

JRC SCIENCE FOR POLICY REPORT

Ten years of lessons learned from operating experience in nuclear power plants

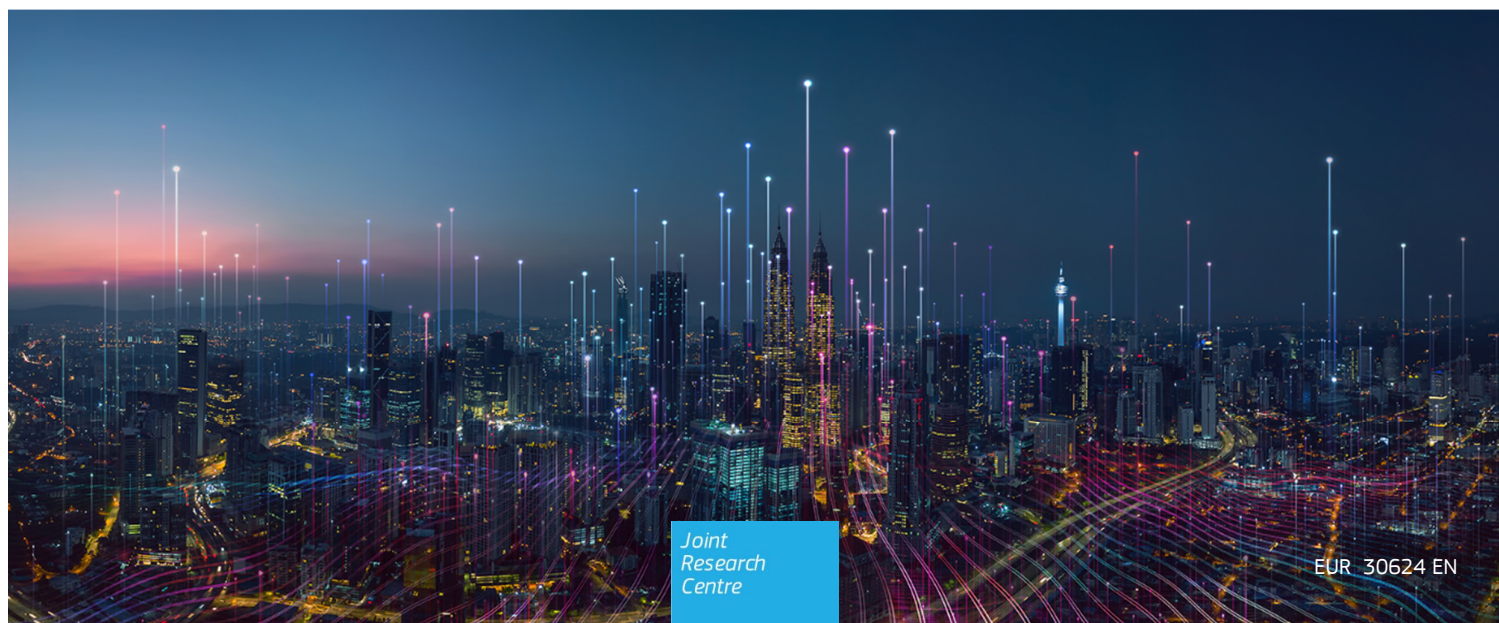
*A review of EU Clearinghouse
topical studies*

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Abstract

The European Clearinghouse on Operating Experience Feedback for Nuclear Power Plants has been established in 2008 to enhance the exchange of lessons learned from operating experience among members. The network of nuclear safety regulatory authorities and their technical support organizations, within the EU region, hosted and operated by the Joint Research Centre (JRC) of the European Commission, has issued, during the first ten years of its activities, twenty-three topical studies reports, on topics defined and selected by the EU Clearinghouse members: each report is the outcome of an in depth analysis of selected international operating experience, with particular attention to the reportable events.

The Joint Research Centre has carried out a retrospective and comparative analysis of the whole knowledge system made of the outcomes of all these reports. The methodology developed by the JRC over this period is outlined. The results of a statistical study of the twenty-three reports are presented, showing that the most recurring contributing factors are related to design, maintenance and management. Moreover, the most common findings across the studies are related to analysis, operating experience feedback and to organisational aspects. The results of a comparative analysis, having the purpose of extracting new insights, are reported. This transversal reading has highlighted four horizontal issues (i.e.: common to all or many of the topical studies): (1) the need for a further enhancement of the sharing of the international operating experience; (2) the need to anticipate and mitigate issues which tend to originate in the pre-operational phases, in particular during the design phase, remaining latent and undetected for many years; (3) the importance of the organisational and human factors as contributors to events; and (4) the safety culture.

This ten-year EU Clearinghouse report provides the network members, and the nuclear community, with key findings and observations. It is also enriched by a comparison of the topical studies' findings with the Western European Nuclear Regulatory Association (WENRA) Safety Reference Levels, confirming the safety relevance of topics raised by operating experience, and suggesting that the EU Clearinghouse products can have a stronger impact in future reviews of the Reference Levels.

Orientations for future EU Clearinghouse works are, finally, proposed. These orientations can benefit from synergies with other nuclear activities carried out at the Joint Research Centre.

Acknowledgements

The idea of a European Clearinghouse for nuclear operating experience was born as a reply to a need identified during the dialogue among European regulators. For ten years the EU Clearinghouse has been a forum in which national regulatory authorities, international organisations and research and technical centres participated sharing a common vision. The outcomes of the EU Clearinghouse are the result of the commitment and coordinated effort of many people within those organisations. Since the shaping of the initial idea, all these contributions have been necessary to reach the achievements of this undertaking. We would like to thank all those who have contributed to this project.

Executive Summary

Policy context

Production of low-carbon electricity is a key contribution to the objectives of the European Green Deal, and nearly half of it is currently generated by nuclear energy. It is crucial that this type of energy is generated in a safe and reliable way, making nuclear safety an absolute priority for the European Union.

Since the construction of the first commercial power reactors, their safe operation and the prevention of accidents has been a constant focus of industry and regulatory bodies, and this focus extends today to many other nuclear applications, like medical (radiology, radiotherapy, nuclear medicine) or industrial (hydrogen production, process heat).

Learning from experience is one of the cornerstones used for decades by the nuclear industry to achieve high safety levels, and is embedded in the international nuclear safety regulatory regime. At European level, the Council Directive 2014/87/Euratom of 8 July 2014 requires Member States national frameworks ensuring that the regulators and the licence holders take measures to promote and enhance an effective nuclear safety culture, including in particular the need to register, evaluate and document internal and external safety significant operating experience, as well as the obligation of the license holder to report events to the competent regulatory authority.

However, the use of external international operating experience has proved to be particularly challenging, as the exchange of lessons learned relies ultimately on the voluntary cooperation of regulatory bodies and operators worldwide.

Regarding the nuclear safety authorities, an initiative from the Nuclear Energy Agency (NEA) established already in 1978 an international system for exchanging information on safety related events. The operation of the system was later transferred to the International Atomic Energy Agency (IAEA), and it resulted in the creation of a comprehensive database in 1995, the Incident Reporting System (IRS). The nuclear safety authorities of IAEA's member states contribute regularly to populate this database, which has become the most important international input to national operating experience programs worldwide.

In parallel, the cooperation of licence holders was strongly reinforced with the creation of the World Association of Nuclear Operators (WANO) in 1989, three years after the Chernobyl accident. Since its foundation, the sharing of operating experience among members has been one of the main WANO's activities.

The EU Clearinghouse, a network of European nuclear safety authorities hosted and operated by the Joint Research Centre, was established in 2008 with the purpose of enhancing the exchange of lessons learned from nuclear power reactors operating experience. In this regard, the EU Clearinghouse has helped the regulators in Member States to follow the mandate of the nuclear safety directive.

Topical studies

One of the main activities of the EU Clearinghouse has been the preparation of topical studies on operating experience. These are in-depth reviews of available operating experience related to a given nuclear safety topic, where the lessons to be learned from past incidents at nuclear power plants are formulated with a broad perspective, so that they can be useful for situations somewhat different from the original event. The EU Clearinghouse has established a specific methodology, outlined in this report, to conduct these reviews in a consistent and objective way.

During the 10 years following its establishment, from 2009 to 2018, the EU Clearinghouse carried out 23 topical studies on request of the member national nuclear regulatory and safety authorities; these reports have been distributed not only to the members of the EU Clearinghouse, but also to the wider audience in the IAEA/NEA IRS. Recently, some topical studies have been translated to Chinese by China's National Nuclear Safety Administration (NNSA), proving their global outreach and positive contribution to the international effort to continuously improve nuclear safety.

The present report has been conceived as an opportunity to transversally read the published topical operating experience reports, in order to add cross-cutting insights for supporting the mission of the regulatory authorities, licensees and, per extension, of all main actors of the nuclear industry. This new approach has allowed extracting from the wealth of information available in the topical studies reports, many other insights, and knowledge, confirming the system of topical studies issued by the EU Clearinghouse to represent

a mine of consolidated knowledge available to the nuclear industry, to the national safety authorities, and to all stakeholders willing to participate in an informed dialogue on the progress of nuclear energy exploitation.

Key findings and observations

The retrospective and comparative analysis of the topical studies issued during ten years of EU Clearinghouse activities, and the comparison versus the Western European Nuclear Regulators' Association (WENRA) Safety Reference Levels for Existing Reactors, has produced the following key findings:

- The importance to valorise the operating experience is an acquired concept in the nuclear industry. In spite of the fact that the importance of operating experience for supporting operational excellence is a well-established conclusion, the message that there should be more attention to the operating experience is emerging from several topical studies.
- Computer networks can present vulnerabilities; stringent requirements should apply to the implementation of interfaces between safety and non-safety-related applications. Moreover, a safety culture around digital instrumentation and control systems requires further consideration.
- It would be very valuable to enhance sharing of construction experience, in a systematic and timely manner at international level, especially considering the number of new reactors in construction or planned to be constructed worldwide, and the knowledge developing in the new and fast growing national nuclear industries.
- More exploitation of operating experience is indispensable in finding the problems which went unnoticed during design, construction, inspection, review and maintenance.
- Design deficiencies emerged in several topical studies. They became fully visible only after many years of plant operation.
- Design deficiencies are rooted on other factors, mainly of human and organisational nature, which often remain unnoticed.
- The nuclear supply chain experienced deep transformations, and specific causal factors became usual, such as shortage of design skills or deficit of manufacturing and engineering capacity in the market (especially in relation to the majority of nuclear power plants getting older).
- The prevalence of identification of technical causes suggests a dominant way of reading the events' reports, the outcome of a search targeted to the specific technical aspects of the event, restricted within narrow boundaries. The real root causes of events seem to be not properly identified in a considerable part of the analysed event reports, especially when they are related with processes managed by suppliers.
- When root causes of events are not correctly identified, corrective actions are ineffective, preventing learning, creating the illusion that the problem has been solved. This missed opportunity has a price in terms of safety, in financial terms, and potential consequences on reputation.
- The occurrence of human and organisational factors is even more evident in those activities which require the intervention of different teams. It is a potential risk, in particular, in the case of subcontracting external contractors, an increasing management practice, which can be anticipated or mitigated by ensuring the sharing of the necessary information and knowledge, the good working conditions, and the appropriate supervision of the contractors.
- Regarding the decommissioning phase, it should be ensured that the organisation in place is adequate (both solid and flexible) for the rigorous and systematic transfer of the responsibilities for safety from the operational organisation to the decommissioning organisation.
- The occurrence of human and organisational causal factors can be exacerbated by a knowledge management risk. It is fundamental to ensure in the long term the retention and new acquisition of the best professional knowledge, skills, and experience. This challenge emerges, in particular, in life extension and decommissioning.
- The impact on the safety culture of the organisation, by the intervention of different teams, of different cultures, for example, those of subcontractors is confirmed.

Besides the listed findings, the following observations, of more general validity, have been extracted by the comparative analysis:

- The safety culture and safety awareness of the personnel involved in the pre-operational stages should be ensured through appropriate training, highlighting the role and the safety significance of the components concerned. Safety awareness should be extended to the performance of all tasks, including the “simple” ones.
- The exploitation of the operating experience would benefit from the harmonisation and alignment of the available databases. If it is not possible to achieve this alignment, the alternative is to pursue a deep and comparative analysis, wherever possible, of the data available. A strategy would be the sharing of resources, both in terms of data, and in terms of analytical efforts of review of the operating experience, with the aim to extract knowledge and applicable lessons.
- The root cause analysis stops at the boundary between the plant operator and the designer. Other stakeholders (reactor vendor, architect-engineer or main supplier) could contribute to the robustness of the entire process by running their own operating experience programs. This would enhance the sharing of experience.
- Issues related to human and organizational factors and management deficiencies are in general not well addressed in the analysed event reports. This problem is partially due to the taxonomy of human errors. The effectiveness of the operating experience feedback system is affected by the lack of information regarding human, organizational and management-related factors; the limitations of the coding system make the retrieval of the relevant information difficult. The need for upgrading the coding systems used for the classification of event reports with an enhanced system, is suggested. The upgraded system should ideally consist of simple and comprehensive set of human, organisational and managerial factors.

Operating experience and WENRA's Safety Reference Levels

The comparative analysis of WENRA's Safety Reference Levels for Existing Reactors against the findings of the EU Clearinghouse topical studies over a period of ten years confirms that the WENRA Safety Reference Levels address most of the topics raised by recent operating experience, and stresses the relevance of the EU Clearinghouse products for future reviews of the reference levels.

The analysis highlights those Safety Reference Levels for which the topical studies provide examples of actual events supporting their relevance. In a few cases, suggestions to expand or clarify the meaning or applicability of some Safety Reference Levels are also provided.

Related and future JRC work

The report, moreover, presents related work carried out by the JRC, highlighting the international context, the fruitful cooperation of the EU Clearinghouse of the Joint Research Centre with reference international organisations in the nuclear area, such as UN/IAEA and OECD/NEA; in particular, the regular participation in technical meetings, the contribution to TECDOCs and Safety Reports Series; the participation in working groups of the Nuclear Energy Agency of the OECD, both within the Committee on Nuclear Regulatory Activities (CNRA) and of the Committee on the Safety of Nuclear Installations (CSNI).

In the future, closer cooperation among national, European and international entities will be needed to avoid duplicities and untimely actions. The JRC actively supports this effort. Indeed, the cooperation formula used by the EU Clearinghouse (i.e.: a limited number of countries willing to work on an equal basis on a nuclear safety topic of common interest with the role of technical secretariat ensured by the JRC) has been successfully applied for the last years, and could be repeated to share regulatory experience in other domains, like research reactors, waste repositories, technical reviews of Small Modular Reactors, etc. These developments could benefit from the knowledge produced within other nuclear activities carried out at the Joint Research Centre.

1 Introduction

Learning from its own mistakes or, even better, from mistakes made by others, is a key safety principle that the nuclear industry has been applying for decades. After each of the three major accidents in the history of nuclear power (Three Mile Island, Chernobyl and Fukushima), regulators and operators undertook extensive actions to improve nuclear power plants' safety. Furthermore, not only major accidents, but also all other events, including minor ones, offer opportunities for safety enhancement.

The international nuclear safety framework requires the operators of nuclear power plants to *establish an operating experience programme to learn from events at the plant and events in the nuclear industry and other industries worldwide* ⁽¹⁾.

At European level, the Council Directive 2014/87/Euratom of 8 July 2014 requires the Member States to ensure that their national framework asks regulators and licence holders to take measures to promote and enhance an effective nuclear safety culture. These measures include in particular the need to register, evaluate and document internal and external safety significant operating experience, as well as the obligation of the license holder to report events to the competent regulatory authority.

The use of external international operating experience has proved to be particularly challenging, as the obligation to report safety relevant events is, in general, limited to the nuclear safety authority of the country², and consequently the information is not automatically available to the international community. Therefore, the international component of operating experience programs relies ultimately on the voluntary cooperation of stakeholders (operators and regulatory bodies) worldwide.

The cooperation of nuclear licence holders was strongly reinforced with the creation of the World Association of Nuclear Operators (WANO) in 1989, three years after the Chernobyl accident. Since its foundation, the sharing of operating experience among members has been one of the main WANO's activities.

Regarding the nuclear safety authorities, an initiative from the Nuclear Energy Agency (NEA), a semiautonomous body within the Organisation for Economic Cooperation and Development (OECD), established already in 1978 an international system for exchanging information on safety related events. The operation of the system was later transferred to the IAEA, and it resulted in the creation of a comprehensive database in 1995. The nuclear safety authorities of IAEA's member states contribute regularly to populate this database, which has become the most important international input to national operating experience programs worldwide.

In 2006, during a NEA/IAEA sponsored conference, participants discussed the suitability of a regional initiative in Europe to establish a common clearinghouse to collect and capitalise on European operating experience. Shortly afterwards, the EU Clearinghouse, a network of European nuclear safety authorities hosted and operated by the Joint Research Centre was established with this purpose.

One of the main activities of the EU Clearinghouse has been the preparation of topical studies. These are in-depth reviews of available operating experience related to a given nuclear safety topic, where the lessons to be learned from past incidents at nuclear power plants are formulated with a broad perspective, so that they can be useful for situations somewhat different from the original event.

The purpose of this report is to summarise the results obtained by the collection of reports over the last ten years and to explain how they have contributed to the EU nuclear safety policies and how they could be further used to continue to enhance the safe operation of nuclear facilities in Europe in the future.

⁽¹⁾ Safety of Nuclear Power Plants: Commissioning and Operation, Specific Safety Requirements, International Atomic Energy Agency

⁽²⁾ Contracting Parties of the Convention on Nuclear Safety have the obligation, under Article 19, to share important experience with international bodies and with other operating organisations and regulatory bodies. This represents however only a limited fraction of the total operating experience available.

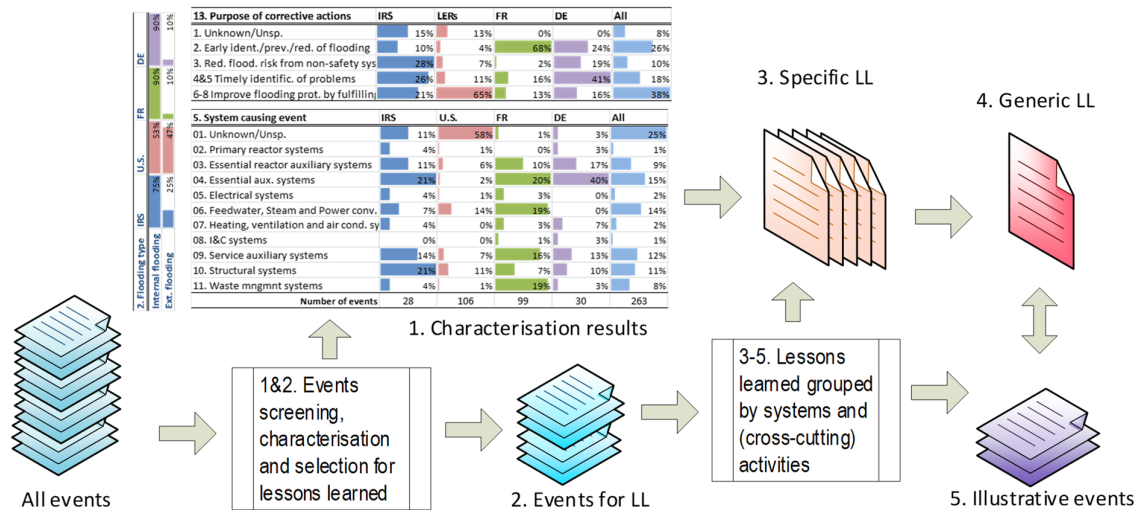
2 Topical Studies prepared by the EU Clearinghouse

2.1 Method for topical studies preparation

Over the years, the EU Clearinghouse has gradually developed a method for topical study preparation in five steps as presented in Figure 1. Events reported by nuclear power plants are first screened and characterised according to pre-defined criteria. Then, a detailed assessment of selected events follows in order to create specific lessons learned. Generic insights can then be derived from specific lessons learned grouped by relevant systems and activities. Finally, a number of events illustrating the generic insights is selected to improve their communication. These insights are often related to the root or direct cause of the events, but also to the equipment or type of component affected, to certain activities or to some type of human behaviour, etc.

As mentioned, insights are derived from operating experience in two steps in order to express both specific and generic levels. First, specific lessons learned attached to individual events are defined. Usually specific lessons learned are understandable and most valuable in the context of the events. The whole range of these event-specific lessons learned is used as a base to build a generic type of lessons learned (insights) as stand-alone formulations, independent from specific events. Generic insights should not be too specific (e.g., they should be applicable to more than one situation or NPP) nor too general (e.g., they should go beyond simple common sense or widespread knowledge). Every insight suggests an action to prevent reoccurrence of known issues.

Figure 1. Schematic of the approach used by EU Clearinghouse to conduct topical studies in five phases: 1) screening and characterization; 2) selection of events for lessons learned (LL); 3) creating and grouping specific lessons learned; 4) formulating generic lessons learned and 5) selecting illustrative events.



2.2 Topical studies' scope

The EU Clearinghouse has published a total of 23 topical studies in the period 2009-2018 (see Table 1).

Four different databases containing reports about nuclear power plants operational events have been used in performing these studies: the IAEA/OECD IRS database (international coverage), the NRC Licensee Event Reports database (US coverage), and the French and German databases. Table 2 shows how often each source has been used in 23 topical studies.

A representative topical study is based on the detailed review of about 550 event reports from 20 years of operating experience, and it identifies 9 contributing factors and 17 findings. Table 3 shows the variation of these parameters across the 23 reports.

The median number of years considered for topical studies is 20 with minimum 6 and up to over 40 years. The number of identified contributing factors ranges from 4 to 16 with a median of 9. Identified findings

range from 4 to 30 with a median of 17, Table 3. These values depend on topic and number of considered databases. The next subsection provides more details on the findings.

Table 1. Topical studies issued from 2008 to 2018.

1. Reactivity Management Incidents, 2008	13. RC Pressure Boundary Leaks and Cracks, 2014
2. Forsmark 1, Report on 2006 Event, 2008	14. Organizational and Management Events, 2014
3. Fuel Failure Events, Analysis, 2009	15. LOOP and SBO Related Events, 2015
4. Maintenance Related Events, 2009	16. Cooling Chain Related Events, 2015
5. Construction, Commission & Manufacturing, 2010	17. Low Power and Shutdown, 2015
6. Ageing Related Events, 2011	18. Control Rods Related Events, 2017
7. Modifications Events, 2011	19. Design Deficiency Related Events, 2016
8. Supply of NPP Components, 2011	20. Maintenance Related Events (update), 2015
9. Decommissioning, 2012	21. Loss of Essential Power System, 2018
10. External Hazard Related Events, 2012	22. Flooding Related Events, 2018
11. Digital I&C Systems Related Events, 2013	23. Digital I&C Systems Related Events (update), 2018
12. Emergency Diesel Generators, 2013	

Table 2. Events databases used in preparation of topical studies (rounded values).

Events database	Used in TSs	Average number of events per TS
International Reporting System (IRS), IAEA/OECD	100%	120
Licensee Events Reports (LER) U.S. NRC	78%	180
French operating experience (SAPIDE), IRSN	64%	220
German operating experience (VERA), GRS	64%	180

Table 3. Time range, number of events, contributing factors and findings statistics for 23 topical studies (rounded values).

Range	Years span	Number of events	Contributing factors ⁽¹⁾	Findings ⁽²⁾
Min	6	50	4	4
Max	42	1200	16	30
Median	20	550	9	17

⁽¹⁾ number identified per topical study.

⁽²⁾ number of lessons learned/recommendations/insights per topical study.

2.3 Summary findings from topical studies

Topical studies provide quantitative as well as qualitative results. Quantitative results are obtained from statistical analysis, like trends over the period observed, or the relative frequency of specific events characteristics contributing factors. As an example, Figure 2 illustrates the trend for number of loss of offsite power events, for each database considered. Qualitative results (findings and insights) are presented in several different ways across various topical studies, i.e.: lessons learned (specific and generic), observations and recommendations.

Events characteristics are mostly topical studies specific and less interesting for comparison while contributing factors are mostly common, and it is interesting to compare results between topical studies. Table 4 presents important contributing factors based on the number of topical studies where they are identified and on their respective ranking within each topical studies. Design, maintenance and management are the three most important contributing factors because they were identified in 5-6 topical studies with very high ranking. A total of 10 contributing factors are identified as very important based on their presence and rankings in the number of topical studies. The total number of contributing factors is 30. Clearly some of them are very specific to certain topics (e.g., extreme weather and cooling).

Findings (lessons learned, insights, observations and recommendations) are the most important results from topical studies. As explained, they are defined at two levels (specific and generic). Table 5 presents the

findings with the highest rank based on the number of topical study where they are present. Analysis, operating experience feedback and organization related recommendations are present in between almost 60 to about 40% of topical studies, respectively. Ten insights are common to almost 20% or more topical studies, Table 5.

This is just a snapshot illustrating the potential value of considering the comparison of results from different TSs.

Figure 2. Number of events per year from four sources in the topical study on loss of offsite power (L&S). (US stands for LER database).

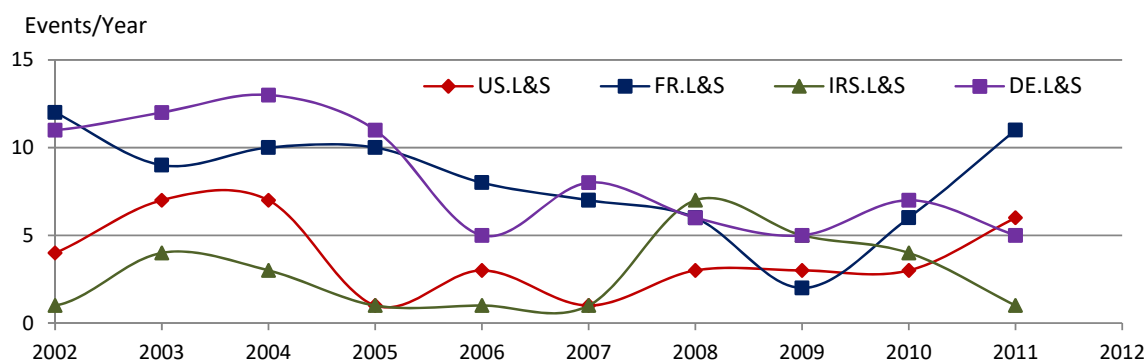


Table 4. Highest-ranking contributing factors identified in topical studies

Contrib. Factors	N° TS ⁽¹⁾	Rankings in TS ⁽²⁾	Score ⁽³⁾	Note
Design	6	1 st 4x, 3 rd 2x	10	-
Maintenance	6	1 st , 2 nd & 3 rd 2x	8.9	Includes testing, in-service insp., inadequacy, etc.
Management	5	1 st 3x, 2 nd & 3 rd 1x	8.3	Management includes planning & work practice.
Organization	5	2 nd 3x, 3 rd 2x	6.5	Organization includes modifications.
Training	4	1 st 1x, 2 nd 2x, 3 rd 1x	5.8	Training includes preparation and qualification.
Implementation	3	1 st 2x, 2 nd 1x	5.2	Implementation includes execution.
Corrosion	3	1 st 2x, 2 nd 1x	5.2	-
Documentation	4	2 nd & 3 rd 2x	5.1	-
Procedures	3	1 st 2x, 3 rd 1x	5.0	-
I&C	3	1 st 1x, 3 rd 2x	4.3	-

⁽¹⁾ Number of topical studies where each contributing factor (CF) was considered important

⁽²⁾ Number of high rankings in topical studies for the corresponding CF.

⁽³⁾ Normalised CF score based on the number of TS' and corresponding rankings.

Human, Installation/equipment, Ageing, Operation, Analysis & Fatigue CFs have score between 3.1÷3.8.

Electrical and Manufacturing CFs have score 2.5.

Extreme weather, Engine, Starting & Fuel system contributing factors have score 1.9.

QA/C, Instability, Heat sink, Funding, Cooling, Welds, Operating Experience Feedback & Lighting CFs have score ≤ 1.4.

Table 5. Highest-ranking findings area identified in the performed topical studies

Findings ⁽¹⁾	Share of TS ⁽²⁾	Note
Analysis	57%	Adequate and sufficient analysis.
Operating experience feedback	43%	OEF program and use of available insights.
Organization	39%	Not including Human and organizational factors.
Management	26%	-
QA/C	22%	-

⁽¹⁾ LL, insight, recommendation and observation related area.

⁽²⁾ Percentage of TS' in which respected insights area is relevant.

3 Horizontal nuclear safety topics

The purpose of the chapter is to provide the main actors of the nuclear industry with horizontal insights extracted from the topical studies produced by the EU Clearinghouse in 10 years of activities. The wealth of information contained in the numerous JRC topical studies reports can be approached from different perspectives and with different purposes. The intention is not to repeat what has been already duly stated and documented in the topical reports, but to transversally read them in order to add cross-cutting insights for supporting the mission of the regulatory authorities, licensees and, per extension, all main actors of the nuclear industry. The outcomes of this horizontal analysis could be considered as the result of a comparative reading of the Topical Studies reports, which is one among many still possible. It is implicit that other different approaches, possible and welcomed, will allow to extract from the wealth of information available in the topical studies reports, many other insights and knowledge. This confirms that the bulk of topical studies issued by the EU Clearinghouse represents a mine of consolidated knowledge, relevant to specific topics, selected and defined by the EU Clearinghouse members. This mine is a reference for the nuclear industry, and still offers many opportunities of exploitation. The outcomes of the horizontal analysis of the JRC topical studies resulted in the identification of trends, which can be linked to four main issues, called horizontal issues. The four issues are: 1) The need to valorise the nuclear operating experience; 2) Emergence of design deficiencies; occurrence and reoccurrence of human and organisational factors; 4) Safety culture issues. The four issues are described and discussed in the following sections.

3.1 Horizontal issue 1: The need to valorise the nuclear operating experience

The importance to valorise the operating experience is an acquired concept in the nuclear industry. This conviction has been at the basis of the establishment, in many countries exploiting nuclear energy, of operating experience databases. Furthermore, learning from the international exchange of operating experience has been the guiding principle for the creation of the IAEA/NEA IRS database, and the EU Clearinghouse has translated in action the vision of contributing to valorising and sharing the experience internationally available. In spite of the fact that the importance of operating experience for supporting operating excellence is a well-established conclusion, the message that there should be more attention to the operating experience, and, even, the warning of the lack of operating experience use, is emerging from several topical studies carried out during the last 10 years by the EU Clearinghouse.

Several IRS events reports on ageing-related events show the relevance of taking into account operating experience to avoid reoccurrence of events. Therefore, a relevant high-level lesson learned has been extracted from a very recent topical studies, dedicated to ageing, in support of the exploitation of the operating experience, and the lesson learned quotes *"Data on operating experience can be collected and retained for use as input for the management of plant ageing. Reviews of operating experience can identify areas where ageing management programmes can be enhanced or new programmes developed"* [1].

In the topical studies dedicated to events on digital I&C systems [2], it is pointed out that operating experience has shown that software programming may include some errors, which should be taken into account by improving the safety culture around new digital I&C. It has also highlighted the possibility of vulnerabilities in computer networks, data overload and communication breakdown between systems; therefore, one of the messages is that stringent requirements should apply to the implementation of interfaces between safety and non-safety-related applications.

However, the same EU Clearinghouse report highlights that the collection of experience of operating digital I&C systems was limited by the low number of available reports with enough detailed information for supporting an in-depth analysis. Therefore, the analysis of digital I&C operating experience demonstrates the need to discuss reporting criteria and event taxonomy, possibly also covering sub-components and all lifecycle phases.

A similar message emerges from the topical study on construction, commissioning and manufacturing events [3], which mentions that the reports of events do not always include information about non-conformances detected and corrected prior to plant operation, as they have no impact on the safety of the operating plant during the reported event. Moreover, in most of the events' reports resulting from construction deficiencies, the lessons learned for current and future construction projects were often not fully considered; instead, they are focused more on the corrective actions required for the operating plant in question. Therefore, it would be very valuable to share more construction experience in a systematic and timely manner at international level, especially considering the number of new reactors in constructions or planned to be constructed worldwide, and the knowledge developing in the new and fast growing national nuclear industries.

Similarly, the topical study dedicated to flooding events [4] highlights the limitation in operating experience, as there is not enough data to select best flooding protection, therefore redundancy, maintenance, inspection and review are essential. Operating experience is indispensable in finding the problems which went unnoticed during design, construction, inspection, review and maintenance. These events can also serve as motivation for additional checking and inspections.

The lack of consideration of operating experience emerges clearly from the EU Clearinghouse study dedicated to maintenance-related events [5]. In fact, for example, internal flooding is not sufficiently considered despite of the fact that it could lead to the loss of equipment important to safety, with a risk for common mode failures. The risk of internal floods can be induced by maintenance activities; for this reason, the different scenarios that could damage the water circuit during maintenance activities have to be identified during risk analysis or safety study.

Attempts aiming at using operating experience in the area related to supply of components have been already made in the past [6]. However, the majority of these works are covering only some issues, related to the supply of components and not encompassing the entire nuclear supply chain as a whole.

Finally, the topical study on emergency diesel generators [7] points out that no comparison of the results among the four different databases analysed was performed, due to the different reporting criteria specific for each database. The same comment is present in the topical study report dedicated to the events connected with low-power and shutdown states [8], where it is stated that the considered operating experience base should not be used to draw overall quantitative conclusions, such as worldwide trends in number or severity of events, comparison among countries, etc., as the reporting criteria and internal structure of databases are not homogeneous. The definition of operational modes in general varies with countries and reactor technology. This may create some confusion on the data presented, and it may explain the differences among the four databases. This is an additional limitation to the best use of available international operating experience.

Therefore, the exploitation of the operating experience would certainly benefit from the harmonisation and alignment of the available databases, which – we are aware – can be concluded and proposed, but difficult to be implemented, considering that most of the databases are national, few are international, and expected differences exist between the national databases, as well.

Therefore, if it is not possible to achieve this alignment, the alternative is to pursue a deep and comparative analysis, wherever possible, of the data available in the databases, adopting different scopes and analysis criteria. Besides the critical approach, which is embedded in the analytical comparison, a great achievement would be the sharing of resources, both in terms of data, and in terms of analytical efforts of review of the operating experience, with the aim to extract knowledge and applicable lessons learned, for the benefits of the nuclear industry.

Key findings:

- 1) The importance to valorise the operating experience is an acquired concept in the nuclear industry. In spite of the fact that the importance of operating experience for supporting operating excellence is a well-established conclusion, the message that there should be more attention to the operating experience is emerging from several topical studies.
- 2) Computer networks can present vulnerabilities; stringent requirements should apply to the implementation of interfaces between safety and non-safety-related applications. Moreover, safety culture around digital I&C systems requires further consideration.
- 3) It would be very valuable to enhance sharing of construction experience, in a systematic and timely manner at international level, especially considering the number of new reactors in constructions or planned to be constructed worldwide, and the knowledge developing in the new and fast growing national nuclear industries
- 4) More exploitation of operating experience is indispensable in finding the problems which went unnoticed during design, construction, inspection, review and maintenance.

Observations:

The exploitation of the operating experience would benefit from the harmonisation and alignment of the available databases. If it is not possible to achieve this alignment, the alternative is to pursue a deep and comparative analysis, wherever possible, of the data available. A strategy would be the sharing of resources, both in terms of data, and in terms of analytical efforts of review of the operating experience, with the aim to extract knowledge and applicable lessons learned, for the benefits of the nuclear industry.

3.2 Horizontal issue 2: Emergence of design deficiencies

Beyond the study conducted specifically on design deficiencies [9], this causal factor emerged also in several topical studies. For example, from the analysis of events carried out within several studies, it emerges that design deficiencies are one of the major causes of events. For example, the recent topical study on ageing [1], has highlighted that deficiencies in maintenance or surveillance are the most important root causes, followed by deficiencies in design and in ageing management programmes. The deficiencies appeared visible in aged components only after many years of plant operation. Design errors appear also among the causes of events related to decommissioning [10]. Design configuration and analysis are the most dominant root-causes and causal factors also within the study on flooding related events [4]. The topical study on Modifications [11] as well confirms from the analysis of the IRS reports, that the two steps where the failures occurred mainly, are design (about 40% of IRS reports) and implementation (about 30%). Similarly, the study on supply chain events [6] recognises in component design the most contributing process of the chain to the supply of inappropriate components (42%), followed by manufacturing (32%), and inadequate technical documentation provided by the supplier (9.4%). These errors in design, and also manufacturing and supplier documentation, are certainly affected by factors which are in the human and organisational domain, which will be treated later on in the chapter.

The same supply chain topical study report warns that, during the last decades, the nuclear supply chain experienced a number of serious changes, and specific factors became usual, such as shortage of skills needed to design, deficit of manufacturing and engineering capacity in the market, and invited to adopt a systemic approach to tackle this issue. In fact, the detected flaws related to design, besides being part of a horizontal issue and cause, require due attention, both for their implications and for the fact that they do not seem to be root causes. Very often, these flaws are issues rooted on other factors, mainly of human and organisational nature, which have remained undetected, and have not being tackled by means of tailored corrective actions. Furthermore, beyond the significance of the design issues themselves, the horizontal reading of topical studies suggests that too often the root cause analysis stops at the boundary between the plant operator and the designer. Other stakeholders (reactor vendor, architect-engineer or main supplier) could contribute to the robustness of the entire process by running their own operating experience programs. This would contribute to the sharing of experience,

The following related high-level lessons learned suggested in some referred topical studies reports, provide some examples of outcomes of the EU Clearinghouse activities: for example, from the topical study on aging [1], the high-level lesson learned n. 1 proposes that *“Appropriate measures should be taken and design features should be introduced in the design stage to facilitate effective ageing management throughout the life of the plant”*. Furthermore, high-level lesson learned n.4 mentions that *“Adequate oversight by the licensee is recommended during all phases of design, procurement, testing, receipt inspection and installation to avoid events where wrong material is used. When a wrong or low performance material is already installed, the rate of material degradation can often be reduced by optimizing operating practices and system parameters.”*

Key Findings:

- 5) Design deficiencies emerged in several topical studies. They became visible only after many years of plant operation.
- 6) The nuclear supply chain experienced deep transformations, and specific causal factors became usual, such as shortage of design skills or deficit of manufacturing and engineering capacity in the market.
- 7) Design deficiencies are rooted on other factors, mainly of human and organisational nature, which often remain unnoticed.

Observations:

The root cause analysis stops at the boundary between the plant operator and the designer. Other stakeholders (reactor vendor, architect-engineer or main supplier) could contribute to the robustness of the entire process by running their own operating experience programs. This would enhance the sharing of experience.

3.3 Horizontal issue 3: Occurrence and reoccurrence of human and organisational factors

The previous sections have already suggested the occurrence and detection of human and organisational contributors, within the identified horizontal issues as lack of operating experience feedback, and deficiencies in design. The present section offers the occasion to extract from the horizontal reading of the EU Clearinghouse topical studies' reports a learning which stems from the human and organisational factors domain.

The topical study on supply chain events [6], highlights that the identified causes in the most populated subfamily of events related to design and manufacturing, are mainly of technical nature. In general, they are considered related to inadequate material used and/or heat treatment applied, inadequate or not followed technological procedures, inappropriate assembling, wrong dimensions, and welding defects. Only in a few cases human factors, organizational or management problems are mentioned as complementary causes. From this observation, the report infers that the real root causes of events seem to be not properly identified in a considerable part of the analysed event reports, especially when they are related with processes managed by suppliers (design, manufacturing).

Unidentified root causes of events produce as consequence the definition and implementation of ineffective corrective actions, and all this prevents the learning from operating experience, creating the illusion that the problem has been solved, whilst high probability for recurrence of analogous events still remains. And this weakness affects the learning from operating excellence at all level, starting from the plant level, to the licensee level, to the regulatory authority level, and, finally, the international learning of the nuclear industry; and has a price in terms of safety and, certainly, in financial terms, without deepening the potential consequences of reputational risks and media impact.

To be noted that the agreement about root causes is not always achieved, and this is because of different reasons, with the incompleteness of event reports being significant.

The occurrence of human and organisational factors is even more evident in those activities which require the intervention of different teams, and the interface with several organisations, external to the licensee. This happens, for example, in the case of construction, commissioning and manufacturing [3]. The EU Clearinghouse study highlights that the average detection time of the defect is rather long, about 8 years after the start of the commercial operation; the proportion of common cause failures can be quite high for some items or components; the largest majority of the events are found fortuitously. Hence the need to minimise the number of deficiencies during construction, manufacturing and commissioning of a new reactor, as they can be major latent failures for a long time and can have actual consequences for safety after the reactors start to operate.

Similar considerations emerge from the analysis of decommissioning events [10]. Although the nature of these events is different, the causes are similar, and always related to the need to adapt the structure and practices of the plant organisation to the new configuration for decommissioning. In effect, several events were caused by the inadequacy of the organisation put in place to carry out the decommissioning. The new organisation missed to rigorously and systematically transfer the responsibilities for safety from the operational organisation to the decommissioning organisation.

The nature of the decommissioning activities, in which many interventions and works are carried out by many workers in many locations of the facility, can trigger the actuation of systems due to human errors, electrical disturbances, and other causes. This risk of mistakes is also common to other types of activities, when many workers and different teams are simultaneously involved.

These facts demonstrate the importance of maintaining a solid, yet flexible organisation that ensures the continuity of important tasks that must be carried out with the highest standards up to the very end of the decommissioning project. To be recalled that these issues are exacerbated by a knowledge management risk, which the decommissioning activities have in common with plant activities during life extension. In fact, during decommissioning projects, especially in the long term, it is very difficult to retain and obtain the best

professionals in terms of knowledge, skills, and experience. This is due to both the difficulty of maintaining in the long term the knowledge and experience of one particular facility, and the scarce personnel skilled and experienced in decommissioning. The life extension of the nuclear facilities also faces this issue.

The occurrence of human and organisational factors shortcomings is also evident in the EU Clearinghouse report on flooding events [4]. The appropriate organisational and managerial decisions support the establishment of the appropriate structural and organisational measures. As highlighted by the report, the structural measures are physically preventing flooding water to reach or damage safety-related systems, and they can be permanent or temporary, and can serve for the prevention of both external and internal flood. Organizational measures are important for temporary protection measures, and for flooding mitigation. Good organization approaches aim at accurate consideration of flooding protection review, inspection, maintenance and flooding prevention. Internal flooding is sometimes caused because of poor organization during maintenance, modifications and operation.

As well, the study on leaks and cracks [12] shows that corrosion is the main root cause of the events analysed. Sometimes, this was just the 'apparent' cause, because in about 50 % of the analysed events, corrosion was triggered by the chemical reactions between the materials being in contact with one another, in the accidental presence of a catalyst. The study reports that manufacturing defects are the second largest root cause of the events, and that these events are nearly all related to welding faults, though in some cases inappropriate quality assurance measures of the manufacturer can be considered as precursors. The other major contributors for triggering corrosion are maintenance defects and faulty operations, which, again, confirms the occurrence of human errors, probably stemming from incorrect work practices, inadequate abilities and training, and inadequate supervision.

Similarly, the analysis of the events due to Loss of Offsite Power and Station Blackouts at NPPs (LOOP) [13] have provided as result that the largest number of events is registered during normal operation, inspection, functional tests and maintenance. The main direct cause for those plant-related events is human failure, with electrical, instrumentation and control failures as second and third largest contributor.

The analysis shows that the root cause of more than half of the events is related to the human performance, followed by equipment related events and other failures. Human failure occurs during tests, service and maintenance, followed by the human failures, due to insufficient or wrong procedures. The largest share in IAEA IRS LOOP events is from equipment failures after the installation, followed by the human failures due to the procedures and human errors during test and maintenance.

From this result, suggestions about the coordination of the maintenance activities on offsite power system with maintenance work on on-site power system have been put forward, especially in conjunction with unavailability of the essential power system trains. In particular, external personnel conducting various works on-site should be adequately trained and informed considering accident prevention rules [13].

As already mentioned, these elements can directly be found in the topical studies' report focused on maintenance activities [5] and limited to NPP operational incidents which resulted directly (direct cause) from maintenance activities or where maintenance was a root cause of such incidents. The statistical analysis shows that the essential reactor auxiliary systems, and the electrical systems are the systems prone to be affected by maintenance failures. They are also the most affected by flooding events. This type of failures should be certainly the result of a human and organisational cause to be identified and corrected. If not, it will certainly continue to be present and produce damage.

There are differences within the identified root causes of the events. In general, in the databases sources of data, the following causes, which are clearly related to human and organisational factors, have been detected: deficiency in the written procedures and documents guiding the maintenance activities; maintenance incorrectly performed; deficiencies in management or organization, and deficiencies in training or lack of knowledge.

Other human and organisational factors have been registered with respect to subcontracted staff, an increasingly frequent industry practice. These events point out essential shortcomings in communication, surveillance by the operator staff. Therefore, to prevent issues during subcontracted activities, it is essential to facilitate the sharing of the necessary information and knowledge, the good working conditions, and the appropriate supervision of the contractors.

These outcomes of the topical study report on maintenance can also be integrated with the outcomes of the topical study on events related to low-power and shutdown states [8]. First, it highlights that the human factor is directly related to events in a vast majority of cases, in particular during outages. It is, in fact,

reported that the increase in the number of activities during refuelling outages, means that a much higher number of people are working on-site, including external contractors, not necessarily as familiar with the plant systems and procedures as the regular staff. Consequently, deficiencies in communication, supervision and planning, stress and organizational factors in general may have a stronger impact on safety than in power operation.

In nearly all cases, the excessive workload posed on control room operators is cited either as a root cause or as a contributing factor for the event. This is generally linked to deficiencies in the outage planning, in which the workload of control room operators is not properly addressed. Most of these events happened during start-up or preparation for start-up phases.

Many inspection and test activities need to be carried out during shutdown. Very often they reveal latent defects that could otherwise evolve into more serious events. The same can be said about maintenance activities. Among the typical problems reported are human and organisational factors as: confusions about the items which should be subject to maintenance due to labelling deficiencies; errors during RCPB safety valves servicing; wrong torque values applied to valves or other equipment; assembly of components in the wrong sense or inadequate use of temporary plugs.

These insights extracted from the different EU Clearinghouse topical studies are integrated to the outcomes of a specific topical study dedicated to organisational factors [14]. The study has highlighted that retrieving and screening incident reports from the IRS database related to the human, organizational and management related factors presents some difficulties, due to the irregularity of the terminology and the uncertainty of the definitions used by the authors of the IRS reports. Furthermore, the analysis of the IRS and LER reports has shown that in several cases the root causes of events were not properly identified. The study has also confirmed that issues related to human and organizational factors and management deficiencies are in general not well addressed in the analysed event reports; when identified, these issues are considered as human performance errors at the individual worker level. This conclusion does not allow uncovering the organizational deficiencies, and the issue is partially due to the taxonomy of human errors (including slips, lapses, mistakes and violations), which is mostly applied to the workforce and not to management.

Finally, the report has recalled that the effectiveness of the operating experience feedback system is affected by lack of information regarding human, organizational and management-related factors; and the limitations of the coding system make the retrieval of the relevant information difficult.

These observations have highlighted the importance of upgrading the coding systems used for the classification of event reports with an enhanced system, ideally simple and enabling the identification and appropriate classification of human, organisational and managerial factors in the registered events.

Key findings:

- 8) The prevalence of identification of technical causes suggests a dominant way of reading the events' reports, the outcome of a search targeted to the specific technical aspects of the events, restricted within narrow boundaries. The real root causes of events seem to be not properly identified in a considerable part of the analysed event reports, especially when they are related to processes managed by suppliers.
- 9) When root causes of events are not correctly identified, corrective actions are ineffective, preventing learning, creating the illusion that the problem has been solved. This missed opportunity has a price in terms of safety, in financial terms, and potential consequences to the reputation.
- 10) The occurrence of human and organisational factors is even more evident in those activities which require the intervention of different teams. Subcontracting external contractors, an increasing management practice, is in particular a potential risk, which can be anticipated or mitigated by ensuring the sharing of the necessary information and knowledge, good working conditions, and providing appropriate supervision of the contractors.
- 11) The "adequacy" of the organisation put in place requires particular attention and verification.
- 12) Regarding the decommissioning phase, it should be ensured that the organisation in place is adequate (both solid and flexible) for the rigorous and systematic transfer of the responsibilities for safety from the operational organisation to the decommissioning organisation.

- 13) The occurrence of human and organisational causal factors can be exacerbated by a knowledge management risk. It is fundamental to ensure in the long term the retention and new acquisition of the best professional knowledge, skills, and experience. These challenges emerge, in particular, in life extension and decommissioning.

Observations:

Issues related to human and organizational factors and management deficiencies are in general not well addressed in the analysed event reports. The issue is partially due to the taxonomy of human errors.

The effectiveness of the operating experience feedback system is affected by lack of information concerning human, organizational and management-related factors; the limitations of the coding system make it difficult the retrieval of the relevant information.

The need for upgrading the coding systems used for the classification of event reports with an enhanced system, ideally simple and comprehensive of the due classification of human, organisational and managerial factors, is suggested.

3.4 Issue 4: Safety culture issues

A separate discussion deserves, as specific horizontal issue, the weaknesses in safety culture. The inadequacy of the safety culture has been explicitly mentioned in several EU Clearinghouse topical studies ([1], [3], [5], [6], [10]). However, even if not explicitly mentioned, many of the direct causes and root causes reported under the previously discussed horizontal issues, can be related to an organisation lacking safety culture.

In the case of the study on events related to low-power and shutdown states [8], issues related to safety culture have been noted: for example, the recurring issue of the use of parallel, unofficial check lists to verify system status before returning to power. To be noted are the challenges due to the intervention of many different subcontractors, and the implications of the different cultures of the teams. Another observed behaviour was that operators sometimes erroneously assume that the system configuration will be checked later, during the plant start-up, and knowingly leave a system in a wrong configuration. And, finally, other events have been caused by operators deviating from procedures or signing off check lists while no verification was done.

Adherence to nuclear safety principles should be the top priority already at the construction and manufacturing stages. The safety culture and safety awareness of the personnel involved in the pre-operational stages should be ensured through appropriate training, highlighting the role and the safety significance of the components concerned, and supported by adequate communication. Everyone participating in the project needs to understand the safety significance of their work, to promote personal responsibility. This is necessary for all the staff involved in the process, including the manufacturer's staff, the vendor's staff, contractors and sub-contractors, the staff in charge of the surveillance of the activities, and the staff in charge of the acceptance of the components [3]. The referred TS report suggests that this safety awareness should be ensured not only for "complicated" works like welding, but also for more "simple" tasks, like anchoring or cable sheathing, especially since some subcontractors may not have any work experience in the nuclear industry. Special attention should be paid to the communication between the different companies involved in building a plant, and the communication should be regulated by documented procedures within a quality control programme.

An overwhelming majority of the supply-related events seems to be caused by the same group of common fundamental reasons: inadequate quality and safety culture; deficiencies or ineffectiveness of management systems; quality management or quality assurance either of supplier/vendor, designer, manufacturer, or of customer (NPPs) [6]. Consequently, the main opportunity for preventing or decreasing the probability of events, caused by inappropriate supplied components, lies in the improvement of management systems, including management of nuclear supply chain and management of NPPs.

The absence of a safety culture was clearly identified as an accompanying root cause in a few events related to maintenance [5]. The presence of a strong safety culture in maintenance adds a significant value to the safe operation of the plant. With respect to plant maintenance, safety culture means keeping the maintenance process on track and in control at every stage of plant performance. When there is a positive and strong safety culture, maintenance staff excels in the preparation and execution of the tasks in compliance with the safety, quality and technical specifications.

Key Findings:

- 14) The impact on the safety culture of the organisation, of the intervention of different teams, of different cultures, for example, those of subcontractors is confirmed.
- 15) The safety culture and safety awareness of the personnel involved in the pre-operational stages should be ensured through appropriate training, highlighting the role and the safety significance of the components concerned.
- 16) Safety awareness should be extended to the performance of all tasks, including the "simple" ones.

4 Operating experience and the safety reference levels

The Western European Nuclear Regulators' Association (WENRA) published in 2006 a set of Safety Reference Levels (SRLs) [15] for Existing Reactors, reflecting expected nuclear safety practices to be implemented in WENRA countries. The SRLs were established as a major contribution from WENRA to develop a harmonised approach to nuclear safety within its member countries.

The initial version of the SRLs has been updated several times, notably after the lessons from the Fukushima Dai-ichi accident, and after the insights obtained from the EU stress-test exercise. The lessons learned from operating experience are therefore one of the essential inputs to drive the harmonisation effort on the nuclear safety domain.

In its current version, the SRLs are grouped into 19 issues. Furthermore, WENRA has published also a report [16] dealing with SRLs during the decommissioning phase.

In this context, benefiting from the knowledge acquired within the EU Clearinghouse, a comparative analysis of the WENRA SRLs and of the topical studies' findings has been carried out, highlighting the parallelism between them. This systematic analysis confirms the operating experience basis of the WENRA Safety Reference Levels, and shows that the topical studies offer a valuable source of information for future updates of the SRLs, contributing in this way to reinforce the link between operating experience (not limited to major accidents) and future Member States' regulatory nuclear safety practices, standards and requirements.

A comparison between the topical studies published by the EU Clearinghouse and the WENRA's SRLs gives the opportunity to discern to which extent the main lessons derived from operating experience are fully reflected in the SRLs. While this is obvious for major accidents, it is less so for incidents and for other minor events. However, even if an event does not result in any safety significant consequence, it can still provide to the nuclear industry valuable lessons to be learned.

As the SRLs have been defined to support harmonisation, they do not seek to comprehensively cover all nuclear safety related issues, but rather those where the approaches taken by WENRA countries differ more substantially. Therefore, it should not be expected that, for every lesson from an EU Clearinghouse topical study, a corresponding SRL exists. Furthermore, the lessons contained in the topical studies vary widely in the level of technical detail, some of them being very specific to certain types of reactor designs or technologies.

This type of insights is certainly not suitable for a high level document as the SRLs, which is applicable to countries with a wide range of regulatory frameworks and reactor technologies. However, it is still useful to examine the results obtained from the topical studies performed during the covered ten years period in the light of the SRLs, even considering the limitations of the systematic comparison. The next subsections summarise the results of the analysis carried out, covering some of the related issues contained in the WENRA document and discussing some additional topics.

4.1 Operating organisation

Reference levels **B3.1** through **B3.6** set the expectations regarding the staffing of nuclear power plants, both in terms of number and competences.

The topical study on low-power and shutdown modes [8] shows how adequate staffing is particularly challenging in the main control room during certain phases. In particular, it is common during the start-up phase, and the preparatory activities leading to the start-up after an outage, that operators in the control room are subject to an excessive workload; this should be avoided by careful planning of these phases. On the other hand, the simultaneous presence of too many people at the control room may hinder effective communication between operators or create distractions. Again, a careful outage planning should assure that the required number of technicians at the control room remain within certain thresholds at all times.

4.2 Management system

Within the Issue C, a number of SRLs cover the implementation of management systems (from **C5.1** to **C5.8**). Some of these SRLs require strict control and identification of documents, including in particular engineering drawings or specifications. However, there is no equivalent requirement on the identification of equipment across the plant.

Operating experience in topical studies on loss of essential power system [17] and on low-power and shutdown modes [8] shows that inadequate, unclear labelling of equipment has often led to errors during maintenance, particularly affecting the identification of cables in electrical hardware.

4.3 Design basis envelope for existing reactors

The topical study on design deficiencies [9] recommends accounting for local environmental conditions prevailing inside containment during design basis accidents in the design of the component cooling water system.

This can be seen as a particular case of the general SRL **4.1** establishing the design basis of the plant.

Reference level **E7.3** requires specify criteria for the protection of the reactor coolant pressure boundary, including thermal and pressure transients.

This is supported by one of the recommendations from the topical study on design deficiencies [9], based on events where phenomena like thermal fatigue in elbows subject to alternative hot and cold flows in RHR system piping have been observed. Another example is the corrosion found in dead ends of piping in Safety Injection and RHR systems, isolated from the primary system but subject to warming through convection and vortex effects.

Reference level **E8.7** requires safety analyses to rely on justified and conservative methods and assumptions. In particular, the verification that respecting the fuel safety limits under all conditions is usually achieved with the help of software models.

The topical study on analysis of fuel related events [18] recommends particularly carefulness when checking that the fuel model assumptions are applicable to the particular plant conditions under review.

Reference level **E9.2** states that failures of normal operation systems shall not affect safety functions.

Operating experience shows that ensuring this requirement on digital systems is particularly difficult. For example, digital communication technology typically uses networks with a single connection transmitting multiple signals, contrary to analogue point to point connections. There are many valid reasons for safety systems to share data with non-safety systems, or for different safety channels to share data between themselves, which requires some sort of interconnection. Reported events show that digital network communication, if not designed properly, may propagate failures from non-safety systems to safety systems (or from one safety system channel to another redundant channel).

Regarding the use of diversity in order to meet SRL **E9.4**, the topical study on loss of essential power [17] suggests that emergency DC batteries is a case where using diversity in design is particularly beneficial, especially if the concept of diversity is extended to the supplier and complemented by the staging of the system testing and maintenance.

The topical studies on events related to NPPs digital instrumentation and control system [2] finds that, in relation to the digital upgrades to safety-significant systems, licensees should conduct a defence-in-depth and diversity analysis as part of the design process to ensure that the plant is sufficiently able to cope with common-cause software failure vulnerabilities.

This lesson confirms the relevance of such reference levels as **E9.4** and **E10.10**, and provide the basis for further guidance.

Reference level **E10.2** requires that plant instrumentation is adequate, and operating experience (from the topical study on design deficiencies [9]) shows that special attention is needed when different suppliers are involved in the design and installation of I&C loops, and when I&C tubing is field routed.

The topical study on loss of essential power [17] confirms the importance of reviewing the design of these systems with regard to the single failure criterion coincident with loss of offsite power, as required by SRL **E10.11**, particularly when operating experience of the plant suggests potential non-compliance. It also suggests ensuring appropriate separation and isolation provisions when non-safety related equipment is powered from essential power.

Finally, SRL **11.1** mandates regular review of the plant's design basis.

The topical study on external hazards related events [19] gives examples of events that could have been avoided if the maximum effects of certain hazards had been reassessed.

4.4 Design extension of existing reactors

Three topical studies (emergency diesel generators [7], design deficiencies [9] and flooding [4]) provide strong evidence supporting the need for regular review of the design extension conditions selection, in the light of operating experience or significant new safety information (SRL **F5.1**).

4.5 Safety classification of structures, systems and components

Reference level **G3.1** expectation is that structures, systems and components (SSCs) important to safety are designed, constructed and maintained such that their quality and reliability are commensurate with their classification.

Operating experience from topical study on construction, commissioning and manufacturing events [3] suggests that, in addition to design, construction and maintenance, also the handling, packaging, transportation and storage conditions contribute to the items quality and reliability. Furthermore, the topical study on events related to NPPs digital instrumentation and control system [2] points out that the verification and validation of the software should also commensurate with the safety classification.

Reference level **G3.2** demands that the failure of a SSC in one safety class does not cause the failure of other SSCs in a higher safety class.

Operating experience shows that two systems where regulators should be particularly attentive are the digital I&C systems and essential power systems. For instance, voltage transients in non-safety buses have been observed to cause permanent failure in safety-related rectifiers.

According to SRL **G4.1**, the choice of materials for safety related SSCs must take into account the effects of operational conditions over the entire lifetime of the plant.

The topical study on cracks and leaks [12] indeed confirms that, specifically, fatigue and corrosion of the base metal in reactor coolant auxiliary piping has often been an issue.

Reference level **G4.2** covers the environmental qualification of SSCs important to safety.

This requirement is supported by two recommendations in topical studies, in both cases related to the ambient temperature during normal operation and accident conditions in the rooms containing the batteries (Topical study on loss of essential power [17]) and the spent fuel pool pumps (Topical study on design deficiencies [9]).

4.6 Ageing management

The topical study on ageing [1] provides wide evidence supporting every SRLs in the **Issue I**.

Reference level **I2.4** requires the ageing programs to take into account the specific environmental and process conditions.

Several topical studies provide relevant examples supporting this requirement, like the effect of wide differences between day and night temperatures in the ageing of current and voltage transformers used in switchyards (topical study on loss of offsite power and station black-out [13]), or the effect of process conditions on the ageing of reactor coolant pressure boundary piping and components (topical study on cracks and leaks [12]). In general, the topical study on ageing [1] concludes that the environmental and process conditions should be optimised in order to prevent ageing wherever possible.

Furthermore, the topical study on loss of offsite power and station black-out [13] mentions in particular the case of transformers using insulating/cooling oil as a major equipment where ageing monitoring is particularly relevant, as required by SRL **I3.2**.

The topical study on loss of essential power [13] adds two examples where neglecting the ageing management resulted in trouble for some plants: the ageing of grease used in electrical equipment or the inadequacy of tests to detect the inception of ageing mechanisms in safety-related batteries.

4.7 System for investigation of events and operating experience feedback

Many topical studies recommend ensuring an effective operating experience feedback system, in full support of all reference levels in the **Issue J**. However none of the recommendations from the topical studies go

beyond what is already required by the Issue J, except the explicit inclusion of the construction phase in the reporting systems (particularly for I&C systems) suggested by the topical study on design deficiencies [9].

4.8 Maintenance, in-service inspection and functional testing

Out of all the issues in WENRA's Safety Reference Level, maintenance is the one for which more recommendations can be found in the topical studies.

The topical study on maintenance [5] highlights the risk of introducing foreign materials due to maintenance activities. This risk has been consistently confirmed by operating experience (for instance in the topical study on fuel events [18] and maintenance [5]).

Although SRL **K2.5** requires assessing the impact on maintenance upon plant safety, a requirement to address the specific risk of foreign materials is missing.

Three further insights confirm the importance of assessing the risk posed by maintenance and suggest key ideas behind SRL **K2.5**: (i) the risk is particularly high if the plant design has been modified lately (Topical study on maintenance [5]); (ii) the risk of flooding caused by maintenance operations should be addressed systematically (Topical study on flooding [4]); and (iii) the risk of maintenance on electrical systems during power operation should be estimated carefully, given the rate of reactor trips, loss of offsite power events and other transients caused by electrical maintenance (Topical study on loss of offsite power and station black-out [13]).

Additional lessons can be used to support or develop some of the specific SRLs covering the implementation of maintenance, in-service inspection and functional testing, in particular **SRLs K3.2, K3.3, K3.4 and K3.5**.

Reference level **K3.2** points out the need to establish, review and validate the procedures for maintenance. Many events occurred in plants where the procedures, although existing and duly reviewed and approved, were inaccurate or insufficiently detailed, especially regarding the identification of tools or torque values to be applied in components subject to seismic qualification (Topical study on events related to cooling chain [20]).

Reference level **K3.3** requires implementing a comprehensive work planning and controlling system to ensure that maintenance actions are authorised and conducted according to procedures. Operating experience tells us that deviations from this requirement have been observed when subcontracted staff is not adequately supervised (Topical study on maintenance [5]) or when unofficial check-lists circulate among the plant staff (Topical study on low-power and shutdown [8]).

Reference level **K3.4** addresses the risk of maintenance causing incorrect plant configurations (e.g., a valve left inadvertently in a wrong position after a test). These errors are often caused by misunderstandings.

Two topical studies identify two common sources for these misunderstandings: (i) work orders are deemed as completed even though not all equipment has been restored to nominal status (Topical study on low-power and shutdown [8]), and (ii) the labelling of equipment is missing or illegible (Topical study on loss of essential power [17] and on low-power and shutdown modes [8]).

Finally, the relevance of SRL **K3.5** (requiring to define in the procedures the actions to take in case of deviations from the acceptance criteria) is confirmed by topical study on loss of essential power [17] for the case of DC batteries.

4.9 Plant modifications

Reference level **Q1.2** requires treating modifications according to their safety significance.

Operating experience (Topical studies on plant modifications [11] and flooding [4]) recalls that the potential to affect safety functions during the implementation or testing of a modification) needs to be taken into account, even if the equipment itself does not have safety functions.

Reference level **Q2.1** requires the licensee to establish a process to ensure that all permanent and temporary modifications are properly designed, reviewed, controlled and implemented.

The topical study on plant modifications [11] warns against the risk of considering only physical modifications as relevant for this requirement. Indeed, when system operating conditions are modified (for instance, when the system is used for a purpose different from its original intended use), this change should go through the same control process. Furthermore, large modifications often go through changes during its implementation

phase. Operating experience suggests that these changes need to be subject to appropriate control. Therefore, the process established for managing the modifications should include instructions to handle the changes.

Other topical studies provide specific examples supporting the relevance of SRL **Q3.1**, requiring that a safety assessment must be carried out for plant modifications. The changes in fuel assemblies' design, length of operating cycles or core operations strategies are examples of modifications that need to be carefully reviewed. Some examples of modifications where the safety impact was not properly assessed include modifications of equipment without properly estimating the impact on the electrical load of power cables, or changes in non-safety related piping that created unexpected flooding risks in areas containing safety-related equipment. Finally, the case of modifications of certain digital I&C equipment is challenging in the sense that the licensee might not be aware of these changes introduced by the manufacturers, so that no proper safety assessment is done.

4.10 Natural hazards

Issue T establishes that natural hazards shall be considered as an integral part of the safety demonstration of the plant. The section 5 of Issue T includes requirements related to the protection against design basis events. None of these requirements however is related to the need to ensure appropriate training for plant crew or maintenance on the equipment providing protection against the natural hazard. It may be argued that overarching requirements on training are already provided under **Issue D**, and on maintenance and inspections under **Issues I and K**.

However, the topical study on external events [19] has found many instances of plants where flooding or other natural hazards revealed insufficient training or insufficient inspections of protective measures and related SSCs. Because these SSCs are seldom or never used, they are particularly prone to become insufficiently maintained or subject to unnoticed deterioration from ageing and other processes. For this reason, it might be worth to consider including specific requirements in section 5 of Issue T.

4.11 Decommissioning

One of the safety issues identified by the decommissioning Safety Reference Levels report is the decommissioning plan during design, construction and operational phases. It contains seven SRLs, including **DE-25**, where the decommissioning plans are expected to identify the major existing systems and equipment that may be used, and the changes in the systems that will be required.

Indeed, the topical study on decommissioning events [10] recalls that operational parameters of systems during the decommissioning phase will be in general very different from the normal operation phase, and encourages to retain expertise and knowledge of plant systems as much as possible.

Observations:

The comparative analysis of the WENRA Safety Reference Levels for Existing Reactors against the findings of the EU Clearinghouse topical studies over a period of ten years confirms that the Safety Reference Levels address most of the topics raised by recent operating experience and, moreover, suggests that the EU Clearinghouse products are useful inputs for future reviews of the reference levels.

5 Related and future JRC work

The establishment of a EU Clearinghouse has represented a breakthrough policy innovation in the European nuclear industry safety policy context. The innovative idea came from a national nuclear safety authority, and expressed an emerging underlining need, felt by several European Members States, to enhance their cooperation and create synergies for the regional international sharing, and valorisation, of the nuclear operating experience. The EU Clearinghouse has replied to that voiced need, becoming a regional forum of dialogue, among the European nuclear regulatory authorities, for European regulators and has enlarged progressively the participation to regulatory authorities in neighbouring countries, considering the international dimension of nuclear safety and the history of the regional industry, which reflects the historical and political evolution of the regional geography.

In particular, the main fundamental actors of this evolution of the regional nuclear history have been the people, expert citizens with a specific knowledge put at the service of society and of Member States, having in common the vision of providing their country with a fundamental and powerful source of energy, to reply to the societal developmental, and consequent energy supply, needs.

The EU Clearinghouse has been the space where national nuclear regulatory representatives have been, and are meeting, to discuss about what they know about nuclear, what they have experienced, what they consider necessary to be deepened, for proceeding in the development of the industry safety and performances, considering the political requirements, reflecting the views of the citizens.

In this context the EU Clearinghouse has been the cross-road of different nuclear traditions, stemming from different scientific and technical solutions and designs, and from different organisational cultures. The EU Clearinghouse has been also the place where experts have been discussing about the nuclear knowledge related both to western and eastern designs, exchanging information on technical solutions and regulatory practices, based on the legal framework of their respective countries, which presupposes a state of law.

In this sense, the EU Clearinghouse has established a dialogue, involving nuclear stakeholders, whose meaning and implications go well beyond the nuclear domain, and the EU boundaries, supporting integration, societal development, and the dialogue with neighbouring countries interested in the nuclear industry developments.

During its history, the EU Clearinghouse has rooted its activities on the cooperation with national nuclear safety authorities and technical support organisations, and with reference but also with International Organisations in the nuclear domain, in particular the International Atomic Energy Agency (IAEA) of the United Nations, and the Nuclear Energy Agency (NEA) of the Organisation for the Economic Cooperation and Development (OECD). EU Clearinghouse staff, in particular, the EU Clearinghouse JRC experts, participate regularly in technical meetings hosted by these bodies: in the Technical Working Groups set up by the IAEA, contributing to drafting relevant technical documents and Safety Report Series, nuclear safety international guidance reports, and participating in IAEA OSART international or European peer-reviewed missions. EU Clearinghouse experts participate in several Working Groups of the OECD/NEA, both within the framework of the Committee on Nuclear Regulatory Activities (CNRA) and of the Committee on the Safety of Nuclear Installations (CSNI). Furthermore, EU Clearinghouse also provided experts to participate in the EU stress-tests carried out at the European power plants, following the Fukushima Dai-ichi nuclear power plant accident.

In a time where international organisations are constantly searching for better efficiency on the use of scarce resources, closer cooperation among national, European and international entities is needed to avoid duplicities and untimely actions. The JRC actively supports this effort. Indeed, the cooperation formula used by the EU Clearinghouse (i.e.: a limited number of countries willing to work on an equal basis on a nuclear safety topic of common interest with the role of technical secretariat ensured by the JRC) has been successfully applied for the last years, and could be repeated to share regulatory experience in other domains, like research reactors, waste repositories, technical reviews of Small Modular Reactors.

The future activities of EU Clearinghouse could benefit from synergies with other activities carried out by the JRC, within and outside the nuclear areas.

6 Conclusions

The retrospective and comparative analysis of the topical studies carried out in the first ten years after its establishment, by the EU Clearinghouse, has given the opportunity to review the knowledge produced during ten years, and documented in twenty-three topical operating experience reports, distributed to the nuclear industry through the IAEA/NEA's Incident Reporting System.

Whilst the individual reports offer a topical analytic deepening of the international nuclear operating experience available, this report has conducted a horizontal analysis of the knowledge generated over the years, extracting additional insights and observations of general validity for the nuclear industry. As for the individual topical studies, also the idea of this ten-year report, has been shaped by the Joint Research Centre of the European Commission together with the representatives of the national nuclear regulatory and safety authorities, members of the EU Clearinghouse.

The report has provided background information on the methodology developed at the JRC for the production of the EU Clearinghouse topical studies' reports, and general statistical data extracted from the reports, indicating the main contributing factors. Furthermore, a horizontal analysis of the topical reports has been carried out, to explore the emergence of new, or the confirmation of known, horizontal, common issues. This horizontal comparative analysis has confirmed the need for reinforcing the operating experience, further developing the international share of data and knowledge. It has, as well, suggested to strategically focus on pre-operation activities, as design, for anticipating and mitigating design deficiencies; and has reiterated the suggestion to go beyond the technical conclusions, to focus on the rooted organisational and human contributors.

A comparison with the Safety Reference Levels for Existing Reactors, developed by the Western European Nuclear Regulators Association, has been as well carried out, which has given full evidence to the correspondence between the Safety Reference Levels and the nuclear operating experience, suggesting that the knowledge produced and available within the EU Clearinghouse can be helpful for future reviews of the Safety Reference Levels.

This ten-year report confirms that the knowledge produced by the EU Clearinghouse, hosted and operated by the Joint Research Centre, is a mine of knowledge, available to the nuclear industry, to countries hosting nuclear power installations, and countries starting or willing to embark in the development of this industry. Beyond the operating experience of power reactors, the cooperation formula used by the EU Clearinghouse could be applied also to the exchange of regulatory experience in other domains.

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List of abbreviations and definitions

CF	Contributing Factor
CNRA	Committee on Nuclear Regulatory Activities
CNSI	Committee on the Safety of Nuclear Installations
DC	Direct Current
GRS	<i>Gesellschaft für Anlagen- und Reaktorsicherheit</i> (Global Research on Safety)
HOF	Human and Organisational Factors
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IRS	International Reporting System (IAEA/NEA)
IRSN	<i>L'Institut de Radioprotection et de Sûreté Nucléaire</i> (Institute for Radiological Protection and Nuclear Safety)
JRC	Joint Research Centre
LER	Licensee Event Report (US NRC)
NEA	Nuclear Energy Agency
NNSA	National Nuclear Safety Administration
NPP	Nuclear Power Plant
NRC	US Nuclear Regulatory Commission
OECD	Organisation for Economic Co-operation and Development
OSART	Operational Safety Review Team (IAEA)
RCPB	Reactor Coolant Pressure Boundary
RHR	Residual Heat Removal system
SAPIDE	French operating experience database
SRL	Safety Reference Level (WENRA)
SSC	Structures, Systems and Components
TECDOC	IAEA Technical document (report)
UN	United Nations
WANO	World Association of Nuclear Operators
VERA	German operating experience database
WENRA	Western European Nuclear Regulatory Association

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