
Evaluation of operating experience with regard to passive mechanical components – approach and new insights

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Abstract:

Evaluation of operating experience is a powerful tool for the safety assessment of nuclear installations. GRS as a Technical Safety Organisation has been evaluating operating experience with nuclear power plants for more than 35 years. For the evaluation of operating experience with passive mechanical components, specific data and knowledge bases are used. The developed approach is described and examples of typical applications are given. This comprises the issues: ageing behaviour of passive mechanical components, chloride-induced stress corrosion cracking, degradation in essential service water systems, and determination of leak frequencies of piping for PSAs.

The results so far demonstrate the suitability of the developed approach, the robustness of the design chosen for passive mechanical components in German NPPs, and the effectiveness of measures taken to avoid or early detect any degradation. It is emphasised that international co-operation in the field of operating experience feedback is an important element in order to ensure that sufficient information for the safety assessment of nuclear installations is available.

1 INTRODUCTION

GRS has been evaluating operating experience (OE) with nuclear power plants (NPPs) for more than 35 years. Over the years, a special approach has been developed for the evaluation of the OE with passive mechanical components, i.e. with pressurised components and reactor pressure vessel (RPV) internals. OE is used for the safety assessment of individual events. Typical questions regarding the evaluation of individual events are:

- What is the safety significance of the event?
- Have any comparable events already occurred in this or other plants?
- Under which conditions can such an event occur?
- What are the lessons learned from the event?

Moreover, generic evaluations are performed. Typical questions in the generic evaluation of OE are:

- Are there any indications of weak points in the design?
- Which systems / components / parts of components are mainly affected?
- What are the relevant root causes / degradation mechanisms?
- Are the measures taken to address recognised issues effective?

Depending on these questions, specific data are required. Typical questions are:

- Where to get the necessary data from? / What are appropriate sources?
- How to store and administrate the data and how to evaluate them?
- How to make the gained insights retrievable for future work?

The intention of this paper is to provide information on the GRS approach for evaluation of OE with passive mechanical components and to present some typical generic applications.

2 GRS APPROACH

The overall approach of GRS for evaluation of the OE with passive mechanical components is outlined in **Fig. 1**. GRS is collecting the relevant OE of German as well as of foreign NPPs. The information is stored and administrated in several databases. The available information is used for the assessment of individual events that have occurred. Moreover, generic evaluations are performed on different levels, in particular

- generation- / plant- / system- / component- / subcomponent-specific,
- mechanism-specific, or
- topic-specific.

The results of this work are documented mainly in Position Papers, Information Notices and Technical Reports. To get quick access to former results for current evaluations, a browser-based knowledge base was established at GRS.

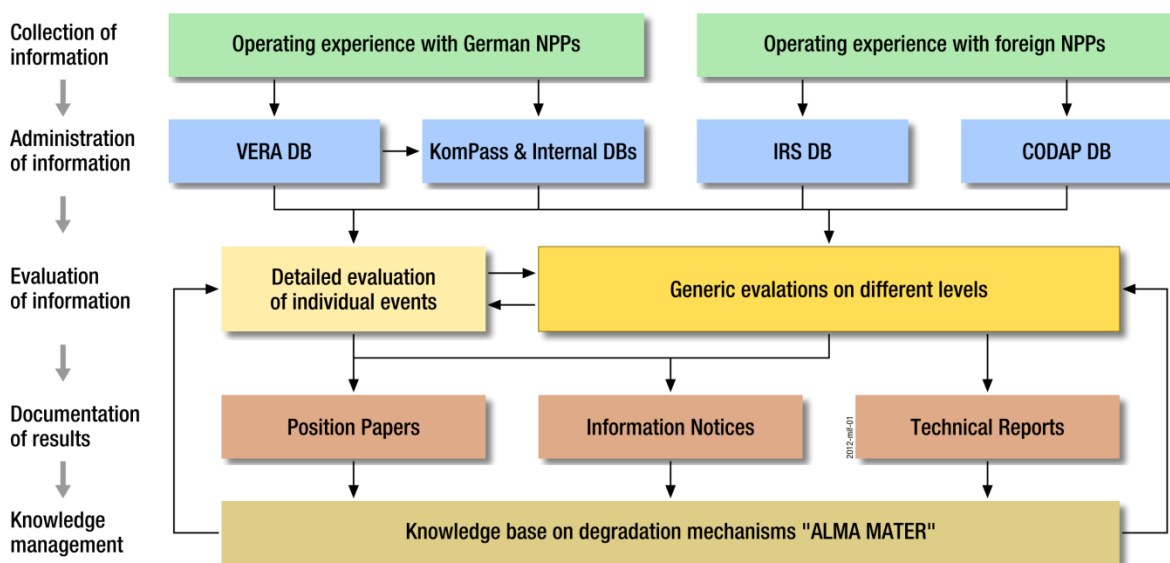


Fig. 1 GRS overall approach to evaluate operating experience with passive mechanical components in NPPs

2.1 Specific databases used

Table 1 provides an overview of the most important databases used at GRS for the evaluation of OE with passive mechanical components. These are the databases VERA, KomPass, Internals, IRS, and CODAP.

2.1.1 VERA database

In the VERA database all events are collected which are reported from German NPPs according to the reporting criteria stipulated in the current “Ordinance on the Nuclear Safety Officer and the Reporting of Accidents and other Events (Nuclear Safety Officer and Reporting Ordinance)” [1] of October 14, 1992, last amendment of June 18, 2002. The reportable events are collected in the VERA database from 1965 up to now. Today, a total of about 6,000 events that have occurred in German NPPs are captured.

Tab. 1 Characterisation of databases used at GRS for evaluation of OE with passive mechanical components

Database	No. of records	Acquisition period	Scope	Criteria for data capture	Countries involved
VERA	~ 6,000	since 1965	Safety-related SSCs	Reportable events	DE
KomPass	~ 1,000	since 1972	Safety-related pressurised components	Reportable events	DE
Internals	~ 100	since 1973	RPV internals	Reportable events	DE
IRS	~ 3,800	since 1978	Safety-related SSCs	Selected safety-related events	IAEA / NEA member states
CODAP	~ 4,500	since 1970	Safety-related pressurised components + RPV internals	Selected safety-related events	CA, CH, CZ, DE, ES, FI, FR, JP, KR, MX, SE, SK, TPE, US

2.1.2 KomPass database

The KomPass database contains comprehensive information on pressurised components in German NPPs. It is mainly based on the information from database records in the VERA database. As the data on these events contained in the Written Reports are not sufficient for in-depth evaluations on component behaviour, they were supplemented by information on design characteristics and operating conditions of the components concerned as well as by other information, originating particularly from root cause analysis reports. In order to achieve a fast survey of the existing data under different aspects as well as the best-possible data management, the data are stored in an ACCESSTM database.

At present, the KomPass database contains all safety related events that have occurred in pressurised components since 1972. These are altogether about 1,000 events, including detected non-through-wall cracks and pits, wall thinning, and leaks. Possible criteria for queries are:

- plant generation, plant type, plant, system, component, part of component;
- date of event, operating time;
- degradation type, location, mechanism, cause;
- ageing relevance;
- design parameters such as dimension, and material used;
- operating conditions such as medium, pressure, temperature, and water chemistry;
- isolability of systems;
- safety significance;
- kind of detection;
- safety impact; and
- measures taken.

2.1.3 Internals database

The Internals database is based on the information from database records in the VERA database for RPV internals. Its structure and IT platform is similar to the KomPass database. However, the Internals database is a comparatively small database. At present, it contains altogether less than 100 events that have occurred in German LWR plants since 1973. Mainly, events in connection with fasteners such as fuel assembly alignment pins and core barrel or baffle-former bolts are captured.

2.1.4 Joint IAEA/NEA IRS database

As is well known, at the end of 1978 the OECD Nuclear Energy Agency (NEA) took the initiative to establish an international system for exchanging information on safety related events occurring in operating NPPs. By the end of 1981, NEA countries had formally approved the operation of the International Reporting System (IRS). With the creation of the first comprehensive database, Advanced Incident Reporting System (AIRS), in 1995, the responsibility of processing and reviewing reports including quality checking was transferred to the IAEA. In 2006 the web based IRS was created to facilitate efficient data input and report availability. To reflect the evolution of the 'Incident Reporting System' to one which includes an expanded view/use of OE feedback, the name of the system was revised to 'International Reporting System for Operating Experience'. The system retained the abbreviation 'IRS' [2].

The main objective of the IRS is to ensure that feedback of OE gained from NPPs worldwide on safety related events is widely shared amongst the international nuclear community to help prevent the occurrence or recurrence of serious events. GRS has been participating in IRS as a national co-ordinator from the very beginning. The current database contains approximately 3,800 events. However, since the IRS focuses on significant events important for the international community, it should be viewed neither as a source for statistical studies nor for component reliability studies.

2.1.5 CODAP database

The CODAP database is a qualified mechanical component-specific international database. The OECD Component Operational Experience, Degradation and Ageing Programme (CODAP) aims to combine the follow-up of two previous OECD projects: the OECD Pipe Failure Data Exchange Project (OPDE) and the Stress corrosion cracking (SCC) part of the SCC and Cable Ageing Project (SCAP) [3].

The OECD Pipe Failure Data Exchange Project (OPDE) was established in May 2002 to produce an international database on the piping service experience applicable to commercial NPPs. OPDE, which is operated under the umbrella of the NEA, has been run successfully for eight years. The OPDE project was completed at the end of May 2011. In total, more than 3,700 piping events were collected. In 2006 the SCAP project was established by the NEA to assess two subjects, stress corrosion cracking (SCC) and degradation of cable insulation, due to their implication on nuclear safety and their relevance for plant ageing management. The project ran successfully from June 2006 to June 2010.

Following the completion of the SCAP project, SCC participants were interested in some form of continuation. It was recognised that there are many similarities between the OPDE and SCAP SCC projects and therefore, the concept of a new project was envisaged to combine the two projects in a new project called CODAP. The current CODAP database contains approximately 4,500 events. GRS participated in OPDE and SCAP-SCC as a national co-ordinator and is now actively involved in CODAP. This allows permanent access to the CODAP database as well as to the former OPDE and SCAP SCC databases.

2.2 ALMA MATER knowledge base

OE as well as comprehensive R&D has yielded a large variety of information on degradation mechanisms relevant for passive mechanical components in NPPs. Practical experience has shown, however, that quick access to this information and in particular access to the corresponding technical and chronological context often cause difficulties. Especially in connection with the analysis of rare events, the retrieval of relevant information is often a time-consuming and difficult process. The period between comparable events may in many cases be longer than the time actually spent by the individual experts working in the corresponding departments. In these cases, those involved cannot draw on their own experience for an assessment of the event but have to rely on information stored in available documents and databases. Against this background, GRS has established the browser-based ALMA MATER knowledge base [4] which provides quick access to the world-wide OE with relevant degradation mechanism, results from R&D, and relevant requirements in codes and standards. Starting with a survey of relevant degradation mechanisms, materials susceptible and components affected, the navigation gives access to detailed information on the individual degradation mechanisms (see **Table 2**).

Tab. 2 Lead-in to the Alma Mater knowledge base

Degradation mechanism		Materials susceptible	Components affected
Embrittlement	neutron activated	Low alloy steels, stainless steels	RPV belt line, RPV internals
	thermal activated	Cast duplex stainless steels, low alloy steels	Piping, housings
Corrosion	IGSCC	Stainless steels	BWR piping, RPV internals
		Nickel-base alloys	SG-tubes, nozzles, dissimilar welds
	TGSCC	Stainless steels	Piping, housing, flanges
	SICC	Carbon steels, low alloy steels	Piping, nozzles
	FAC	Carbon steels, low alloy steels	Piping of water-steam circuit
	BAC	Carbon steels, low alloy steels	Bolts, piping, vessels
	MIC	All	Components of service water systems
Fatigue	mechanical	Carbon steels, low alloy steels, stainless steels	Piping, nozzles, fasteners
	thermal		
Synergisms	corrosion fatigue	Carbon steels, low alloy steels, stainless steels	Piping, nozzles
	IASCC	Stainless steels, nickel-base alloys	RPV internals, core internals

The lead-in to the category "operating experience" is via so-called time bars, showing a summary of national and international OE with the respective mechanism over a period of several decades (see **Fig. 5**). From such survey diagrams the user can jump to more detailed information, especially in the form of event reports and the associated documentation on the evaluation of the event and corresponding statistical data.

With the described system, the most important information on comparable events can be viewed on PC within a few hours. Thus, the system supports in particular those involved in the assessment of events. However, it can also be used as a learning procedure and gives an introduction to the topics to young professionals.

3 EXAMPLES OF RECENT GENERIC STUDIES PERFORMED

Over the years, a number of generic studies on OE with passive mechanical components were performed by GRS in several projects on behalf of different customers, using the data and knowledge bases described before. Recent studies performed were focused in particular on the following topics:

- Ageing behaviour of passive mechanical components
- Chloride-induced transgranular stress corrosion cracking (TGSCC)
- Degradation in essential service water systems
- Changes in leak frequencies of piping over time.

3.1 Ageing behaviour of passive mechanical components

During the previous EUROSAFE in Paris, an overview of the joint GRS and IRSN evaluations of operating experience for the European Clearinghouse on Operating Experience Feedback (OEF) was given [5]. Within this framework a Topical Operational Experience Report (TOER) on ageing-related events was produced. The overall results obtained were presented at the International Conference “PSAM 11 & ESREL 2012” in Helsinki this year [6]. The GRS studies on the ageing behaviour of passive mechanical components in German NPPs, which are presented below, were part of this work.

In **Fig. 2**, the number of ageing-related individual events affecting passive mechanical components in German NPPs is presented by calendar year and reactor type over 20 years. As can be seen, a number of two up to 32 ageing-related individual events in passive mechanical components were identified each year from PWRs as well as from BWRs. The number of corresponding events remains more or less constant over the whole observation period, which is explained by an effective ageing management implemented in German NPPs. The increase of the number of individual events in the years 2007 and 2009 corresponds to supplementary inspections performed in all plants because of chloride-induced TGSCC in components made of austenitic stainless steel and a change in the procedure of capturing these events in the GRS KomPass database (see Section 3.2).

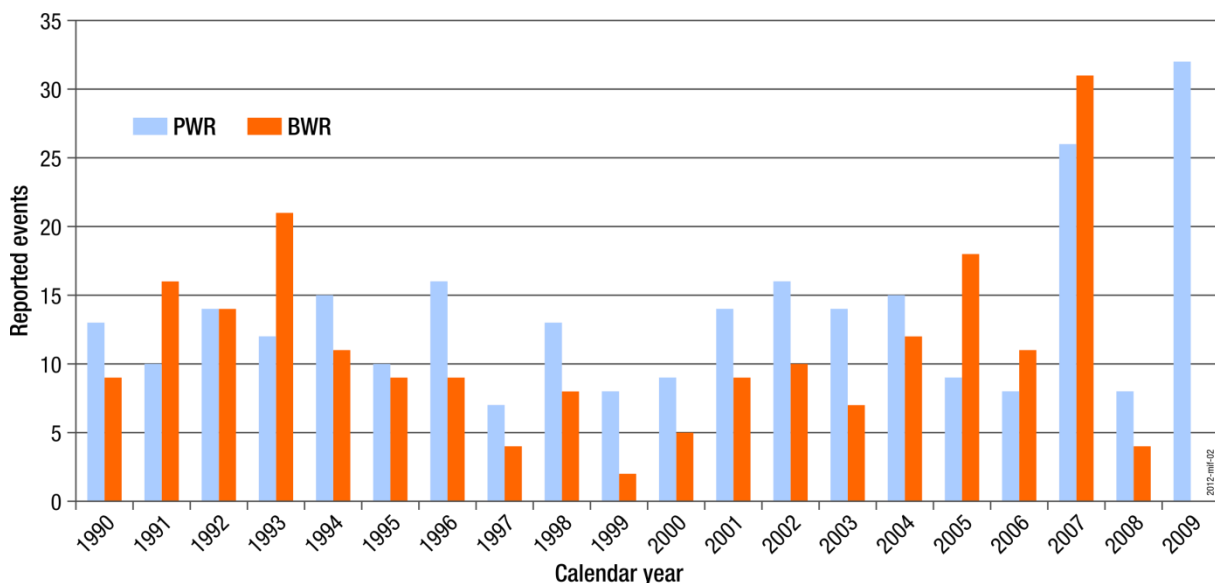


Fig. 2 Number of ageing-related individual events in passive mechanical components of German NPPs

In **Fig. 3**, the proportions of degradation mechanisms are presented. In German PWR plants, about 74% of the individual events were caused by different corrosion mechanisms and 17% by fatigue. There are also some events (about 3%) where a combination of fatigue and corrosion led to the degradation. In German BWR plants, about 82% of the events were caused by different corrosion mechanisms followed by 11% originating from fatigue.

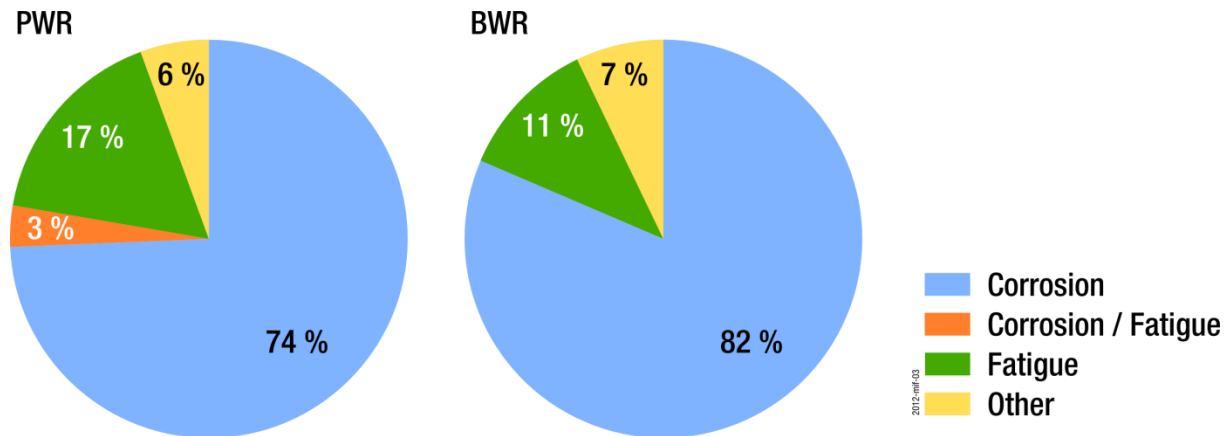


Fig. 3 Proportions of degradation mechanisms in ageing-related individual events in passive mechanical components of German NPPs between 1990 and 2009

In more detail, 38% of the corrosion-related events in PWR plants were caused by chloride-induced TGSCC in components made of stainless steel (see Section 3.2), followed by 20% due to shallow pit corrosion, mainly in piping of essential service water systems made of carbon steel (see Section 3.3).

About 58% of the ageing-related individual events in passive mechanical components of PWR plants occurred in piping, particularly in piping of small nominal bore ($NB \leq 50$). Moreover, 15% of these events pertained to heat exchangers; particularly tubes of closed cooling water heat exchangers were affected (see Section 3.3). Core internals, such as core barrel or baffle bolts and fuel assembly alignment pins, contributed with 10%. The remaining events occurred in vessels (7%), valve housings (7%) and pump housings (3%).

In comparison to PWR plants, differences exist for BWR plants with regard to the contributing individual corrosion mechanisms. Besides chloride-induced TGSCC (about 32% of corrosion induced events), components made of stainless steels were also affected by intergranular stress corrosion cracking in the weld regions (IGSCC, about 9%), and strain-induced corrosion cracking (SICC) occurred in ferritic piping (about 18%) as well as flow-accelerated corrosion (FAC, about 18%) and shallow-pit corrosion (about 12%). To manage the issues of IGSCC and SICC, measures were taken such as extensive replacement actions, using improved materials and manufacturing procedures. As a result of these measures, incidents due to IGSCC and SICC have not been reported in recent years anymore.

About 65% of the ageing-related individual events in passive mechanical components of BWR plants occurred in piping. In contrast to PWR plants, large piping was also affected, mainly due to different environmentally-assisted cracking mechanisms such as SICC, IGSCC and chloride-induced TGSCC. Moreover, 11% of these events pertained to valve housings, particularly due to chloride-induced TGSCC. Heat exchangers contributed with 9%, followed by core internals (7%), vessels (6%) and pump housing (2%).

3.2 Operating experience with chloride-induced TGSCC

On behalf of the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), GRS evaluated in detail the recent national and international OE with environmentally assisted cracking in safety-related passive mechanical components in NPPs [7]. The analysis showed significant differences between the main corrosion mechanisms and areas of degradation. Due to the chosen material concept, intergranular stress corrosion cracking of nickel alloys (PWRs) and unstabilised chromium-nickel steels (BWRs) dominate in foreign plants of Western design. In German plants with PWR and BWR, environmentally assisted cracking occurred in recent years mainly due to chloride-induced TGSCC in various parts and components made of austenitic stainless steels.

The OE with chloride-induced TGSCC in German NPPs is shown in **Fig. 4** over 20 calendar years. A few events caused by this mechanism were reported each year. Several passive mechanical components made of stabilised austenitic stainless steel were affected. Cracks initiated from the inner and outer surface as well.

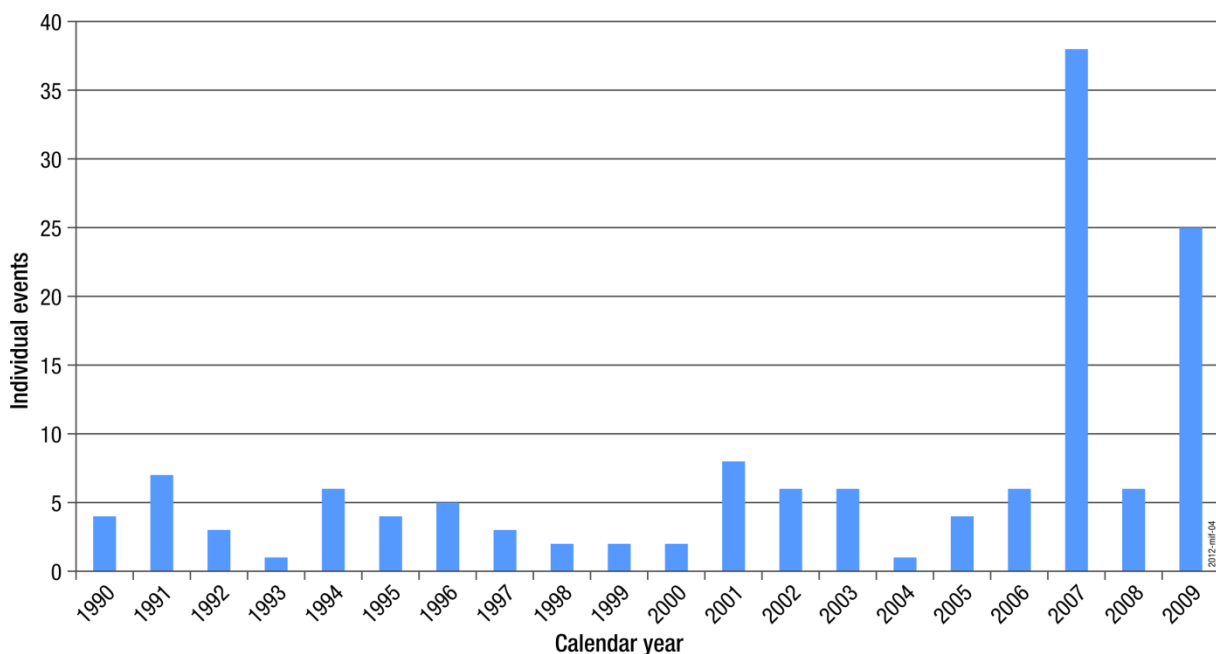


Fig. 4 Number of individual events due to chloride-induced TGSCC in German NPPs by calendar year

Further crack formations have been identified as a result of supplementary non-destructive inspections since 2007. However, it is important to note that the number of events presented in **Fig. 4** is not identical with the number of reportable events. This is due to the fact that in many cases, several identified cracks which occurred in different systems / components / are summarised in one reportable event. In the KomPass database of GRS these cracks are taken into account as individual events for in-depth evaluation.

Most cases of chloride-induced TGSCC in German NPPs resulted in non-through-wall cracks or minor leakage. The majority of cracks were found in small pipes. Also, pitting and limited cracks were observed in thick-walled valve bodies. Their direct safety impact was low. However, chloride-induced TGSCC, if not detected in a timely manner, can lead to pipe rupture or other component failure with the result of an unisolable leakage. Moreover, some events demonstrated the potential of this degradation mechanism to degrade systematically redundant trains of safety systems, which implies a significant impact on safety. The mentioned events have induced in total eight GRS Information Notices (see **Fig. 5**).

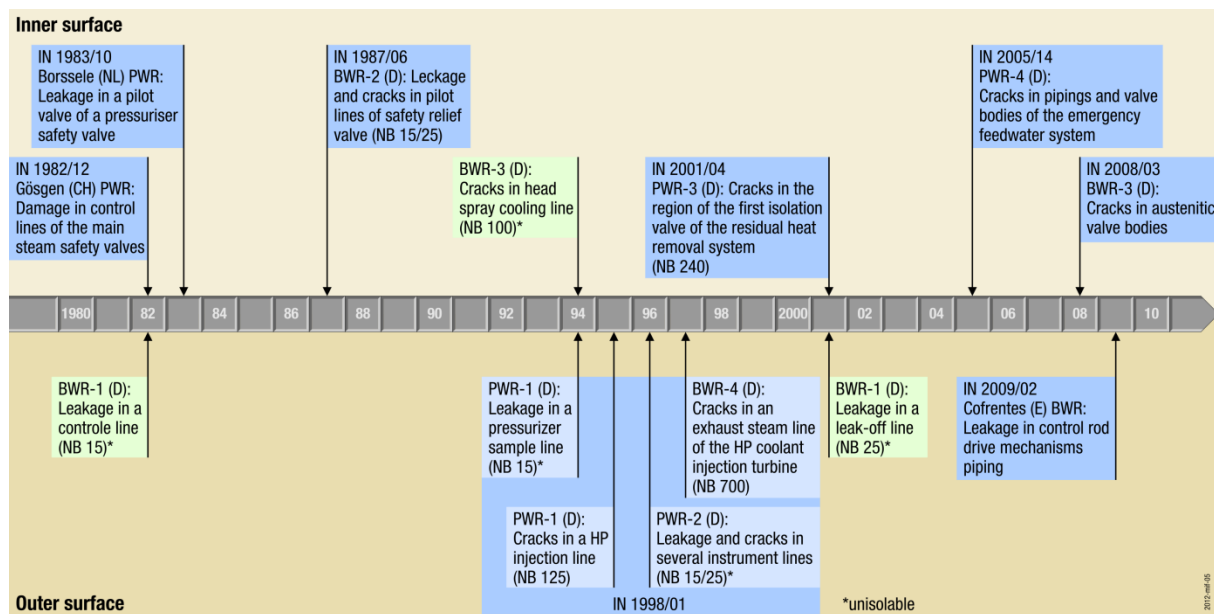


Fig. 5 Historical overview on safety-related events due to chloride-induced TGSCC in pressurised components made of austenitic stainless steel in German NPPs and events which induced Information Notices (IN)

To avoid TGSCC, any contact of chlorides with stainless steel components has to be avoided. However, what is obvious in theory may not always be easy to apply in practice. In fact, the sources of chlorides are manifold and only tiny amounts are necessary to initiate TGSCC. In 43% the source of the chlorides could not be identified. It is assumed that evaporation of the coolant in partially filled stagnant systems may be sufficient to accumulate enough chlorides to induce TGSCC [8].

In order to avoid any contamination of austenitic components with chlorides, German operators have established instructions and implemented procedures. The instructions included also the specification of any items (e.g. adhesives, gaskets, lubricants) which may get into contact with austenitic components in order to assure their low chloride content. Besides, supplementary inspections were performed at locations where chloride contamination had potentially occurred according to the OEF. All cracked components were repaired or replaced. The in-service inspections programmes were enhanced, particularly with regard to those regions which are expected to be vulnerable to chloride-induced TGSCC. Remaining questions are if chloride-induced TGSCC from inner surface is a specific issue in German NPPs only and, if so, why.

3.3 Degradation in essential service water systems

On behalf of the BMU, GRS performed a generic study on the recent OE with components in essential service water systems in German NPPs [9]. For this reason all reportable events occurred between 1997 and 2009 were evaluated. Based on this study two issues were identified:

- degradation in piping, and
- degradation in cooling water heat exchangers.

Fig. 6 shows the number of individual events that have occurred in piping of essential service water systems of German NPPs. In total, 44 events were identified; 3 of them affecting buried pipes only.

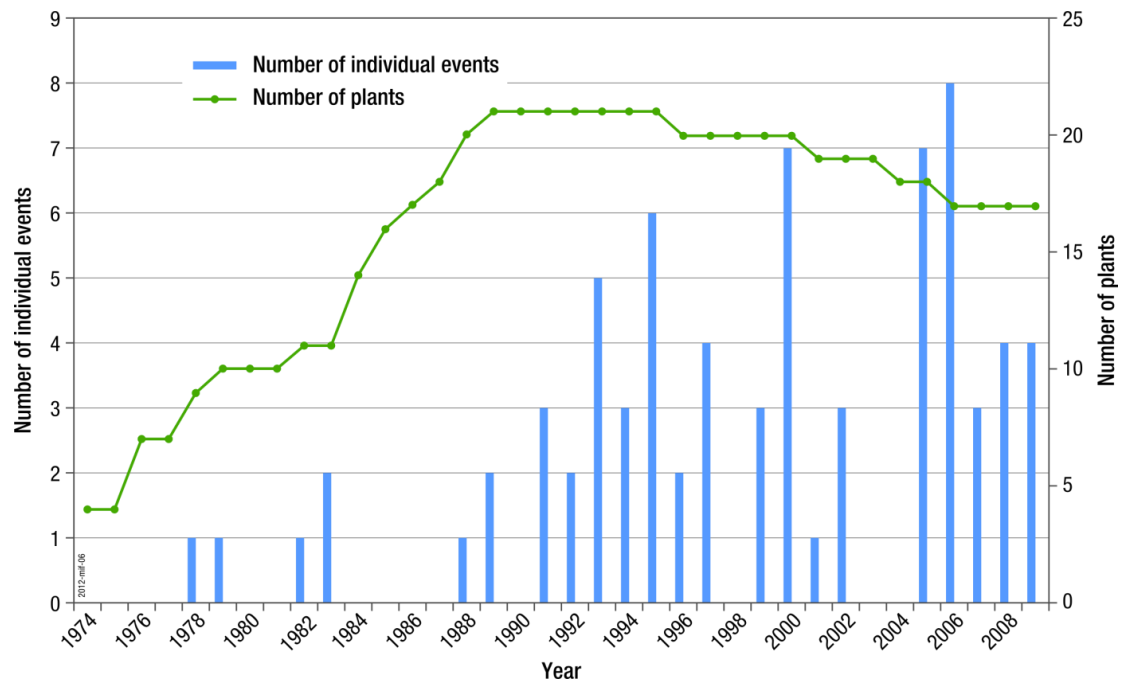


Fig. 6 Number of individual events due to degradation of piping in essential service water systems of German NPPs per calendar year and number of plants in operation (1974-2009)

The number of individual events that have occurred in piping of essential service water systems of German NPPs broken down by nominal size ranges is presented in **Fig. 7**. Piping of all ranges was affected, in particular also safety-related piping of larger diameters. However, events in piping of NB ≥ 400 mm were only reported from older plants of the first and second PWR generation or BWR construction line 69. The majority of events were identified by walk-downs, whereas degradation in large piping was mainly detected within the framework of in-service inspections.

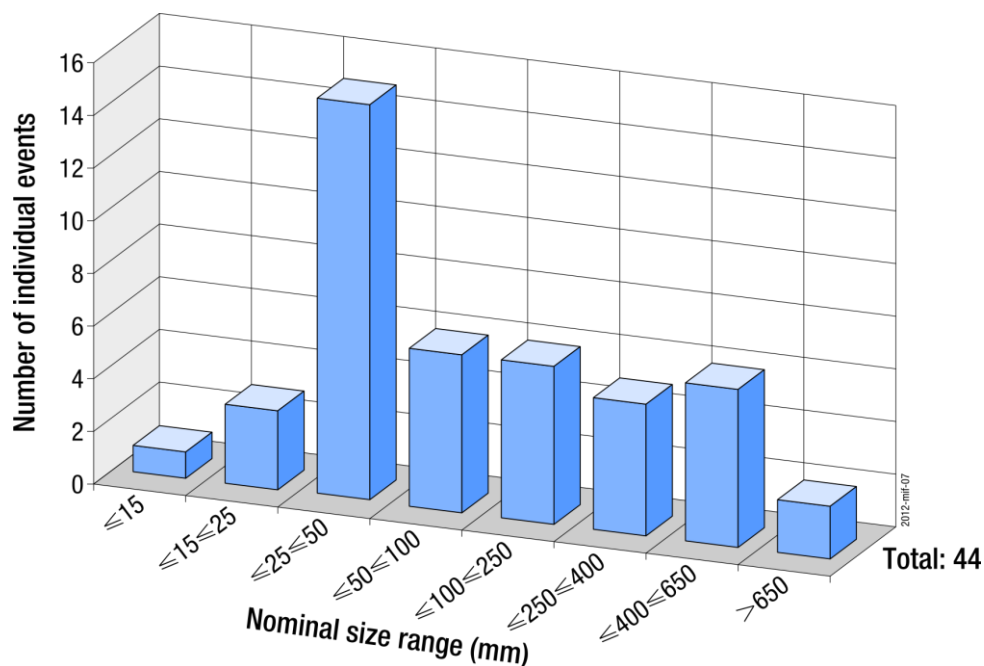


Fig. 7 Number of individual events in piping of essential service water systems of German NPPs broken down by nominal size ranges (1997-2009)

The proportions of degradation mechanisms are broken down in **Fig. 8**. The great majority of events were caused by corrosion, in many cases in connection with coating failure due to manufacturing defects or mechanical impact. The typical damage is characterised by through-wall shallow pits in the base metal of piping made of ferritic steel. Particularly areas with stagnant flow conditions were affected, where fouling may take place. In some cases erosion corrosion was also identified in areas of turbulent flow conditions.

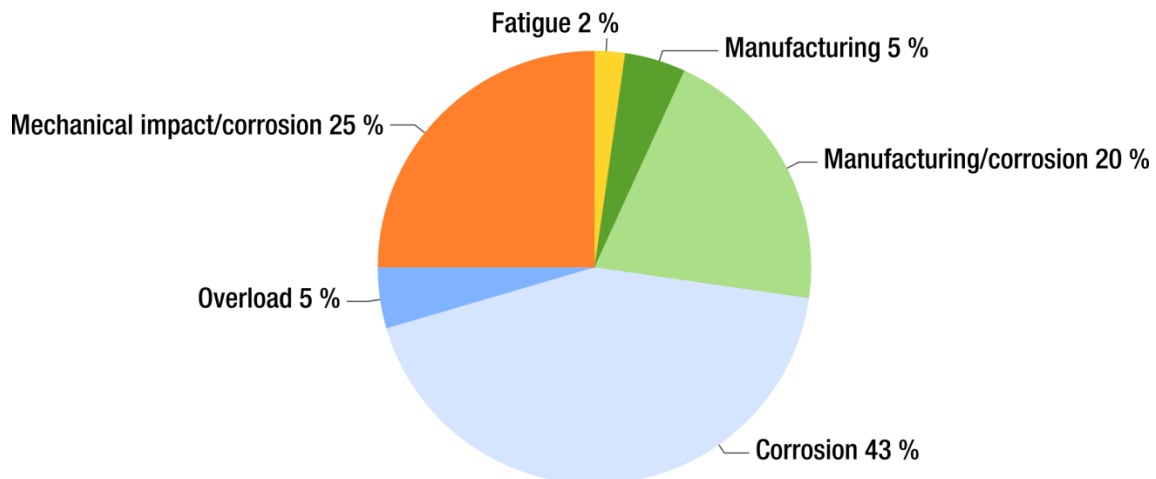


Fig. 8 Proportions of degradation mechanisms in events pertaining to piping of essential service water systems of German NPPs between 1997 and 2009

The new insights from OEF have been considered in the revision of the relevant German Nuclear Safety Standard KTA 3211.4. The current draft amendment [10] requires non-destructive testing of ferritic piping (NB > 50) with regard to wall thinning by UT or RT and the consideration of vulnerable areas, such as areas with stagnant and turbulent flow conditions, in the scope of inspections. Moreover, a targeted visual inspection of outer surfaces has to be performed within an interval of eight years.

Regarding the issue “degradation in coolant water heat exchangers”, 29 individual events were identified, 26 of them due to degradation of heat exchanger tubes. 80% of these events occurred in older plants of the first and second PWR generation or BWR construction line 69. Most of them were caused by different corrosion mechanisms such as erosion corrosion, fretting corrosion, pitting and stress corrosion cracking, in certain cases combined with fretting or manufacturing defects. Moreover, external mechanical influences, particularly due to loose parts, contributed to the damage. However, measures taken, such as replacement, use of more resistant materials and modifications in construction, have led to a decrease of these events since the end of the nineties.

3.4 Changes in leak frequencies of piping over time

Data from OE are also used for determination of specific leak and break frequencies of piping systems, taking into account the nominal size and so-called leak-relevant positions [11]. On behalf of the Federal Ministry of Economics and Technology (BMWi), GRS performed investigations for the further development of methods used for PSA. As part of these activities, changes in leak frequencies of piping over time were investigated [12]. Such changes may result particularly from learning effects, i.e. from measures taken to avoid or early detect known degradation mechanisms, or contrary from ageing effects. The OE with safety related piping, i.e. with piping of the nuclear heat generation and nuclear auxiliary systems, in German NPPs was evaluated by using data captured in the KomPass database. For comparison, data on US OE, as captured in the OPDE database, were analysed too.

First of all, leak events that occurred in safety-related piping in German NPPs between 1973 and 2008 were identified. Thereby it was confirmed that the number of leak events in safety-related piping in German plants with PWR and BWR is generally low. Afterwards, time-dependent leak frequencies were determined and further discussed regarding the

- influence of nominal size,
- role of different degradation mechanisms, and
- leak-relevant positions.

Fig. 9 shows exemplarily the determined leak frequencies of safety-related piping in German plants with BWR depending on nominal size range by calendar year. The nominal size dependency of leak events in safety-related piping already ascertained in previous tests was confirmed, i.e. leak events effected mainly piping with smaller diameters. This is true of both BWR and for PWR plants. In contrast to German BWR plants, for which a decreasing trend for leak frequencies is recognisable for the majority of nominal size ranges over the years, the leak frequencies for German PWR plants remain roughly on the same low level over the whole observation period.

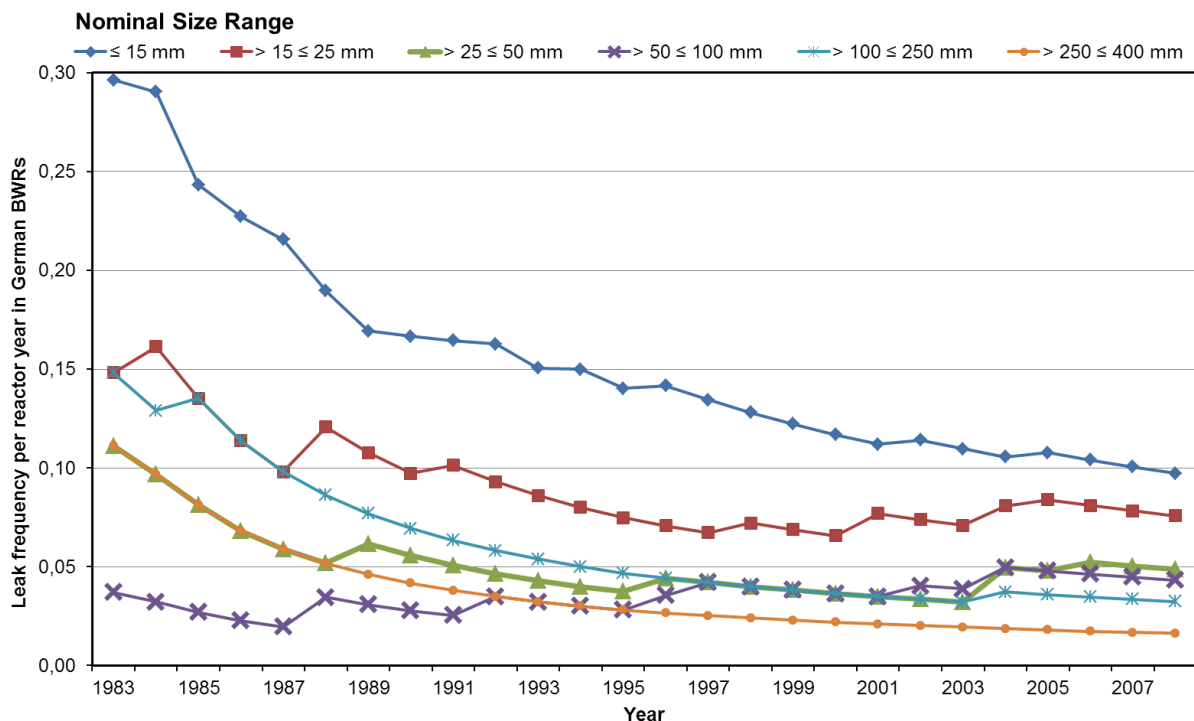


Fig. 9 Leak frequencies of safety-related piping in German plants with BWR depending on nominal size range by calendar year

The determined leak frequencies of safety-related piping in German plants with BWR depending on the root cause by calendar year are given in **Fig. 10**. Besides due to manufacturing defects, leak events were initiated by various degradation mechanisms, of which no one dominated over the total period of observation. A significant, decreasing trend with regard to the leak frequency was only recognisable for mechanical fatigue.

The number of leak-relevant positions is a decisive parameter for the determination of leak frequencies in individual piping systems [11]. It is assumed that discontinuities, particularly flanges or welds, have to be considered as such. However, in it was found that the frequency of pipe leaks at welds of safety-related significant piping in German plants has decreased during the period of observation and pipe leaks occurring in the base material area, especially in plants with PWR, have gained in importance (see **Fig. 11**). As a result of our study it was therefore suggested to reconsider the criteria for leak-relevant positions.

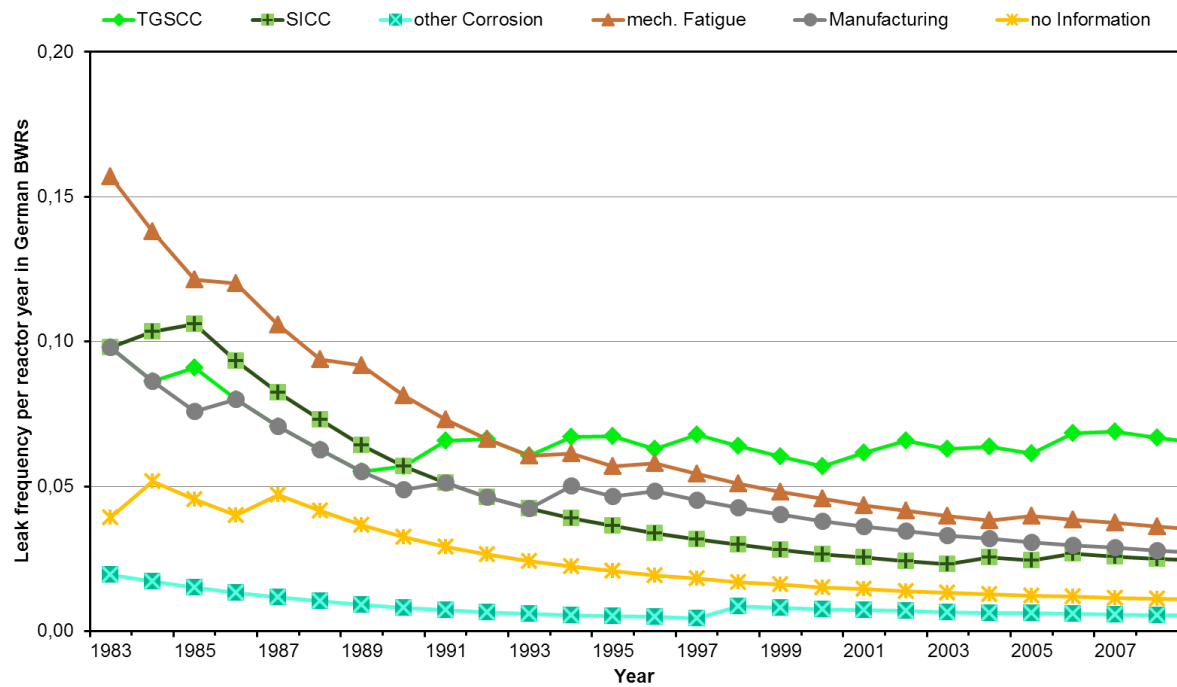


Fig. 10 Leak frequencies of safety-related piping in German plants with BWR depending on the root cause by calendar year

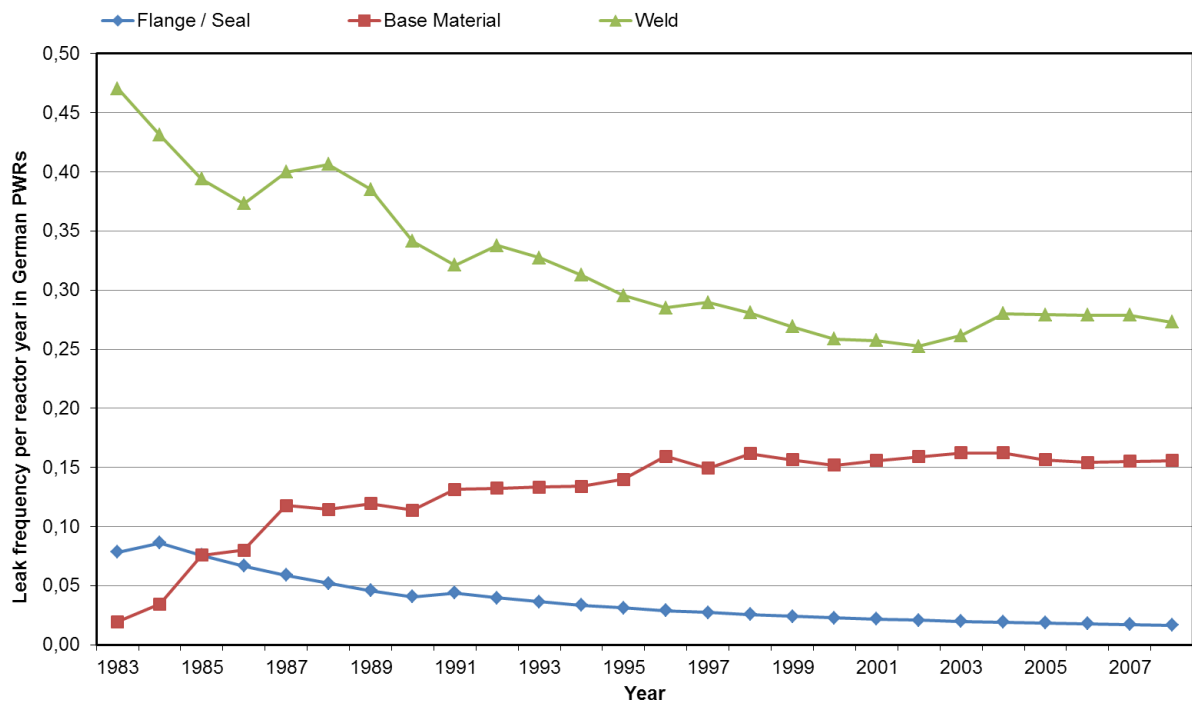


Fig. 11 Leak frequencies of safety-related piping in German plants with PWR depending on location of damage by calendar year

4 CONCLUDING REMARKS

GRS as a Technical Safety Organisation (TSO) is evaluating OE in order to early identify changes in the reliability of passive mechanical components in NPPs and corresponding safety issues. For this reason, GRS has established appropriate data and knowledge bases as well as tools and methods.

The investigations performed confirm the robustness of the design chosen for passive mechanical components in German NPPs as well as the effectiveness of measures taken to avoid or early detect any degradation so far. Typical measures taken are:

- Extended plant monitoring in order to enhance the understanding of system behaviour and load conditions.
- Optimisation of operating conditions in order to minimise stressors.
- Optimisation of inspection programmes and enhancement of non-destructive examination techniques in order to early detect degradation.
- Replacement of components sensitive to degradation, particularly by using optimised materials and manufacturing in order to enhance safety margins.
- Enforcing technical requirements in codes and standards in order to avoid repetition of non-optimised technical solutions.
- Implementation of target-oriented R&D programmes in order to better understand relevant degradation mechanisms and their contributing factors.

From our experience, international co-operation in the field of operating experience feedback is an important element in order to ensure that sufficient information for safety assessment of nuclear installations is available. Therefore, GRS is also actively participating in international co-operation regarding the evaluation of OE with passive mechanical components, particularly within the framework of

- the European Clearinghouse on OEF in close co-operation with IRSN,
- the OECD Component Operational Experience, Degradation and Ageing Programme, and
- the IAEA Programme on International Ageing Lessons Learned (IGALL).

Future GRS work on OE evaluation with passive mechanical components will comprise maintaining, updating, and extending of the available data and knowledge bases as well as further evaluation of it. Current generic studies under way or scheduled at GRS are focused in particular on

- long-term behaviour of RPV internals (on behalf of BMU),
- cracks and leaks of the reactor coolant pressure boundary (European Clearinghouse), and
- flow-accelerated corrosion in water-steam cycles (CODAP).

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