specific analysis of which plant interventions and tests may be allowed during mid-loop operation and more generally all operational phases with reduced RCS water inventory, including the transitional RCS drainage phases.

In addition to these faults, other configuration activities led or could have led to the RCS draining not because the activities were not properly carried out but because these activities resulted in drain down paths which were not previously identified. This shows that **design vulnerabilities of RHRS** and connected systems with potential RCS drain down should be thoroughly analysed so as to eliminate configurations with potential for drain down paths. Accordingly, creation or modification of configuration procedures for

RHRS and connected systems (for tests, maintenance or other purposes) should consider the potential for drain down paths.

There are also numerous possibilities for interconnecting both CCWS trains. This normally triggers an alarm in the control room as such an interconnection could lead to the loss of both trains. However, experience has shown that existing configuration procedures and alarm may not be enough to prevent human errors. It is therefore recommended to reduce the risk of human failure by **providing interlocks on isolation valves on redundant trains**.

4.3. Mid-Loop operations

Related to mid-loop operation, three barriers of defence should be maintained:

1. Prevention of RHRS vortex formation by installing instrumentation to make the primary coolant level measurement more reliable (for instance additional Ultrasound Testing sensors) and arrangement of RHRS operating parameters limits in order to increase the margin relative to the risk of pump losses.
2. Enhance monitoring by implementing RHRS pumps vortex detection based on monitoring the operating parameters of these pumps (flow rate, pressure and motor current).
3. Automatic makeup of borated water into the primary cooling system in case of loss of RHRS pumps due to vortex formation.

If feasible, a requalification test for the Instrumentation and Control of the automatic makeup function should be scheduled right before the RCS is taken to mid-loop operation. An overall availability check of the automatic makeup function should be carried out with the reactor fully unloaded and RCS water at minimum level, whereby RHR pumps are stopped.

These hardware precautions should include the consideration of human and organisational factors:

- Direct indication of the critical parameters such as water level as well as automatic alarms should be available to the control room command.
- Detailed procedures should be available for the RCS drain-down process, which should clearly describe the respective responsibilities. Procedures should require recording of the actual water level during drain down to maintain awareness of level. It should also be made clear how the potential calculations are used to evaluate the water level from different sensors, including uncertainty and round-off. These procedures should be based on information relevant for a specific unit and on specific operating conditions for the definition of limiting parameters (such as minimum RCS water level or maximum RHRS flow rate).
- Specific emergency procedures for the recovery of the cooling function in case the RHRS fails should be established.
- Although problems related to operation of the RHRS at mid-loop are well known, it seems necessary to permanently refresh the attention of the operators to the precautions to be taken. Operators should be trained for operating phases where the risk of losing the residual heat removal function is high and for procedures mentioned above. A full-scope simulator would allow training in mid-loop operation.
- The rarely performed drain-down operation is a type of operation where operator performance can be enhanced by focusing on briefings and review of commands, control, and communication at the beginning of the operation and after shift changes.

4.4. RHRS operating in safety injection mode

Another characteristic of RHRS is the potential for reaching vortex conditions at the RHRS pumps suctions because RHRS may be connected to systems with unfavourable pressure and temperature values (apart from mid-loop operation).

It should be ensured in the analysis of design basis accident that the operation of RHRS as Low Pressure Safety Injection is not compromised by limiting conditions of water bodies (pressure / temperature / level) from which the water is pumped up and which could lead to vortex conditions in the RHRS suction pipes. If needed, corrective measures should be taken such as design or procedure modifications.

Other reported potentials for RHRS failure when being used as ECCS are pressure differences between RHRS and ECCS. These could cause the connection valve thrust to be insufficient and thus prevent valves from operating. Temperature differences between the two systems mentioned could result in steam voiding when the systems are connected.

It should be also ensured in the analysis of design basis accident that the limiting difference of conditions (pressure and temperature) between RHRS and ECCS do not impair the safety injection when these are lined-up. If needed, corrective measures should be taken such as design or procedure modifications.

4.5. Unavailability of RHRS due to lubrication issues

Adequate measures related to lubrication practices should be taken to avoid a common mode failure that would not be limited to the residual heat removal pumps. For example:

- Ensure traceability of lubrication operations.
- Limit the number of types of grease intended for lubrication of safety-related rotating machines, with a reasonable objective of two types of grease per plant.
- Use of different types of grease, depending on whether the components to be lubricated are located inside or outside the reactor building.
- Choose types of grease that are reputedly mutually miscible.
- Use the same type of grease and the same lubrication frequency for both motor and pump.
- As concerns the RHRS pumps which operate intermittently and are located inside the reactor building (problems associated with frequency of lubrication and premature ageing of grease caused by ionizing radiation), it is requested to make-up the grease at the beginning of refuelling outages so as to expel all old grease. Such make-up is recommended at the beginning and end of each ten-yearly outage.
- Ensure clear labelling of lubricators.

4.6. Inadequate calibration of RHRS flow rate meters

Considering the wide range of RHRS operation conditions (mainly temperature conditions), appropriate adjustments should be made to the RHRS flow measurement to ensure measurements are correct and requirements of minimal flow rate for the RHR as the Ultimate Heat Sink are fulfilled.

4.7. Cooling to RCP thermal barriers

Considering that CCWS is a barrier between the radioactive fluid and the environment, appropriate attention should be paid to the design and maintenance of the CCWS isolation valves. CCWS may convey fluids with high levels of impurity on both sides of CCWS heat exchangers and a leak at these heat exchangers could lead to a direct path of radioactivity out of the Reactor Building. In particular, a leak of RCP thermal barriers with non-operable isolation valves could lead to a non-isolable LOCA.

All analysis (for example the plant fire safe shutdown analysis) should recognize the need to protect the RCP thermal barrier heat exchanger for hot safe shutdown and should evaluate the ramifications of not protecting the heat exchanger. The applicable design basis documentation should incorporate the actions to isolate the RCP seal water return line in the applicable (fire, for this example) area, while respecting the compliance strategies and the manual action timeline analyses.

4.8. Operation of CCWS in accident conditions

During accidental conditions CCWS as a closed cooling water system is subject to significant transient temperature variations because of the limited system heat capacity and the potential for substantial changes in heat addition and heat rejection rates. The complex nature of some of the sub-systems may make it difficult to correctly identify the most limiting potential operating configuration of CCWS. Certain safety-related components served by CCW systems, such as air conditioning units and emergency diesel generators may fail in a non-recoverable manner as a result of temperature transients outside the system design basis. Because temperature transients initiated by an accident may affect redundant parts of the closed cooling water system, safety-related components in redundant trains necessary for mitigation of an accident may be affected.

In addition, the configuration of the CCW system may change in the course of the accident as some sections are first isolated, and then de-isolated, which could lead to pressure and temperature transients and which should be considered as well to identify the CCWS limiting conditions.

It is therefore recommended that **CCWS limiting operation conditions** (Pressure / Temperature) should be carefully identified <u>during and after</u> accidental phase and that those limiting conditions should be included in the design of CCWS and CCWS-cooled components and/or for the establishment of Emergency Operating Procedures.

4.9. Pressure locking and thermal binding (concerning both CCWS and RHRS)

The potential for failure of systems to perform their safety functions as a result of thermally-induced over-pressurization is dependent on many factors. These factors include leak-tightness of valve seats, bonnets, packing glands and flange gaskets; piping and component material properties, location and geometry; ambient and post-accident temperature response; pipe fracture mechanisms; fan coast-down characteristics and the effect of fan operation on water in the associated fan cooling system; relief valves and their settings and system isolation logic and set-point. Engineering design and modification evaluations which include systematic assessment of heat input to systems and components with consideration of factors mentioned above should detect conditions influencing system operability under normal operations, operational transients and accident conditions. Following identification of those conditions, corrective actions should be taken including design modifications (drilling an internal hole, adding a vent line…) and operation procedures (emptying pipes …). In some cases after proper assessment an internal valve leak rate rather than complete water tightness may be accepted by the Technical Specifications.

Moreover, thermal over- pressurization should not be understood as an independent active or passive failure in the sense of the "single failure" concept. This means that active or passive failures due to over-pressurization should be considered in the same system and other systems in evaluating plant response to a postulated accident. For instance, if relief valves are installed to prevent overpressure conditions, consideration should be given to the effects of a stuck-open relief valve and consequent diversion of system flow, associated environmental flooding and radiation hazards.

4.10. Temporary device rendering one CCWS train unavailable

Temporary devices (used during periodic tests for example) should be managed effectively. These devices represent a certain type of equipment modification which should remain in place only exceptionally after having conducted a risk analyses showing the absence of impact on any safety feature. In any case they should be managed according to existing rules.

4.11. Failure of the 10kV circuit breaker of a CCWS pump

For safety reasons the expansion shafts of the circuit breakers should be changed after a number of switching cycles considerably less than recommended by the vendor/manufacturer. Circuit-breakers with a comparable construction should be checked if there is a risk of micro-cracks caused by the manufacturing process.

4.12. External corrosion of ESWS components

Experience has shown that ESWS components may be subject to cracks which are not due to inner corrosion or erosion but also to external corrosion induced by environmental factors or to structural fault (inadequate supporting…). The layout and structure of ESW systems is generally plant specific but it may include piping sections that are buried and not readily accessible for inspection. Buried sections of piping can be subject to periodic wetting from storms or local flooding conditions. Exterior protective coatings may not be fully intact due to improper installation, age degradation, or maintenance practices. It is also possible for some ESW piping sections to be located in vaults or pipe chases that are subject to periodic flooding and/or high humidity. Other components like hatch neck and hatch neck flanges are subject to corrosion too.

This shows that:

- Exterior surface of ESWS piping and other ESWS components should be protected against **humidity-induced corrosion** (coating, prevention of rainwater intrusion…).
- ESWS piping and other ESWS components should be subject to periodic inspections aiming at:
    - Detecting initiators for corrosion or cracking (for instance water infiltration through gallery walls or roofs, presence of water on the floor, inadequate supporting...),
    - Verifying the quality of corrosion protection (coating…) and
    - Detecting corrosion before leaks occur.
- Piping and components conditions should be recorded and trended appropriately.

Visual inspection of the outer surface of those piping and components is not always possible and it may be needed to remove interfering material such as mortar. Consequently it should be defined in the inspection programme how and under which conditions this material should be removed (systematically or depending on findings made in the surrounding).

Inspection may be of different nature (visual, NDT, etc…) depending on the access to the components. More detailed information about the different types of inspections can be found in [9].

4.13. Prevention of Micro-biologically Induced Corrosion

The ESWS is responsible for cooling the CCWS, also in emergencies. The ESWS heat sink is a water reservoir such as a river, lake or sea which involves by nature that ESWS components can be exposed to harsh environment. Apart from clogging of ESWS filters by debris (see [3]), experience has shown that this harsh environment causes damage of components by corrosion due to saline environment, rainwater or micro-organisms. This is not a new phenomenon; corrosion of ESWS components has been already been described in e.g. [4], [5] and [6].

MIC on carbon steel increases general through-wall pitting and fosters the formation of tubercles. Tubercles consist of corrosion products, microbes, and debris. Tubercle growth could restrict cooling water flow to equipment.

It should be noted that stainless steel piping is not immune to MIC because microbes can attack at the weld heat affected zone in stainless steels when this zone becomes sensitized. MIC can also damage metals lined with polymeric materials, typically at coating imperfections.

Treatment against established colonies of tubercles involves a combination of mechanical or chemical pipe cleaning, continued water treatment and regular maintenance. Continuous flow conditions have been found to prevent the attachment and growth of microbial films.

In case of biocide injection, it should be ensured that the injection point allows biocide to reach all parts of the ESW system potentially subject to MIC, in particular dead-end lines and small diameter pipes where injection may be problematic.

It may be necessary to replace materials if MIC severely damages them or where mitigation measures cannot bring the system conditions under control. Possible alternatives include replacing carbon steel with stainless steel or replacing stainless steel with more resistant materials, such as 6-percent molybdenum stainless steels, nickel base alloys, titanium, or non-metallic materials.

In any case, the material selection should be done in close collaboration with the manufacturer. Especially the material of safety related components for low flow areas should be tested in conditions representative of the fluid carried by ESWS.

4.14. ESWS liner peeling off

Experience with numerous cases of ESWS piping inner coating peeling off exists. Coating material is entrained in the system and can cause clogging and/or results in the piping inner surface to be unprotected against corrosion. This shows that bonding of the coating material should be ensured with adequate procedures and good adhesive properties, especially if the coating is applied in-situ over an existing layer of coating. Proper measures (procedures, tools, training…) should also be taken to limit the damage to inner coating when inner surfaces are cleaned up from foreign material; coating conditions should be verified after such activity.

An inspection programme should be established for the inner surface of ESWS piping and components in order to verify the condition of the inner coating (proper adhesion, absence of air bubbles) and to detect the presence of corrosion or erosion.

The ESWS piping and components should be inspected exhaustively with an inspection frequency which should be adapted to the potential for corrosion (for instance locations with low or no flow or influenced by cavitation). In case visual inspection is not possible (such as for small diameters) other techniques should be envisaged (fiberscope, CDD camera, inspection robot…).

4.15. Leakage of ESWS heat exchangers

Although leaking ESWS/CCWS heat exchangers are not an immediate threat to safety because they still provide sufficient cooling, it should not be forgotten that these exchangers constitute a containment barrier and that leaks in this barrier undermine the defence in depth (experience has shown that a direct path of radioactive fluid from RCS to the environment via simultaneous leaks of two lines of barriers cannot be excluded). For this reason, in order to avoid that the situation of a leaking exchanger lasts and deteriorates over an extended period of time, maintenance programmes should be defined for these exchangers: preventive and predictive maintenance but also corrective maintenance triggered by pre-defined leak rate thresholds. The maintenance programmes should consider the design of exchangers in relation to the corrosive environment as well as the potential impact of mechanical (or high pressure) cleaning of the exchangers. The programmes may also include chemical treatment and replacement of parts.

4.16. ESWS pump not starting during periodic test

The function of indicator lamps of different operation modes (automatic/manual) of safety relevant components has to be checked to ensure that the component is always at the right mode.

4.17. Loss of seismic qualification of several valves caused by inadequate maintenance

Maintenance teams should regularly be informed about standard practices (proper screw identification, tightening torque, choice of tools, etc.) that affect seismic qualification in the long term. Very precise maintenance procedures that include all information required to ensure seismic qualification of equipment and to compensate for any lack of worker knowledge with standard practices should be established.

4.18. Valves setup when connecting ESWS with non-safety related system

In case ESWS is connected to a non-safety related Service Water System, proper measures (maintenance and tests) should be taken to ensure that isolation valves between the two systems would fulfil their isolation function in case ESWS is in operation. A failure could challenge the sustainability of the alternate ultimate heat sink.

5. Conclusions

This report has studied more than 1000 unusual events related to the reactor cooling chain with information obtained from both, international sources and national databases (USA, France, and Germany).

Although the different reporting systems of the four databases used in this report did not allow identifying a common pattern for the root cause analysis of events, it became evident that Human and Organisational Factors have a significant share of the root causes. One representative example is configuration errors. All three technological systems studied (ESWS, RHRS and CCWS) are prone to such weaknesses because of the existing possibilities for interconnection between trains or even units (for ESWS), the existing connections with other systems (mainly for RHRS where configuration errors can lead to so called "Inter Systems LOCA") and the complexity and relatively low frequency of some activities like draining down the RCS to operate at mid-loop.

There is consensus that mid-loop operation, especially at the beginning of an outage, is an activity inducing a significant risk. Progressive improvements of measures aiming at reducing this risk have been implemented: new equipment, improved procedures and work organization, more training, etc…It is however not possible to conclude that these measures allowed to reduce the event frequency: events were still reported to the IRS in the 2000s while the oldest one dates back to the 1980s. According to [10], the loss of RHRS at mid-loop operation has occurred more than 50 times in a period of 25 years. It indicates that mid-loop operation should remain in the focus starting from outage planning to the phases of preparation and implementation.

As for equipment-related causes, the three systems concerned are subject to specific issues:

- Pressure locking and thermal binding mainly for RHRS and CCWS because these two systems may experience different operating temperature conditions; both in normal and accident conditions.
- Overpressure of RHRS. Although this type of event may also be caused by human or organizational factors which can affect many other systems, overpressure is a concern specifically for RHRS as this system is connected to RCS. The operating pressure of RCS may exceed the RWRS relief valves pressure set-point creating the risk that these valves do not reseat as expected.
- The CCWS is a closed cooling system, providing coolant to many different users and in many different conditions. The multiplicity of users and operational conditions (normal operations, different accident scenarios) makes it difficult to evaluate the different heating loads and the limiting temperature conditions which may exceed the design value of CCWS or CCWS-cooled components.
- CCWS and ESWS may include non-safety related sections, which makes it possible that safety-related sections are jeopardized by failure or potential failure of non-safety related parts.
- ESWS is by nature subject to harsh and corrosive environment. This environment together with a very difficult access to some sections of ESWS may allow for corrosion-induced defects on both, inner and outer surfaces. Consequently it initiates, allows propagating, and if it remains undetected, eventually leads to catastrophic ruptures as seen in this report.

The described issues and their potential consequences may be safety relevant and require adequate measures to ensure the continuity of the cooling function and help to maintain the containment barrier function. Lessons learned from the many events reviewed were used as a feedback to develop specific recommendations to minimize or avoid any safety impact of similar events in the future operation of related NPPs. The recommendations proposed cover all three cooling systems reviewed in this report.

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List of abbreviations and definitions

BWR	Boiling Water Reactor
CCW(S)	Component Cooling Water (System)
ECC(S)	Emergency Core Cooling (System)
ESW(S)	Essential Service Water (System)
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
HOF	Human and Organisational Factor
IAEA	International Atomic Energy Agency
IRS	International Reporting System
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
JRC	Joint Research Centre
LED	Light Emitting Diode
LER	Licensee Event Report
LOCA	Loss of Coolant Accident
MIC	Microbiologically induced corrosion
NPP	Nuclear Power Plant
NSS	Nuclear Sampling System
OEF	Operating Experience Feedback
OECD/NEA	Organisation for Economic Cooperation and Development / Nuclear Energy Agency
PWR	Pressurized Water Reactor
RCP	Reactor Coolant Pump
RCS	Reactor Coolant System
RHR(S)	Residual Heat Removal (System)
RWST	Refuelling Water Storage Tank
TOER	Topical Operating Experience Report
TS	Technical Specification
US NRC	United States Nuclear Regulatory Commission

List of figures

Annex: Lessons learned

Typology	Lessons learned
Vibration or thermal fatigue leading to RHRS piping leaks/breaks	• The positioning and condition of the pipe supports have a strong effect on the pipe vibration phenomenon. The residual heat removal system is particularly sensitive to vibration during the evacuation phase and during the transition to mid-loop operation (the minimum primary coolant level with the core loaded). It is important to remove any nozzles that are effectively unnecessary and are sensitive to vibrations in safety-related systems. • The analysis found that the natural frequency of valves may come very close to the frequency of the flow induced vibration by the RHR pump because the relevant valve was replaced by one with a larger diameter during a previous periodic inspection. After replacement, it was estimated that the relevant drain valve became resonant whenever the RHR pump was in operation and this caused fatigue crack at the joint portion of the valve and the RHR pump outlet piping. This could result in a through-wall crack too. Each valve should only be replaced with those designed. • Prolonged use (above normal) of the RHR system with a high flow in the cold leg aggravates thermal fatigue stress in the mixing areas. The plasma technique used to weld the shells of RHR system elbows may be also an aggravating factor which could explain the existence of long cracks, source of leaks in the RHR system. The main mixing area and the mixing area of the mini-flow line should be designed to improve resistance against thermal fatigue.
Loss of RHR cooling function due to configuration errors	• Execution of two test procedures in parallel should be avoided, especially when dealing with valves (even different) on the same circuit. Lack of accurate preparedness, planning and communication could lead to staff injury when losing inventory. A typical example is to open a vent valve for performing a test and then, without receiving confirmation that the vent valve is closed, to open the isolation valve – thus aligning the circuit to the inlet of the still open vent valve, causing a hot water risk for workers and a cooling water loss. • More attention should be paid to valve manoeuvres especially when the reactor is in an operating mode that poses a significant restriction to natural circulation, e.g. open vessel with the upper internals still in the vessel and steam generators having nozzle-dams installed. • Perfect coordination should be maintained at all times, via redundant channels and using a 3-way communication between the control room and auxiliary building personnel. Valve testing and manipulation, in particular, must be carefully coordinated so that system status is maintained for accomplishing safety-related functions and preventing inadvertent spills. • Whenever the need is recognized, piping design should be improved. Inappropriate isolation valves positioning while RHR is on cooling could result in a fast loss-of-coolant event and

Typology	Lessons learned
	consequently a common-mode loss of ECCS capability. • Work orders should be controlled and compared against each other also from the time-line point of view. The analysis showed the need to reinforce the work control process.
Vortex formation at the RHRS pumps suction	• A significant risk is involved in draining RCS and decreasing the RCS level, – at mid loop operation before unloading the core. Studies to prevent loss of water inventory have been made and resulted in the following improvements: • Implementation of a system to detect vortex formation at the RHRS pump suctions, based on monitoring operating parameters of these pumps (flow rate, pressure and motor current); • Implementation of an automatic borated water makeup system in the RCS, making it possible to guarantee that the water inventory will be maintained in the extreme situation of loss of the RHRS due to vortex formation.; • Improvement of RCS water level monitoring (clear calibration procedures, inter-comparison of sensors, etc…) • More attention should be paid to level gauges and sensors configuration. Vacuum or gas presence in the instrument legs can cause a false level indication, potentially leading to a water level drop and subsequently to a loss of the RHRS pumps due to vortex formation causing cavitation. • Increasing or decreasing flow rates should be preceded by computer simulations and should be at all times correlated with the water level. The effect of flow rate increase or decrease should be examined under conditions representative for the plant and for each process (e.g. degasing). • Drain-down is a sensitive, infrequently performed, operation. Such operation, if manually controlled, should be based on a direct indication of the critical parameter (water level) available to the control room command and should benefit from an automatic alarm on decreasing level (due to high nitrogen pressure, for example). Loss of control of the primary water level during draining to mid-loop has the potential of leading to loss of shutdown cooling.
RHRS operating in Safety Injection mode	• Events pointed out that the adequacy of the net positive suction head (NPSH) available for emergency core cooling (including core spray and decay heat removal) and containment heat removal pumps may not be adequate under all design-basis accident scenarios. In some cases this inadequacy was the result of changes in plant configuration, operating procedures, environmental conditions, or other operating parameters over the lifetime of the plant. • The temperature of the fluid at the RHRS pump suction is a factor that could also render the pumps inoperable. If a design modification cannot be performed, then at least the operation procedures should be revised to ensure that when RHRS is aligned to ECCS injection mode, the temperature of the RHR suction lines from the RCS isolation valve are within prescribed limits.

Typology	Lessons learned
	• Periodic Engineering Reviews are extremely useful to recognize un-analysed conditions or to revisit scenarios previously analysed using designer assumptions and hypotheses. The setpoint calculations proved to be a design issue when used to prevent air ingress into the safety-related water-systems, potentially resulting in damage to pumps and a degradation or loss of the safety function. A level setpoint calculation should: • Use appropriate methodology to predict the conditions when vortexes appear in tanks; • Use conservative assumptions to allow for the time required to complete switching of pump suctions (operator response times and valve stroke times); • When needed translate analysis results into operating procedures as soon as possible; • Account for instrument uncertainties in order to assure an adequate "vortexing" margin for the RHRS pumps during reactor coolant system mid-loop operation; • Account for the potential effect of gas ingress on the level of instrument sensing lines.
Interconnection of both redundant trains of CCWS	• Usually the plants use purely administrative measures extensively to prevent wrong manoeuvrings; these measures should be doubled by physical interlocks on isolation valves on redundant trains to avoid interconnections which, in the event of a leak in one train, may lead to the loss of the entire system. • Visual alarms close to the equipment (a panel light, for example) should be in place to display a warning when an interconnection between two redundant trains is established. In addition to this the operating teams should be provided with alarm processing instructions.
Loss of cooling of Reactor Cooling Pumps (RCP) thermal barriers	• Some events reported the disruption of RCP seal cooling water due to clogging of filters installed upstream the seal cooling water pumps. More attention should be paid to the periodic maintenance of these filters. • An analysis was carried out on this type of events which occurred at different occasions and lessons learned are as follows: • It should be analysed and identified whether sufficient alarms, protection systems and interlocks in place; • Where applicable intermediate circuit systems should be equipped with intermediate circuit pump recirculation lines and the operating algorithm for the intermediate circuit system should be altered consequently; • It should be thoroughly analysed for how long RCPs can operate with no intermediate circuit water supply; safe operating conditions in the technical specifications should be amended wherever necessary; • Taking into account ergonomic factors only one activation algorithm for operation of the light mimic panels and sound alarms in the unit control room should be applied. • Periodic engineering reviews should identify whether the conditions described in the abnormal operating procedures

Typology	Lessons learned
	include steps to ensure that at least one CCWS pump is operating while the other operating pump is affected by a hazard (fire, for example). The applicable design basis documentation needs to incorporate all actions to isolate the water return line in the area affected by the hazard, while respecting the compliance strategies and the manual action timeline analyses.
Operation of CCWS in accident conditions	• When establishing the maximum post-accident CCW system temperature, (i.e. combination of maximum heat transfer from systems cooled by CCWS and minimum CCWS heat rejection capability) appropriate methodology should be utilised. The methodology should take into account local conditions around the coolers, together with the impact of the harsh environmental conditions in other places of the plant on the quality of the cooling fluid used to remove heat elsewhere. In addition, when designing the post-accident conditions for monitoring plant parameters, the equipment's procurement specifications should be based on the post-accident conditions and not on the normal CCWSS temperatures. • Similarly, in case of steam line break inside the containment and subsequent isolation of CCWS, the temperature of water contained in the CCWS isolated sections (in this case sections cooling RHRS and RCS excess let-down) would increase temperature to beyond design, leading to potential line damages during or after isolation phase when the "hot plug" of water is released. Moreover, the margin to vaporisation would be reduced. The safety analysis should also consider the possibility of restarting the CCWS lines that had been previously isolated. • Regarding pipe reinforcement for preserving its integrity under accident conditions: • The need to reinforce the existing support structures of CCW sections supplying RHR components which could potentially be affected by the passage of the hot plug should be verified. Operability of CCW/RHR sections under all accident conditions including restart has to be ensured. Reinforcements should be designed to withstand seismic loads. • Safety margins should be increased with respect to the risk of vaporisation through modification of accident operating procedures during restart with a view to ensure the proper behaviour of the CCWS pumps. Special precautions will be necessary to restart the CCWS section supplying the RHR components after containment isolation, i.e. containment isolation valves must be opened corresponding to the fluid flow direction. This will ensure that the hot plug is subjected to the discharge pressure of the CCWS pumps, thereby ensuring the elimination of potential steam pockets formed during isolation; • Although it is considered very useful, serious efforts should be made to limit the use of the excess let-down line in the accident operating procedures.
Pressure locking and	• The thermal expansion of water in CCWS piping could produce undesirable consequences. When water trapped inside an

Typology	Lessons learned
thermal binding	isolated portion of the circuit is exposed to increased ambient temperature, the inside pressure will build-up, thus potentially preventing normal operation of valves and requiring operation of drain valves. This kind of phenomenon could also jeopardize the structural integrity of the containment penetrations. • Pressure relief valves should be installed on each of the containment air cooler branch lines. The postulated accident scenario (e.g. a loss-of-coolant accident), should take into account that depending on the scenario, the containment isolation logic could initiate closure of the outlet valve, thereby causing water flow to cease. Heat from the containment environment would cause the water in the fan coolers between the inlet check valve and closed outlet valve to expand, potentially causing a rupture in the system. The rupture would depressurize the isolated portion of the system and re-establish water flow from the operating safety-related portion located outside containment through the inlet check valve. The water would spill from the rupture and deplete the surge tank, thereby causing failure by overheating of safety-related equipment served by the remainder of the system.
ESWS piping outer corrosion	• Operational experience of BONNA pipes had demonstrated tendencies of corrosion problems, especially when the environment is a marine (salty) one. In order to prevent such weakness, modifications of the original design should be made appropriately such as introducing an inner anode made of a platinum-titanium along the pipe. It may sound trivial, but simply painting the external surface of pipes minimizes the potential for corrosion. • The inspection manholes usually connected to the pipe through a vertical neck made of steel proved to be another point prone to corrosion due to the harsh environment, as well as condensation phenomena and flooding with rainwater inside the hatches. Periodic thickness measurements of all manhole necks should be performed in order to determine the minimal thickness required guaranteeing the structural integrity of necks – conservative assumptions should be made when performing such calculations. In addition hydraulic tests should be made at a frequency to be determined based on local environmental conditions. • Any surveillance programme should include "blind spots" such as the ESWS gallery. The licensees tend to reduce the frequency of inspections for the underground locations between the main plant buildings and the raw water (sea, river, and pond) intake area. Two types of inspections should be carried out: routine inspection for piping external parts and in-depth inspection for piping internal sides. • Related to buried ESWS piping, precautions should be taken to assure the adequacy of their supports (e.g. concrete supports), especially at points where mechanical tensions may appear (for example when passing from sand to normal soil, or when exiting the pump house or filter house). These features should be addressed starting from the design phase; for adequacy of future inspections and repairs, the blueprints should be easy to

Typology	Lessons learned
	track to facilitate any work that may need to be performed. If the ESWS piping is located near adjacent trenches (for other cables or pipes), analyses should be made to determine the consequence of an ESWS pipe leak for the adjacent trenches.
Micro-biologically induced corrosion	• OEF shows that stagnant or intermittent-flow conditions, as in the case of emergency diesel service water supply headers, are conducive to the growth of microorganisms that can accelerate corrosion rates. It shows that crevices such as those in piping welds that lack penetration can enhance MIC attack by giving a place for deposits and in turn for bacteria to collect. • All the licensees should regularly treat the water supply lines with biocide or corrosion inhibitors at least when the chlorination injection point for the main water headers is located, per design, downstream of the branch lines to plant equipment (e.g. the emergency diesel generators). The program of hypochlorite injection should be designed to mitigate MIC problems also within stagnant dead-end sections. • The generic evaluation of operating experience feedback showed that the degradation mechanism MIC can basically be important regarding the impairment of heat removal. At the ESWS the chosen materials as well as the constructive and operational boundary conditions should be analysed taking into account the potential for MIC. The specification of inspections should include measures to check if MIC mitigation programme is sufficient.
ESWS piping inner coating peeling off	• Foreign materials may be an issue for ESWS heat exchangers, for example debris from ESWS piping inner coating material. Special attention should be paid during engineered safety features/loss of power testing. These tests which are performed at higher than normal operating pressure can transport material and clog the heat exchangers. Whenever possible, supplementary inspection of heat exchangers should be performed immediately after such tests. • Inner coating can be applied both in the field and in the shop. The procedures in place, especially those regulating such activity performed in the field, should be adequate to ensure proper bonding between coating and the piping body, as well between separate layers of coating. • To avoid material compatibility problems, lining layers should be made of similar materials. For both lining and coating adhesion tests should be made to test the material adhesive properties. Since ESWS piping transports raw water, it would be desirable to perform chemical tests for determining the corrosion resistance of the coating, lining and of the adhesive materials. • The inspection tools and methods should fit to their purposes. Improper liner application (e.g. un-noticed caption of small air bubbles between liner and pipe body), together with the use of a tool for removing biological live developed inside piping, could crack the liner.

<table>
<tr><th>Typology</th><th>Lessons learned</th></tr>
<tr><td>Degradation of ESWS heat exchangers</td><td>

A significant event raised attention about the simultaneous failures of two ESWS/CCWS heat exchangers and one heat exchanger between CCWS and the RCS Nuclear Sampling System (NSS), which caused the breach of two barriers and established a path for radioactive fluid to the environment. Particular lessons learned were raised:

Repeated thermal stress at start-up can develop pinholes inside a NSS heat exchanger (temperature of the hot fluid side higher than 300°C compared to 35°C on the cold side). Modifications in the primary coolant sampling operating procedures or practices may involve an increase in thermal conditioning cycles of the NSS heat exchanger. This can induce mechanical aging, corrosion and leaks in related system equipment. The need for a risk analysis prior to any changes in operating practices is stressed;
Adequate preventive maintenance should be performed even when there are strong materials such as titanium. Marine sand erosion of the titanium plates separating the CCWS water from the ESWS can cause internal leaks from exchangers to the service water circuit.
The recurring nature of internal leakage in exchangers originates from the fact that only perforated plates were replaced systematically and periodically. The decision to replace the entire set of plates would have been allowed to replace plates already subject to erosion with only reduced thickness. There should have been permissible leak criteria in place applicable to leakage from the CCWS to the ESWS.
The radioactive monitoring of effluents should be improved and utilised to detect leaks. The detection and alarm thresholds of CCWS activity measuring channels should prevent gradual pollution of the system. Likewise, radiochemical pollution protection, particularly from tritium, should be also enhanced.

The chemical treatment of the CCWS/ESWS heat exchanger tubes (on ESWS side) to deposit a protective layer of ferrous sulphate on inner tube surfaces should be performed carefully and inspected each time after treatment. Particular lessons learned follow:

The pressure used to remove carbonate calcium from tubes should be high enough to clean the tubes but also low enough to prevent protective layer peel-off;
After inspection and high pressure cleaning of the heat exchanger tubes during maintenance, ferrous sulphate should be injected without delay after starting the sea water flow operation;
Ferrous sulphate solution should be injected in such a concentration to minimize the period needed for the initial protective film to be formed.

Sea water operation of the heat exchangers should be started only after the ferrous sulphate injection system is confirmed to be operational. This requirement shall be incorporated into the operational procedure. In addition, in order to prevent clogging

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Typology	Lessons learned
	in the ferrous sulphate injection piping, the piping should be thoroughly cleaned after injection. This shall also be reflected in the operational procedure.
Other typologies	<u>Unavailability of RHRS due to lubrication issues</u> • Wrong practises consisting in mixing different lubricants have been revealed concerning the RHR pumps. This is particularly significant for those pumps which are located inside the reactor building and are consequently exposed to radiation. The weak point of mixed lubricants is their behaviour in a radiative environment which may lead to a common mode failure. In one of the events both pumps were lubricated with the same mixture. Adequate experience feedback is raised with regard to lubrication practices to avoid a common mode failure that would not be limited to the residual heat removal pumps: o Use of different types of grease, depending on whether the components to be lubricated are located inside or outside the reactor building; o As concerns the RHRS pumps which operate intermittently and are located inside the reactor building (problems associated with frequency of lubrication and premature ageing of the grease caused by irradiation), it is requested to make-up new grease at the beginning of refuelling outages and remove old grease. Such make-up is recommended at the beginning and end of each ten-yearly outage; o Limit the number of types of grease intended for lubrication of safety-related rotating machines to, if possible, two types of grease per plant; o Choose types of grease that are reputedly miscible with each other; o Use the same type of grease for lubricating both motor and pump; o Arrange the frequency of lubrication to be the same for both motor and pump. <u>Inadequate calibration of RHRS flow rate meters</u> • Problems were reported concerning inaccurate readings of a RHRS flow element because the instruments were calibrated for high temperature water flow and readings were not corrected for operation at other temperatures. • Such kind of events are happening, usually, due to personnel error, cognitive, in that the flow element design information was not incorporated when establishing the Surveillance Test Procedure flow settings. The temperature used in the instrument scaling calculation should be evaluated and the Surveillance Test Procedures and Operating Procedures should be revised to include a temperature correction. <u>Temporary device rendering with one CCWS train unavailable</u> • The possibility to perform a quality control at the end of manufacturing process of these devices in collaboration between end user and manufacturer should be investigated.

Typology	Lessons learned
	Organisational dysfunctions in their use and management, together with improper application of procedures in compliance with existing general operating rules, have the potential to cause the operator to declare the equipment unavailable. • Whenever possible and if the in-house capabilities can support it, new temporary testing and/or signalling devices should be manufactured (by an automation or electrical shop) to assure a more rigorous quality control procedure and to guarantee correct operation before actual use. • The manoeuvring sheets for actions that must be conducted by the operator should be clarified and be concise, in order to simplify the procedure of installing and removing temporary testing and/or signalling devices. <u>Failure of the 10kV circuit breaker of a CCWS pump</u> • Micro cracks caused by the manufacturing process can induce degradation. This degradation can occur after a long term, too. Circuit breakers with similar design (carrier compressed out of the expansion shaft by cold forming) should be inspected (for example by dye penetrant testing) if they have comparable deficiencies. In this case it should be investigated, if the extensions shafts have to be changed prematurely. • When dealing with a spurious failure of a certain type of electrical equipment (in this case a circuit breaker), the investigation should be extended to all similar equipment in the plant to avoid the risk of a common cause failure. If this extent of condition assessment is not done by the licensee, the regulator should request it after a second failure. <u>ESWS pump not starting during periodic test</u> • When performing periodic test on equipment and requiring service water, it is important to have the correct mode selected (manual/automatic) to assure that the required ESWS pump will start as expected. • When performing in-service inspections or periodic maintenance, all items should be checked and verified. Even non safety relevant components as small lamps, diodes and other indicators can lead to undetected unavailability of safety relevant components. The function of such non safety relevant components should be tested during periodic tests and in service inspections too. <u>Loss of seismic qualification for several valves due to inadequate maintenance</u> • A simple inversion of two sets of screws could cause ESWS valves to lose their seismic qualification. Efforts should be made to provide these valves with individually marked screws. • OEF underlines the importance of maintenance quality and of monitoring the respective operations. Qualification intended to demonstrate equipment ability to perform in the event of an earthquake shall be done prior to installation of equipment at the site. Long term qualification cannot be verified with regular tests of equipment.

Typology	Lessons learned
	• The need for regular efforts is highlighted to increase awareness in maintenance teams of certain standard practices (proper screw identification, tightening torque, choice of tools, etc.) that affect seismic qualification in long term. <u>Inadequate valve closure setup renders one ESWS train inoperable</u> • Preventive maintenance proved to be useful to detect, through tests, valve seat leakage. When looking at the isolation valves between the Service Water system (i.e. non-safety related part of the system) and one train of the Essential Service Water System (i.e. safety related part of the system), a specific Post Maintenance Testing matrix, to consolidate testing requirements for such valves, should be developed and applied. • During the process of establishing the ESW leak monitoring program and closing the related documents to reduce the corrective action program backlog, special attention should be given to avoid inappropriate closure of the monitoring program following receipt of calculations which may alleviate the concerns addressed by the program.

LD-NA-27691-EN-N

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doi:10.2790/067759

ISBN 978-92-79-54551-1