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Report on Leaks and Cracks of the Reactor Coolant Pressure Boundary

Summary Report of an European Clearinghouse Topical Study

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Abstract

Leaks and cracks of the Reactor Coolant Pressure Boundary are a clear indication of degraded conditions inside the nuclear power plants, challenging the barriers against radioactive releases into the environment. Thus it is important to investigate the existing operational experience in this kind of events. The objective is to determine the adequacy of protection of nuclear power plants against leaks and cracks and the effectiveness of the corrective actions implemented, as well as to provide recommendations on how to prevent or mitigate the impact of such events on NPP operation.
Leaks and cracks in the Reactor Coolant Pressure Boundary cannot be avoided. Because of this, even the Technical Specifications (or the Plant Normal Operation Procedures) allow a limited leak rate, or a specific time of unavailability, for different systems needed for normal operation of the plant. However, any leak and crack of the Reactor Coolant Pressure Boundary which remains undetected long enough will raise particular challenges for the Systems, Structures and Components within the affected part of the Reactor Coolant Pressure Boundary. Even if the leak is timely detected, there is usually a significant impact on the overall radioprotection of the plant. In some cases, the total reactor coolant loss is important and prolonged outage periods are required for recovery. So, even in the case of successful detection of such events, to analyze them is necessary in order to fully understand the mechanism which provoked such events.
This Summary Report presents the results of a comprehensive study performed by the European Clearinghouse on Operating Experience Feedback of NPP with the support of IRSN and GRS.

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LIST OF ACRONYMS

GRS	Gesellschaft für Anlagen- und Reaktorsicherheit mbH
HAZ	Heat Affected Zone
IAEA	International Atomic Energy Agency
IRS	International Reporting System for Operating Experience jointly operated by IAEA and OECD/NEA
IRSN	Institut de Radioprotection et de Sûreté Nucléaire
IGSCC	Inter-Granular Stress Corrosion Cracking
LER	Licensee Event Report
NPP	Nuclear Power Plant
OECD/NEA	Nuclear Energy Agency
OEF	Operating Experience Feedback
QA	Quality Assurance
R&D	Research and Development
RCP	Reactor Coolant Pump
RCPB	Reactor Cooling Pressure Boundary
RCS	Reactor Cooling System
RPV	Reactor Pressure Vessel
RVH	Reactor Vessel Head
SCC	Stress Corrosion Cracking
SICC	Strain Induced Corrosion Cracking
SG	Steam Generator
SGTR	Steam Generator Tube Rupture
SRV	Safety Relief Valve
SSC	Systems, Structures and Components
TGSCC	Trans-Granular Stress Corrosion Cracking
US NRC	United States Nuclear Regulatory Commission

1 INTRODUCTION

Leaks and cracks on the primary circuit boundary are evidence of degradation of a barrier against radioactive releases into the environment.

Any leak and crack of the Reactor Coolant Pressure Boundary (RCPB) that remains undetected long enough will raise particular challenges for the systems, structures and components (SSCs) within the affected part of the RCPB. Even if the leak is timely detected, there is usually a significant impact on the overall radioprotection of the plant. In some cases, the total reactor coolant loss is important and prolonged outage periods are required for recovery. Thus it is important to investigate the existing operating experience in this kind of events.

The objective of this study is to determine trends and lessons learned, in order to draw recommendations and conclusions to prevent re-occurrence of such events. The main goal is to identify and share good practices among the nuclear community.

This Summary Report presents the results of a comprehensive study [1] performed by the European Clearinghouse on Operating Experience Feedback (OEF) of NPP with the support of IRSN (Institut de Sûreté Nucléaire et de Radioprotection) and GRS (Gesellschaft für Anlagen und Reaktorsicherheit mbH). The study [1] was performed by analysing the events contained in four different databases, for a period covering 20 years.

2 METHODOLOGY

Four different event report databases have been searched in order to analyse the operating experience of events related to leaks and cracks of the reactor coolant pressure boundary, namely:

- The International Reporting System for Operating Experience (IRS), operated jointly by the International Atomic Energy Agency (IAEA) and the Organisation for Economic Co-operation and Development/Nuclear Energy Agency (OECD/NEA). The fundamental objective of the IRS is to contribute to improving the safety of commercial nuclear power plants (NPPs) operated worldwide. The IRS is a worldwide system containing events which are reported on a voluntary basis, and the reporting criteria vary with countries.
- United States Nuclear Regulatory Commission Licensee's Event Reports (US NRC LER) national database which consists of reports from the licensees for those types of reactor events and problems that are believed to be significant and useful to the NRC in its effort to identify and resolve threats to public safety.
- The French database developed and operated by the IRSN, in order to classify and to analyse the OEF. It contains events reported by French nuclear power plants under French regulations.
- The German database, operated by GRS in Germany. This database contains specific information on the behaviour of pressurized components in German NPPs. The events are reported by German plants under German reporting criteria for systematic evaluation of operating experience.

All databases were searched using keywords and other specific searching tools, yielding a list of potentially relevant events. The reports of these events were reviewed individually to determine the pertinence of these events for the study, thus obtaining a screened list of relevant events.

Screening the databases' search results helped identify the events that are relevant for the topic of this report. Event screening results are largely dependent on the criteria used to report significant nuclear safety and/or radiation protection events. The criteria used to report cracks and leaks events in one country may be (and usually are) different from those used in another country, even for similar types of events and plants.

After screening, the following families were created for a short quantitative analysis:

- Event causes.
- Part of component affected.

The families created for the analysis of lessons learned are the following:

- Reactor pressure vessel and pressurizer (RPV).
- Steam generators (SGs).
- Reactor cooling pumps (RCPs).
- Piping.
- Safety relief valves (SRVs).
- Valves, other than safety relief valves.
- Flanges.

For every family of events, the report summarizes the lessons learned as well as the recommendations which can be drawn from the operating experience.

3 MAIN FINDINGS

This section presents the main results of the quantitative analysis performed on the events identified.

When performing the analysis for the databases selected as sources of information, it is imperative to take into account that these databases are not built in respect to the same reporting criteria, thus no common integrated analysis can be carried out. For the same reason, comparison should be made in a very careful manner.

The search for incidents in the IRS revealed 144 events involving leaks and cracks of the RCPB. As referring to US NRC LER database, screening resulted in 74 applicable events. In the case of SAPIDE and KomPass databases, the search resulted in 129 and 61 applicable events respectively. Given to the different nature of the databases, the study concentrated on statistical analyses on the data to gain insights of the events distribution.

3.1 Components affected by events

Although there was no intention to account the number of events occurred at a certain type of reactor, the analyses were made taking into account the differences between plant designs.

Figures 1 through 4 show the distribution of the events according to the types described in the previous section, for every database.

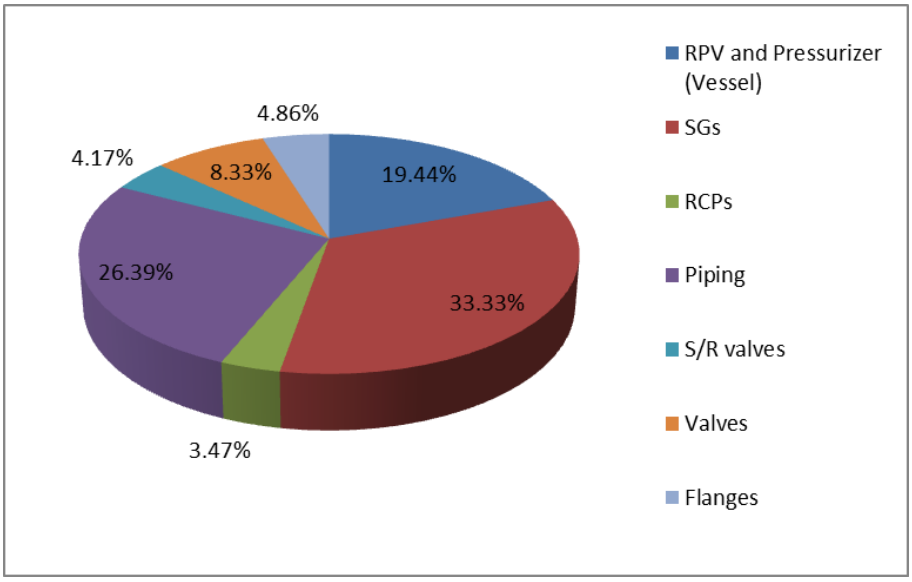

Figure 1 – Distribution of leaks and cracks reported to the IRS

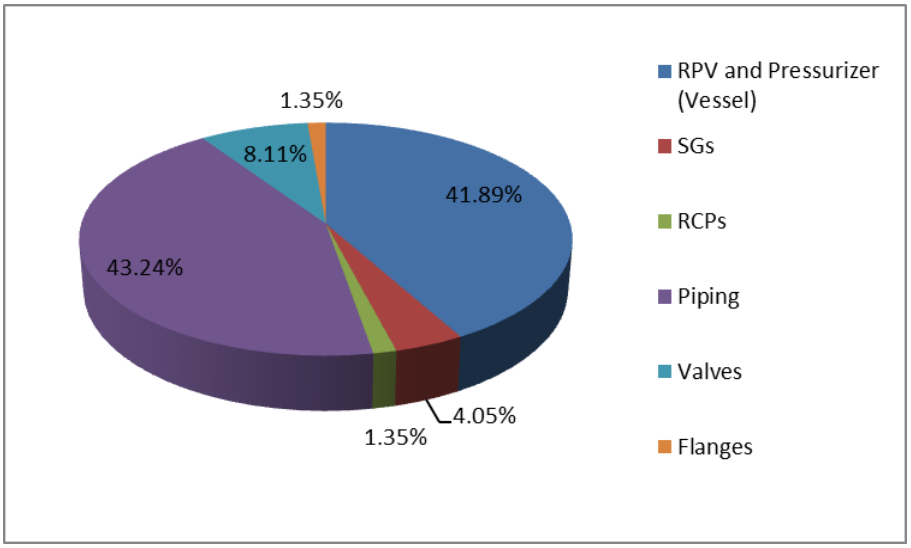

Figure 2 – Distribution of leaks and cracks in United States of America

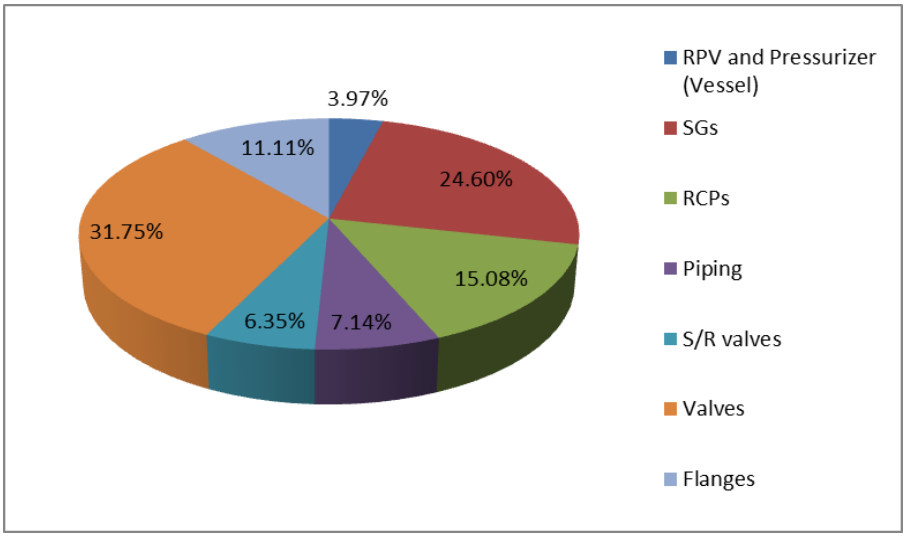

Figure 3 – Distribution of leaks and cracks in France

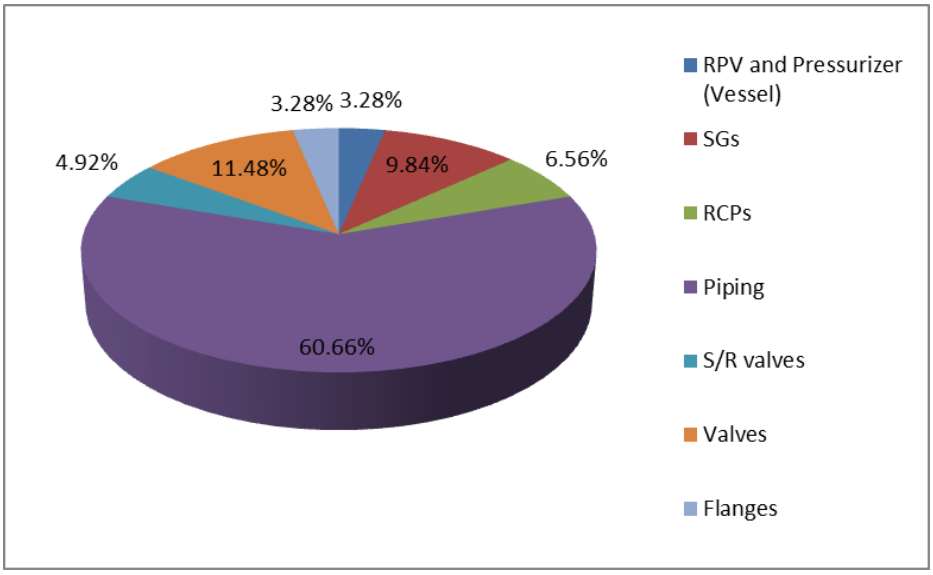

Figure 4 - Distribution of leaks and cracks in Germany

Referring to all events, the analysis revealed that the most affected component by leaks and cracks are the pipes (116 events). The other most affected components by these types of events are SGs (88 events, most of them involving tubes and installation of nozzle dams), RPV and pressurizer (66 events) and valves (65 events). The less affected component affected by leaks and cracks proven to be the safety relief valves (17 events).

3.2 Event causes

For all the 408 events, Table 1 presents the distribution of events regarding their causes.

Table 1: Number of events by their root causes (percentages are rounded)

	IRS	US NRC	French database	German database ([1])	*TOTAL*
Corrosion	*48*	*42*	*30*	*26*	***146***
Manufacturing defects	*25*	*15*	*2*	*21*	***63***
Fatigue	*22*	*7*	*8*	*11*	***48***
Maintenance defects	*15*	*7*	*22*	*2*	***46***
Faulty operation	*16*	*1*	*20*	*1*	***38***
Others/unknown	*18*	*2*	*47*	*14*	***81***
TOTAL	**144**	**74**	**129**	**75**	***422***

Corrosion is the main root cause of the events analysed. Sometimes, this was just the 'apparent' cause. Indeed, in about 50 % of the cases corrosion was triggered by the chemical reactions between the materials being in contact one with each other, in the accidental presence of a catalyst (e.g. Stress Corrosion Cracking (SCC) phenomenon, for alloy 600, in the presence of a chloride medium and oxygen, or Trans-Granular Stress Corrosion Cracking (TGSCC) of stainless steel — from exterior to interior — in the presence of chlorides). In about one third of the cases, corrosion was triggered by manufacturing defects that were the precursors for Inter-Granular Stress Corrosion Cracking (IGSCC). The other major contributors for triggering corrosion are maintenance defects and faulty operations (e.g. strain-induced corrosion cracking (SICC) as a result of

([1]) Fourteen events were identified as having double root causes. This led to a total of 75 events for the German database.

a groove at a weld seam that acted as a starting point for the degradation, or inhibited movement of components, which induced additional strain).

Manufacturing defects are the second largest root cause of the events. These events are nearly all related to welding faults, though in some cases inappropriate Quality Assurance (QA) measures at the manufacturer can be considered as precursors. However, no unique trend can be identified for this root cause.

Fatigue (both mechanical and thermal) is also an important contributor to the root causes family.

Mechanical fatigue appeared, in certain cases, in combination with another cause, like manufacturing or maintenance defects, especially on welds. Mechanical fatigue appeared especially on those SSCs exposed repeatedly or periodically to various aggressive conditions (i.e. instrumentation line during outage operations, particularly during vessel head removal and set-back operations, or while operating/testing valves and pumps).

Thermal fatigue usually appears mainly in conjunction with the Farley–Tihange phenomenon[2], but also could be triggered by high temperature differences from one side to the other of a tube, for example — but in this case thermal fatigue is only the initiating mechanism, the propagating mechanism being mechanical fatigue.

Maintenance defects and faulty operations, together, share 20 % of the causes of the events. Most of these were triggered by human factors, either by non-appropriate establishment of the 'Foreign Materials Exclusion Zone', or by incomplete manoeuvring or inappropriate positioning especially of hand-operated (isolation) valves. Installation errors, especially regarding SG inlet or outlet nozzle dams and drain plugs, were the source of recurring leaks. However, not all the events within these two categories can be explicitly attributed to human errors.

3.3 Part of component affected

Defects, cracks and leaks are often located in specific areas with geometric or metallurgical (weld) discontinuities. Table 2 presents the most affected part of components by these events.

Table 2: Number of events by the part of the component (percentages are rounded)

	IRS	**US NRC**	**French database**	**German database**	***TOTAL***
Base metal	*78*	*37*	*41*	*31*	***187***
Welds	*33*	*35*	*5*	*23*	***96***
Seals	*33*	*2*	*37*	*5*	***77***
Other	*0*	*0*	*46*	*2*	***48***
TOTAL	**144**	**74**	**129**	**61**	***408***

The base metal is the part of the component most frequently involved in events related to leaks and cracks. As base material, alloy 600 is widely used in NPPs, and not only for the SG tubes (i.e. vessel head penetrations). Another base material widely used is the austenitic stainless steel, which can be titanium or niobium stabilised (i.e. piping, pump

[2] This phenomenon can be described as thermal fatigue in the terminal section of the safety injection lines, which are connected to the reactor coolant loops, due to the simultaneous mixing of cold water from the charging system and hot water from reactor coolant loops.

housings and valve bodies).

Welds (including Heat Affected Zones - HAZ) are subject to thermal fatigue. It is not only that any weld represents a geometric discontinuity, but that they could also be a material discontinuity (because of the binder material added to the base material, the behaviour of a weld part could be — and usually is — different than the behaviour of the base material under the same conditions). Even when the binder material is the same as within the welded parts, quite often the damage in the weld area/HAZ has more than one root cause, which favours a special degradation mechanism or at least makes it possible. So, the cracks on welds could appear both on the inner and outside surfaces of the material.

Static and dynamic seals are important for ensuring the leak integrity of the second containment barrier. The events that had as affected component the seals were, in most cases, leakages (i.e. through the RCP dynamic seals, through valve packing, through pressuriser relief safety valve spacer seals, though flanged connections). These events having seals as affected component are sometimes associated with human errors during installation or maintenance (insufficient tightening, incorrect positioning of seal, etc.). However, the seal leakage and failure events are not necessarily indicative of generic manufacturing, operating or maintenance issues. Nevertheless, some of these events show the importance of preventing human errors during operation and maintenance

4 LESSONS LEARNED

This section presents the most important lessons learned from the events. They have been grouped according to the component affected.

4.1 Reactor pressure vessel and pressurizer

- *The material compatibilities with the environmental and working conditions should be assessed properly, as well as their performances and expected lifetime, especially for pressuriser heater insulations and for the components made out of alloy 600. For instance, avoiding the usage of hygroscopic materials will reduce the water ingress and swelling, and thus the probability of corrosion initiation*.

- *Components made of materials that are recognised as sensitive to SCC should be replaced by ones made of less sensitive materials or at least considered within the framework of in-service inspections in order to avoid or detect early on cracks, and thus to avoid leaks. If in-service inspections programmes are not sufficient to preclude propagation of cracks, equipment made out of materials sensitive to SCC should be monitored for early detection of leaks and cracks*.

- *Analysis of events had drawn attention to the risk of inadvertent dispersal of reactor coolant into the reactor containment building. These risks argue for early detection of reactor coolant leaks and show the importance of systems and devices expected to detect and to collect predictable and unpredictable reactor coolant leaks independent of the reactor status. In case of leak inside the reactor containment building, the management of the leak should not be limited to the elimination of the leakage but should include an* a priori *assessment of the leakage dose impact (on the workers in charge of the localisation, repair, cleaning, etc.) and an assessment of the waste processing for the waste and effluents generated by the leakage (leakage itself, clean-up activities, decontamination and others)*.

- *The OEF assessment emphasises the need to pay special attention to all equipment subject to frequent manoeuvring. While particular man-powered operations are being*

deployed in an area, at least for the periods when activities are deployed, that area should be subject to close monitoring. For recurrent events, the quality of training should be enforced.

- *Visual inspections are of major importance at the start and conclusion of refuelling outages. The inspections should be performed by paying particularly close attention to all vulnerable or sensitive areas, including the Reactor Vessel Head (RVH) and its extensions. Considering the potential consequences (contamination and corrosion), RVH extensions should be subject to visual (and TV) inspection at the start and conclusion of outages (and shutdowns) to confirm the absence of leaks and boron traces*.

4.2 Steam generators

- *Shutdown states are highly sensitive configurations during which monitoring should be maintained and even intensified. Water movements and transfers during such states also constitute sensitive transient conditions. Temporary sealing devices such as SG nozzle dams and associated drain plugs should be specifically monitored*.

- *The sufficiency of the detection means should be assessed for all the situations, all the reactor states and all the reactor transients, which can reveal the potential for improvements of these detection systems (i.e. a radiation alarm on the secondary side of an SG in combination with any change in the make-up water tanks)*.

- *Consequently, actions to detect early a leak associated with operating procedure permitting to monitor and decrease this leak should be encouraged in order to reduce the risk of a Steam Generator Tube Rupture (SGTR)*.

- *Components made of materials that are recognised as sensitive to SCC should be replaced by ones made of less sensitive materials or at least considered within the framework of in-service inspections in order to avoid or detect early on cracks, and thus to avoid leaks. When performing specific repairs, like welding, the binder material should be selected in respect to compatibility with the base materials and the water chemistry control*.

- *The OEF assessment emphasises that in many cases material incompatibility was a causal factor that initiated a crack or a leak, so all the equipment made out of materials sensitive to SCC, like Inconel 600, should be considered as sensitive areas and monitored for early detection of leaks and cracks*.

- *A better, stricter water chemistry control will decrease the probability that corrosion is initiated, thus reducing the frequency of leaks, but only within the framework of a rigorous control of materials that can be forgotten in or utilised for performing repairs of the SGs*.

- *Any leak rate, even those within the technical specifications, should be watched rigorously and continuously and the leak measurement sensors' operability should be checked periodically*.

- *The operators should perform corrective and preventive plugging in damaged tubes with a risk of rupture, even when the leak is proven to be below the accepted leak rate*.

- *The national and international operating experience should be screened in a systematic manner with regard to cracks and leaks events. In the case of these events occurring under comparable design and service conditions, supplementary actions*

should be performed to ensure against their reoccurrence. Relevant research and development (R&D) insights and advances should also be taken into account. Important approaches in this context are the optimisation of operating conditions, the replacement of components affected, and the enhancement of monitoring, inspection and maintenance measures.

4.3 Reactor coolant pumps

- *The reduction of the seal ring spring force due to ageing should be the subject of a rigorous engineering process. In order to restore the seating force, the seal ring springs should be replaced periodically. In order to recognise timely the degradation of the seal ring spring and to ensure a correct replacement, the maintenance personnel should receive proper training*.

- *In view of the operating staff's inappropriate responses to these transients and to their consequences, all operators should produce a training manual on RCP operation under normal and incident conditions to improve operators' knowledge of the physical phenomena, automatic systems and operations involved. This manual should be used for in-house training of shift personnel*.

- *All leak collection systems, especially the RCP leak collection system, should be subjected to appropriate maintenance and surveillance programmes*.

- *The RCPs and their associated areas require special measures such as in-service inspections or monitoring with the objective to detect any cracks or leaks as early as possible. The locations and the parts identified as being sensitive should be equipped with local, targeted detection systems to detect early and quickly any leakage, even those leakages that are slow and very slow leaks. Analysis of reactor coolant leakage events demonstrates the usefulness of combining local detection systems that target equipment with overall detection systems, as well volumetric detection systems with radiation detection systems and remote visual observation means*.

- *Visual inspections are of special importance. An assessment to check the sufficiency of these detection means for all the situations, all the reactor states and all the reactor transients can reveal the potential for improvements of these detection systems*.

- *The risk of backseat seal leakage during outages remains present (particularly during fuel handling operations). This issue deserves particular analysis, even though the backseat seal position is a brief and marginal configuration*.

- *During shutdown states, it is required a continuous and rigorous suitable monitoring of sealing components and of signals that may indicate the appearance of a reactor coolant leak such as water level changes in pools, tanks and sumps. For power operations, all these systems may be complemented with targeted radiation monitors*.

- *The temporary modifications of systems for recovering and collecting RCP leaks and effluents (hoses, temporary lines, etc.) should be the subject of a safety review in order to assess the efficiency of the recovery, collection and confinement of leaks escaped from the RCPs. At least periodic monitoring is required. Moreover, the operating procedures associated with the temporary system should be drafted*.

- *In order to prevent the degradation of the studs affected by corrosion and to avoid the leak-induced steel losses, each operator should implement strict measures for avoiding the existence of erosive and corrosive particles within the reactor coolant*.

- *Whenever possible, permanent design modification of RCPs should be performed in order to prevent the reoccurrence of events, or to address their effects*.

4.4 Piping

- *Operation instructions regarding the cleanliness of components and the usage of adhesives should also take into account areas connected to the RCPB at lower or room temperature, and not only the pipes operating at higher temperature, in order to prevent chloride contamination ([3]) (for instance the adhesive used to attach fire protection sleeves to the pipe through wall penetrations might contain chloride-inducing TGSCC)*.

- *The compatibility of materials constituting SSCs should be checked also with respect to the operating conditions and environment*.

- *It is desirable that the components made of corrosion-susceptible materials be replaced by similar components made of more corrosion-resistant materials. Whenever possible and when compatibility can be assured, at least the repairs should be made using materials more resistant to corrosion*.

- *It is recommended to employ very skilled staff to interpret the Ultrasonic Test results. It is also useful to take into account the documentation of the previous test performed on a particular pipe, like the method used, the area controlled, and whether the cladding has been included or not*.

- *All the small bore piping should be subject to targeted visual inspections (removing isolation) at the beginning and conclusions of shutdowns to verify the absence of outside leaks and boron traces*.

- *Any plant with un-isolable piping which could be subjected to temperature distributions (like, for example, the portions where the cold water injected by Emergency Core Cooling System mix with the hot water already inside Reactor Cooling System – RCS), which would result in unacceptable thermal stresses, may be affected by the "Farley-Tihange" phenomenon. All the pipes potentially subject to thermal stress should be identified, and carefully and regularly inspected looking for cracks; additional preventive measures should be considered, such as continuous pressure monitoring and addition of a discharge line, for relieving pressure in the injection line.*

4.5 Safety relief valves

- *Documentation for technical maintenance and repairs of the pilot-operated relief valves should be in compliance with the technical specifications of the manufacturer. In case of any doubts, the manufacturer should be consulted for filling the gap in the knowledge inside the plant. All the spare parts that are non-compliant with the technical specifications of the equipment manufacturer should be forbidden to use. All the human activities (e.g. operation and maintenance) should be performed in accordance with the latest working instructions provided by the manufacturer. A programme should be implemented for maintaining the relevant documentation up to date with the additional technical documentation provided by the manufacturer*.

- *For preventing the reoccurrence of such events, the fitting, the assembly procedure,*

([3]) A comprehensive report assessing susceptibility and structural integrity, 'Chloride stress corrosion cracking in austenitic stainless steel', can be found at http://www.hse.gov.uk/research/rrpdf/rr902.pdf online.

the tightening of the fitting and the plug itself should be improved. Additional training should be conducted for staff performing technical maintenance and repair work on pilot-operated relief valves, after validating the procedures for technical maintenance and repair of safety valves.

- *Systems for monitoring the temperature inside the pilot cabinets of the SRV should be utilised not only to deliver alarms on a specific threshold, but also as an indicator of the degradation of the operating conditions of the equipment, with the aim of avoiding plant trips and scrams by taking in due time the corrective actions needed for improving the plant conditions*.

- *In the operating instructions for safety valves, a description should be included of alternative methods for closing the valves in the event of spontaneous opening and failure to close*.

4.6 Valves other than safety relief valves

- *The design of flap valves should consider not only operation pressure but also different hydraulic tests' pressure levels (usually, the test pressure is higher than the normal operating pressure)*.

- *The testing procedures should embed the designer recommendations regarding the valves pre-sets for testing. If necessary, the maintenance and operations personnel should receive additional training (both theoretical and practical) at the manufacturer/designer's place.*

- *The maintenance procedures and associated manufacturing QA measures should be periodically verified for their efficiency.*

- *Sometimes, for preventing leaks, materials quality improvements are needed (e.g. gradual withdrawal of asbestos packing). By this means, while keeping the chemistry of the cooling agent as required by the normal operating procedures, the conditions that could lead to corrosion of materials can be avoided.*

- *The opening, emptying, closure, vacuum refill and filling of the RCS and associated operations should be subject to enhanced, heightened and formalised monitoring. The RCS isolation procedures should receive enhanced and formalised attention, since depending on the operational state the same defect could lead to different consequences. In particular, manually operated valves contribute to leak tightness and their operation should also be subject to enhanced and formalised attention.*

- *Special measures should be taken to avoid the concentration of chlorides above limits. In the case that chloride contamination cannot be avoided, concepts should be established to eliminate these contaminations frequently.*

4.7 Flanges and mechanical fittings

- *If faults repeat, the area of troubleshooting should be enlarged to all other similar equipment in order to avoid any common cause deficiency.*

- *The flange joints require special monitoring and maintenance, especially those located above or near large equipment (vessel head, pressuriser, RCS pumps, etc.).*

- *Any abnormal indication (for example, change of containment atmosphere conditions) could be a reactor coolant leakage indication, so these indications should be*

investigated deeply. Visual inspection systems (remote cameras) will be an asset.

- *During installation of flanges, a uniform tension between the bolts should be ensured. The quality control system for the associated operations should be enhanced for preventing any faulty operation (i.e. step-by-step instructions, the signature of the technician and the supervisor after each step).*

- *Maintenance of the sensitive equipment should be performed under special conditions and by qualified staff. Faulty maintenance, even if it is resulting in such small deviations that they are not discovered immediately, has been proven to develop in time unforeseen impacts on the plant's operation.*

- *The risk of leak and impact from borated water should be taken into account in in-service maintenance and monitoring. Reactor coolant leaks at the flange joints often lead to corrosion in the fasteners (bolts) holding the flange tight – thus impacting the integrity of neighbouring components.*

- *Flanged joints should be subject to close monitoring and maintenance, especially those located above or near large equipment (vessel head, pressuriser, RCS pumps, etc.).*

5 RECOMMENDATIONS

The recommendations contained in the present report are based on the lessons learned derived from the events analysed. They are classified in two large categories: recommendations regarding leaks and cracks prevention, and recommendations regarding leaks and cracks detection.

5.1 Leak and cracks prevention

R1: Design should embed corrosion and fatigue resistance.

Corrosion resistance and fatigue resistance of the base metal should be assessed when designing the SSCs. At any time possible, design ameliorations should be performed in order to minimise these phenomena (fatigue and corrosion).

The components of the RCPB should be designed, built and operated in such a way as to avoid any degradation of these components that could lead to reactor coolant leakages.

R2: Manufacturing and storage conditions should be part of the surveillance programme.

More attention should be paid to in-house monitoring of the fabrication process, including packaging and reception of components and equipment manufactured somewhere else. For instance, not all the equipment installed and operated in the plant beneficiated by proper inspection at their reception.

The documentation of the Non-Destructive Tests performed during construction should include measurements and records for anomalies which usually are not recorded (e. g. noise, form indications, lack of coupling, test limitations). In case of welding, it should be requested, for all the cases, that the border between the binder material and base material be checked, recorded and corrected (if necessary).

R3: Chemical compatibility of materials should be ensured at all times.

Because in most of the cases the phenomenon affecting the base metal is corrosion, the chemistry control inside the plant is of great importance. All the areas comprising alloy 600 components, or components made out of a material sensitive to corrosion (given the chemical conditions of the primary coolant) in contact with primary coolant must therefore be considered as sensitive areas.

R4: Ageing management programs should be implemented in all plants. The administrative methods for implementing such programs should be made available since the first day of operation.

An adequate ageing management programs should be utilized. The SSCs are ageing, at different rates, regardless if they are under operation or not.

In order to avoid or mitigate any kind of degradation of components at the RCPB, suitable measures should be implemented based on the results of root cause analyses and R&D. This includes in particular the optimisation of operating conditions and/or the replacement of sub-components or components, if necessary, with improved ones. If required, these actions should be accompanied by design changes.

To prevent operational errors with the potential to accelerate the degradation of the SSCs, actions should be automated by technical systems wherever possible for all the operational states of the plant.

R5: An appropriate maintenance and inspection programme should allow reducing as much as possible the conditions for initiating cracks and leaks.

The surveillance and inspection programs for SRVs should ensure, by special means and techniques, the cleanliness of internal valve surfaces. The periodic inspection programs (especially in-service programs) should be robust enough to timely identify deficiencies and implement all the necessary corrective actions.

Areas comprising “Inconel 600” components, pressurizer SRV “Jet” spacer seals, RVH, RCP static/dynamic seals and flanged connection static seals require specific monitoring and/or maintenance.

Operation instructions regarding the cleanliness of components and the usage of auxiliary substances should also cover areas connected to the RCPB at lower or room temperature to prevent chloride contamination.

R6: Maintenance and operation deficiencies should be considered as possible initiators of cracks and leaks.

To prevent maintenance errors, adequate, precise and ergonomic documentation for the work to be carried out (and the one previously performed) should be available and present at the working place or at the immediate vicinity.

Leak tightness between the RCS and Residual Heat Removal System, which is necessary for the transition from cold shut-down to hot shut-down should receive enhanced and formalized attention, in particular regarding the alignment of manually operated valves. During operation, particular attention should be paid for observing any leak between RCS and Nuclear Island Vent and Drain System – there are many stop valves at this boundary and hot water may escape from RCS.

5.2 Leak detection

R7: High performance of SG leaks' monitoring systems should be ensured.

More precise modelling of the SG particularities in thermo-hydraulic and vibration calculations are needed in order to correctly assess fluid parameters for different repetitive scenarios, even for those that are not considered accident scenarios.

An important leak of a SG tube with a quick kinetic cannot be totally excluded. A high-performance and reliable detection device for primary-to-secondary leaks should be implemented in order to reduce the risk of SGTR.

R8: The leak detection system should consider properly the different operating conditions induced by different reactor states.

Permanent monitoring systems of primary-to-secondary leaks should be implemented. These monitoring systems should allow measuring the relevant parameters (solid mode, liquid mode, pressure, temperature) that characterize each operational state of the unit (start-up/power operation/shut-down).

Under cold shutdown and hot shut down, due to varying pressure and temperature conditions, the uncertainty of the overall reactor coolant leaks rate assessment and the 'non-quantified' reactor coolant leaks rate may be relatively high. Hence, the resources and tools used to detect and assess any possible reactor coolant leak during shutdown should be improved.

R9: Levels in all the tanks and sumps should be monitored for overall leak detection.

The efficiency of the leak detection systems and devices should be assessed notably for leaks with slow flow rate, shutdown states, and sensitive equipment, components and areas.

Complementary to the equipment dedicated to leak detecting and monitoring systems, a suitable level monitoring system for sumps and make-up water tanks should be designated.

Water levels of the spent fuel pool and reactor cavity, RCS recipients (RPV, pressuriser, pressuriser relief tank), and tanks and sumps for collecting leaks and effluents from the reactor and nuclear island buildings should be monitored closely and continuously during refuelling outages.

R10: General instrumentation can usually detect major leaks but not always the minor leaks, hence the need for local, targeted instrumentation in addition to the general instrumentation.

It should be underlined that not all sensitive areas and equipment have the benefit of homogeneous monitoring and instrumentation. The analysis shows the importance of the monitoring as well as the importance of the associated instrumentation of sensitive areas and equipment.

The SG tube bundles, RVHs, RCS pumps and RCS SRVs should be monitored for leaks using targeted instrumentation. In fact, measurements installed on the equipment have often proved useful for detecting or confirming leaks.

Some auxiliary pipe sections (vent and drain lines) should be equipped with sensors to detect any coolant leak, unexpected coolant flow or unexpected pressure. Additional sensors could be introduced for sensitive areas. For example, dedicated monitoring systems for RCP leaks (especially targeted at seals) should be provided.

The instrumentation in and surrounding the pressuriser relief valves and control cabinets, and their associated measurements and alarms, have proved to be very important. Any alarm linked to the RCS SRVs should be immediately followed by actions to check or restore the facility's safety.

6 CONCLUSIONS

The study demonstrates how efficient it is to assess on the basis of the OEF what SSCs and areas are sensitive to potential leaks, in order to allow for corrective actions to be performed before any leak can occur. Also, it was highlighted again the need for an adequate and targeted maintenance and testing programme aimed at detecting non-through-wall cracks and wall thinning at an early stage in order to prevent further crack propagations.

The assessment performed shows that cracks have a low safety impact — many of the cracks were discovered with the plant in cold shutdown, by performing inspection, and their effect on operation was almost negligible. Also, it was observed that when a crack is discovered, the operators take the needed precautionary measures to limit or to control the propagation of the crack — usually, the cracks discovered during power operation are repaired during the next outage.

The mechanism of cracks development varies from case to case, based on the type of the plant and on the type of operation and/or maintenance of the equipment. Regarding the cracks only (68 events), it was found that fatigue (both mechanical and thermal) was the main contributor to the appearance of cracks — for the other cases, ageing, corrosion or combinations of these three contributors were the initiating stressors of the SSCs affected.

Contrary to cracks, once detected the leaks usually require an immediate action. The OEF analysis indicates that leaks often have a significant safety impact, mainly on staff radiation protection, as usually decontamination and cleaning operations require numerous human resources to enter controlled areas. Also, leaks can induce corrosion of base materials and of external surfaces of the pressure boundary — i.e. the vessel head had to be cleaned several times because of boron deposits from coolant leaks. Leaks also induced the production of unaccounted wastes that must be treated according to the waste management plans. Waste volumes produced by leaks and by the subsequent corrective actions are rarely found in databases.

The study revealed that the preferred corrective action is the repair of the damaged component. It has to be noted, however, that in most cases, replacement of parts, components or equipment, or design modifications often need a long time. In most of the cases, cracks and non-through-wall defects as well as slow leaks cannot be detected during power operation, and when they are detected (during shutdowns) their assessment is performed in order to address their safety significance when choosing the adequate corrective action. Nonetheless, after the repairs are performed, operators usually closely monitor the behaviour of the component repaired in order to check for any misses during repairs, as well as just for early detection of any new crack birth or propagation.

In order to fully understand the respective degradation mechanism, the contributing factors and its relative significance, consistent root cause analyses of events that have occurred should be performed. The quality of operating and maintenance operations and their monitoring, in particular those performed during outages, which are at the origin of many leakage events, deserve particular attention.

It is necessary to enhance the detection systems for all the sensitive equipment and areas inaccessible during normal operation. This could be achieved by automatic monitoring and detection systems, which could operate, among others, in conjunction with both level monitoring systems in water make-up tanks and nuclear island sump level monitoring systems.

Moreover, topics needing a safety review regarding the control of reactor coolant leaks were compiled. A distinction was made between topics for which actions could be quickly and easily implemented, and topics for which the actions are more difficult to implement.

The following topics where actions could be quickly and easily implemented were identified:

1. The dosimetry programme and waste management of the effluents resulting from events with a reactor coolant leakage;
2. The quality and the monitoring of operating and maintenance operations, especially those performed during shutdown states and outages;
3. The monitoring of tanks and sumps that collect reactor coolant leaks, especially during shutdown states and outages;
4. The list of equipment, components and areas identified as sensitive to reactor coolant leaks;
5. The visual inspections, both qualitatively and quantitatively, especially during shutdown states and outages.

Topics needing a safety review for which the actions are more difficult to implement comprise:

1. The detection and monitoring systems available and used under shutdown states and outages;
2. The local detection and monitoring systems that target sensitive equipment, components and areas, especially for leaks with slow flow-rate;
3. The detection and monitoring systems for the early detection of leaks with fast kinetics, or of very low rate leaks;
4. The efficiency of the confinement carried out by the waste collecting systems where RCS leaks are recovered and collected.

Among these potential topics, the review of nuclear island vent and drain systems with regard to the faster detection and location of leaks, and to more effective confinement, would appear to be the most beneficial for the facility and for the radiological protection of workers, which makes it a top priority.

7 REFERENCES

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