Database OECD/NEA FIRE – Applications and Applicability Within Fire PSA

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Abstract: Detailed information on fire events having occurred at nuclear power reactors in operation and decommissioning from fourteen NEA member countries is collected in the international fire events database FIRE (*F*ire *I*ncidents *R*ecords *E*xchange) as one of three databases on operational events in nuclear power plants (NPPs) and research reactors currently operated under the auspices of the OECD Nuclear Energy Agency (NEA). This database is meanwhile mature enough for several applications in probabilistic fire risk assessment (Fire PSA). The actual version of the database covers more than 650 quality assured and widely well-documented fire events from nuclear powers reactors during the entire plant life cycle from construction to decommissioning. Already mature possibilities for application of data from the database within Fire PSA are generic component or room type specific fire occurrence frequencies as prior information and data supporting the fire event tree analyses, particularly on fire detection and suppression success data.

Insights from past activities with significance for Fire PSA, regarding e.g. event combinations of fires and other anticipated external and/or internal hazards, or fires induced by high energy arcing faults (HEAFs) have contributed to national and international PSA related safety standards, such as the recent IAEA Specific Safety Guides (SSGs) for Level 1 and Level 2 PSA SSG-3 (Rev. 1) [1] and SSG-4 (Rev. 1) [2].

Most recently, one future action to countries having participated in the ENSREG (European Nuclear Safety Regulators Group) Topical Peer Review on "Fire Protection" is to extend the sharing of the operating experience and the corresponding feedback internationally, e.g. via the FIRE Database, covering not only power reactors but also research, demonstration and other first-of-a-kind reactors. In a later step, the fire protection-related operating experience from non-reactor nuclear installations shall also be shared.

This presentation provides an overview of applications and applicability of the data collected in the FIRE Database for risk analysis, selected application examples and an outlook on the already started and/or planned Database extensions.

1. INTRODUCTION AND BACKGROUND

Fire represents a non-negligible contributor to the risk of nuclear reactor and non-rector installations. Fire events have been observed, recorded, and analyzed at nuclear power reactor sites for more than five decades. Plant internal fires do occur over the entire life cycle of nuclear installations – from construction, over the whole operational period, up to the late phase of decommissioning and dismantling.

Fire safety remains an issue for the overall safety of all types of nuclear installations including new technologies under development. Only limited or no operating experience is available for nuclear reactor concepts of a unique design, prototype facilities and new generation reactors including new or advanced technologies such as small modular reactors (SMRs).

Under the auspices of the OECD Nuclear Energy Agency (NEA), the OECD/NEA FIRE (*F*ire *I*ncidents *R*ecords *E*xchange) Database Project was established in 2003, collecting as far as possible information about fire events in nuclear power stations of the countries participating in this Project on a cost-sharing basis. This exchange of data and information allows us to provide a broad basis for deterministic and probabilistic fire safety assessments and for a better identification and analysis of trends aiming to develop measures for mitigation. The Database has been continuously advanced and extended covering in its version OECD/NEA FIRE 2023:03 [3] event data for 628 fire events observed up to end-2023 in nuclear power reactors from the 14 member countries – two from Asia, ten from Europe and two from North America – representing approx. 11,000 reactor years (ry) of commercial plant operation. For further information and contact details see the FIRE Database Project website (www.oecd-nea.org/jcms/pl_24954/fire-incidents-records-exchange-fire-project).

The main objectives of the FIRE Project are:

- the collection of fire event experience (by international exchange) in an appropriate format in a quality-assured and consistent database (the "OECD/NEA FIRE Database"),
- the collection and analysis of fire events over the long-term to better understand such events and their causes, and to encourage their prevention,
- the generation of qualitative insights into the apparent and root causes of fire events to derive approaches or mechanisms for their prevention and to mitigate their consequences,
- the establishment of a mechanism for efficient operational feedback on fire event experience including the development of policies of prevention, such as indicators for risk-informed and performance-based inspections, and
- recording the characteristics of fire events to facilitate fire risk analysis, including quantification of generic fire frequencies.

The FIRE Database Project is a long-term project, conducted in a phased approach with regular updates and extensions of the work program. The meanwhile eighth phase of the Project from January 2026 to December 2028 is intended (i) to extend the Database beyond the operational phases of commercially operated nuclear power reactors to the decommissioning and dismantling phase. and (ii) to fire events from research, demonstration and other first-of-a-kind (FOAK) reactors with a non-negligible risk potential, typically reactors with a thermal power of 1 MW or more. Moreover, the information exchange on fire events needs to be further adapted in the future to consider specific aspects of fire protection of small modular reactors (SMRs) and other advanced nuclear technologies (ANTs) with non-water-cooled reactors.

2. APPLICATIONS OF FIRE DATABASE PRODUCTS WITHIN PROBABILISTIC RISK ASSESSMENT

The operating experience collected on fire events in nuclear power reactors so far has revealed valuable insights for improving fire safety and provided various lessons, which can be used in probabilistic safety assessments. In the following, some of the applications are highlighted.

2.1. High Energy Arcing Fault-Induced Fires – A Non-Negligible Risk Contributor

Already in the early 2010s an important lesson learned from the fire events collected in the FIRE Database was that high energy arcing faults (HEAF) resulting in ensuing fires represent a non-negligible share of fire events with some significance for safety assessment [4]. Approx. 12 % of the statistically relevant 590 plant internal fire events in the Database version 2023:03 [3] were induced by HEAF having occurred during different plant operational states (POS) – power operation a s well as in low-power and shutdown states. The HEAF-induced fire frequency is in the order of 3 E-03 / ry, thus non-negligible. HEAF fire events need to be addressed in the frame of Level 1 PSA (see also IAEA SSG-3 (Rev. 1) [1], depending on the plant specific design and boundary conditions either within bounding analyses or in the detailed analyses. HEAF-induced fires can occur as single hazards as well as in hazard combinations, which may involve not only HEAF and internal fire but also other external or internal hazards.

The insights gained from the operating experience in FIRE member countries resulted in various national and international experimental and analytical research activities related to HEAF and ensuing fires with significance for safety assessment including an OECD/NEA experimental project on HEAF in two phases with significant insights, see [5] to [7].

National regulations in some member countries meanwhile consider HEAF and HEAF induced fires (see e.g. [8]), HEAF is also addressed in international standards, e.g. in the IAEA Specific Safety Guides SSG-64 [9] and SSG-3 (Rev. 1) [1].

2.2. Combinations of Fires and Other Hazards – Need for Consideration in Hazards PSA

Another activity of the FIRE Database Project was an in-depth investigation of combinations of external and internal hazards with internal fire hazards (observed in the operating experience, see the FIRE Database Topical Report No. 3 [10]. The number of such combined fire events of the different types – categorized(i) as fires occurring consequential to other external or internal hazards or internal hazards occurring consequential to plant internal fires, (ii) internal fires and other hazards correlated by a common cause, and (iii) internal fires and other hazards occurring coincidentally is – with 65 fire hazard combinations recorded in [3], representing ~ 11 % of all fire events included in statistics – non-negligible, and this percentage has remained stable, cf. the most recent Database version 2024:01 [11] with 648 events, 606 of these included in statistics representing ~ 11,292 ry. Details on fire hazard combinations are provided in the following Figure 1 and Figure 2. Most of these did not significantly affect plant safety; however, they are important precursors which need to be addressed within PSA.

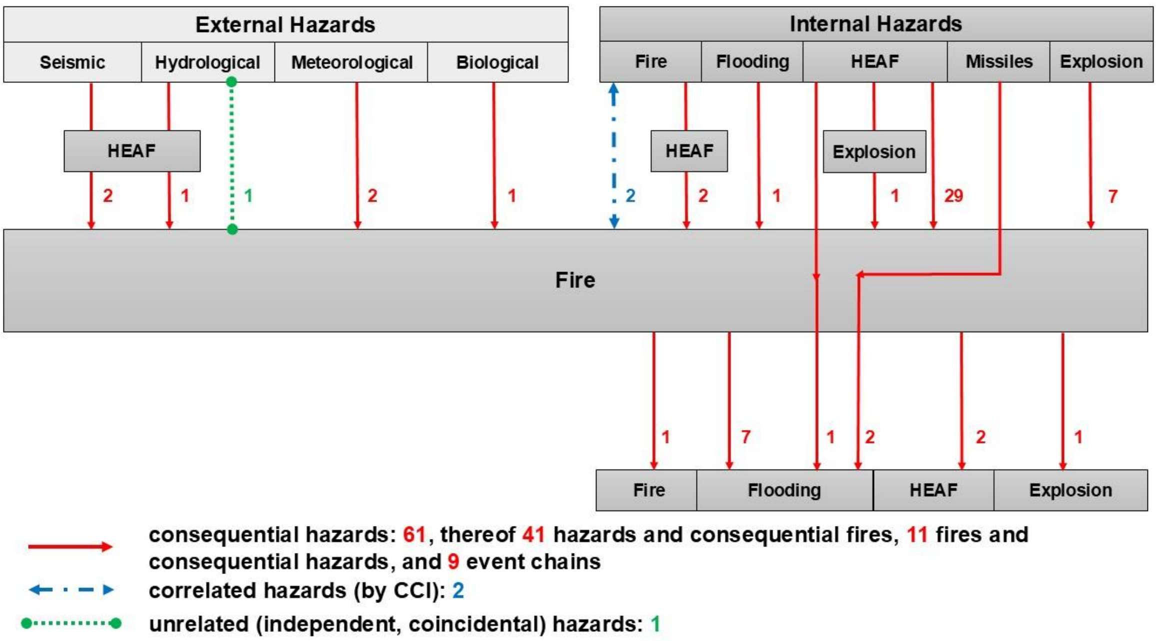

Figure 1: Types of combinations of fires and further hazards, derived from OECD/NEA FIRE 2023:03 [3] for nuclear power reactors

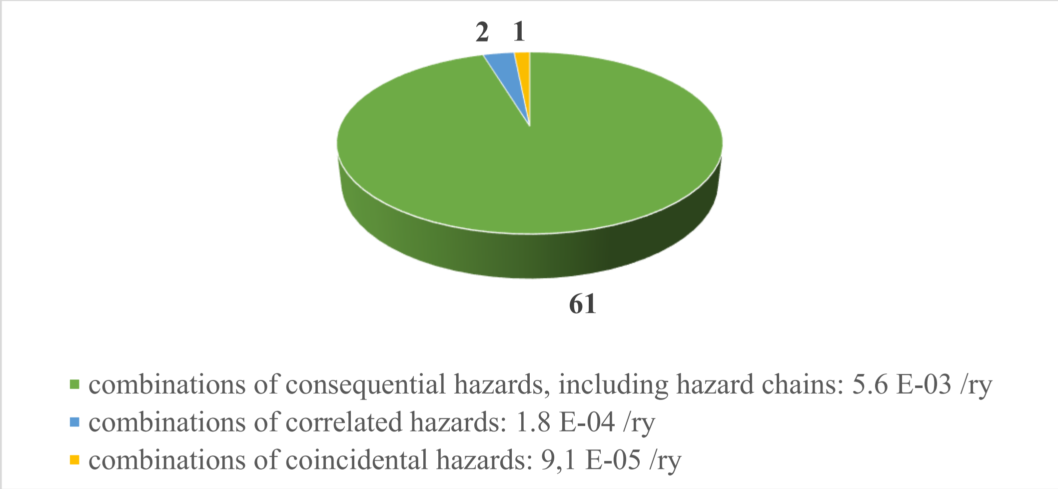

Figure 2: Numbers of combined fire events and their frequencies per reactor year, calculated from [3]

As a lesson learned, combinations of internal fires with further external and internal hazards of all three categories of hazard combinations need to be adequately considered in deterministic and probabilistic fire safety assessments for nuclear installations in the design and operation; for guidance see e.g. IAEA SSG-64 [9] and TECDOC 2129 [12].

2.3. Generic Fire Occurrence Frequencies

The Database also provides a means to consider operating experience from reactor facilities in member countries for generating generic component or room/compartment type specific (per building and/or plant area outside buildings) fire frequencies which can be applied as prior information in typical Bayesian approaches used within PSA if the plant specific database is insufficient. This notably reduces the uncertainties within plant specific Fire PSA, thus increasing realism as recommended by national and international PSA guidance.

So far, such generic fire occurrence data can be easily created for components from individual reactor units if the number of fire events at the given component for the plant under analysis is low or even zero and, in addition, the observation time for the component is too low to be statistically meaningful. For reducing the mean value of the plant and component specific ignition frequency and the resulting uncertainties, typically a two-stages Bayesian approach is applied based on as far as available and applicable generic operating experience. Details on the approach and two example applications can be found in [13]. An update of the example of the turbine generator fire frequency for a single reactor plant with less than 50 reactor years provided in [13], based on the data in [3] is given in Figure 3 below.

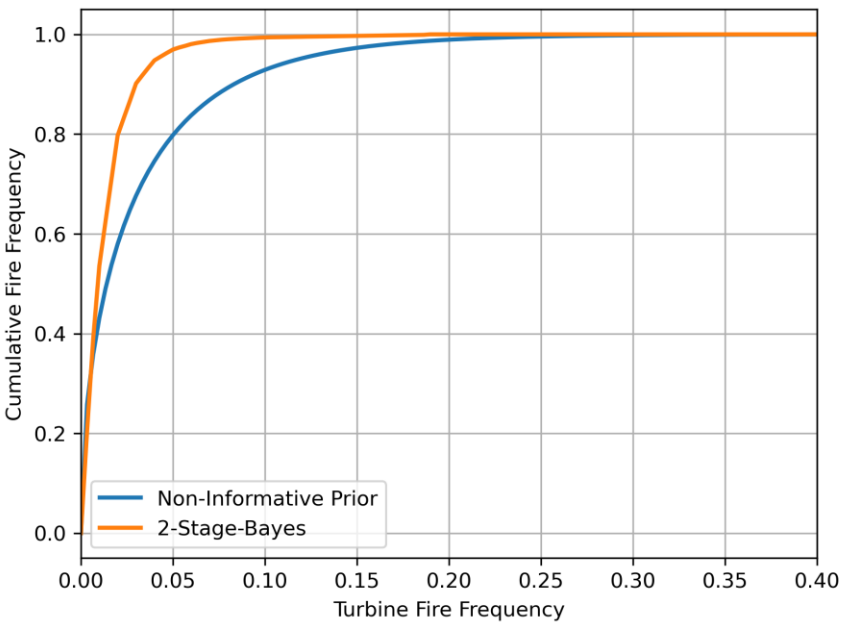

Figure 3: Turbine generator fire frequency distribution during full power operation for a selected power reactor with an insufficient plant specific database applying generic operating experience data from [3] as prior information

No turbine fire events have occurred in this plant so far with an observation period of 16.28 ry in the Database, the mean value of 3.07 E-02 /ry for the plant specific fire occurrence frequency applying a non-informative (Jeffrey) prior approach and the corresponding uncertainty (4.30 E-02 /ry) is therefore high based on the insufficient plant specific database. Using the generic operating experience from the other FIRE member countries with a total of 38 fire events at turbine generators for approx. 8,62 years of turbine generator operation as prior information, the turbine fire frequency distribution shown in Figure 3 has been calculated with the following turbine fire frequencies: (i) 5 % percentile: 7.93 E-04 /ry, (ii) 50 % percentile: 9.10 E-03 /ry, (iii) 95 % percentile:4.10 E-02 /ry, and (iv) the resulting mean value: 1.40 E-02 /ry. In this example, the uncertainty range has notably decreased while the reliability of the overall results has increased. The results can be used e.g. in the Fire PSA update within the next Periodic Safety Review.

2.4. Further Ongoing Activities

Further actually ongoing FIRE activities are briefly outlined in the following paragraphs.

Fire Detection and Suppression Success Analysis

Several other activities are ongoing, one of them focusing on fire detection and suppression success data analysis including the influence of the presence of onsite plant fire brigades. The data analyzed so far have indicated first trends for fire suppression success depending on reliable and timely fire detection and confirmation , but also on the availability of a dedicated onsite fire brigade.

- Approx. 90 % of 537 fire events in the FIRE Database [3] with sufficient information on the time periods for successfully detecting and suppressing fires, which were detected early – typically in less than 5 min – resulted in successful fire suppression within a short time period if firefighting was started within 15 min.
- In case of late detection and an early start of firefighting still a small number of the fires could be successfully suppressed within 15 min.
- Various event sequences demonstrated that the presence of a dedicated onsite fire brigade has been highly beneficial for preventing core and/or fuel damage resulting from plant internal fires and is essential for the success of the fire protection provisions in place.

In-depth analyses of fire suppression success data are ongoing; corresponding generic event trees with success probabilities are in preparation. More detailed results are expected by the end of 2026.

First Insights from Apparent and Root Causes Analysis

Another important topic for increasing nuclear safety is an in-depth investigation of apparent and root causes of the 550 quality-assured, statistically countable fire events, 375 of them having occurred during full power operation and 175 ones during low-power and shutdown states with information on the root causes identified and confirmed so far in the Database [3]. In a broad majority of the recorded events, not only technical causes (root cause type: equipment), but human behavior (root cause type: human) and missing or inadequate procedures (root cause type: procedure) have also contributed to causing the event, see Figure 4 for full power and Figure 5 for low-power and shutdown states. The activity is ongoing, the underlying apparent causes, particularly the failure mechanisms for equipment related root causes, are still under investigation, The respective FIRE Topical Report is expected to be available in 2027.

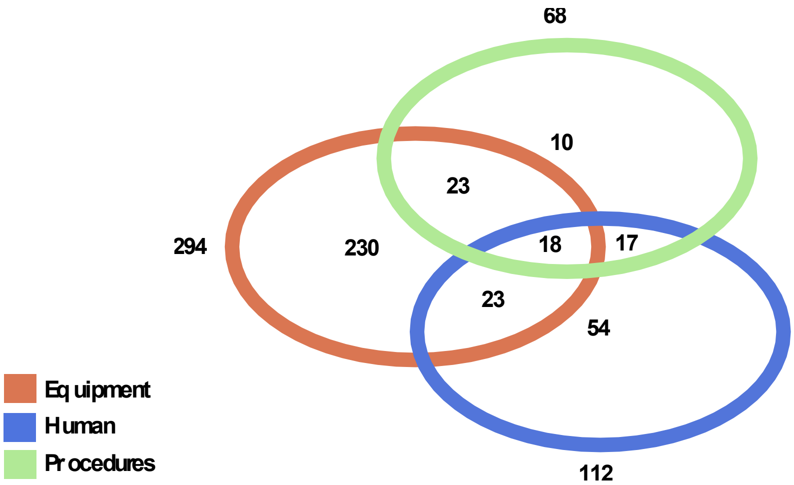

Figure 4: Identified and confirmed root causes of 375 fire events in [3] having occurred during full power POS

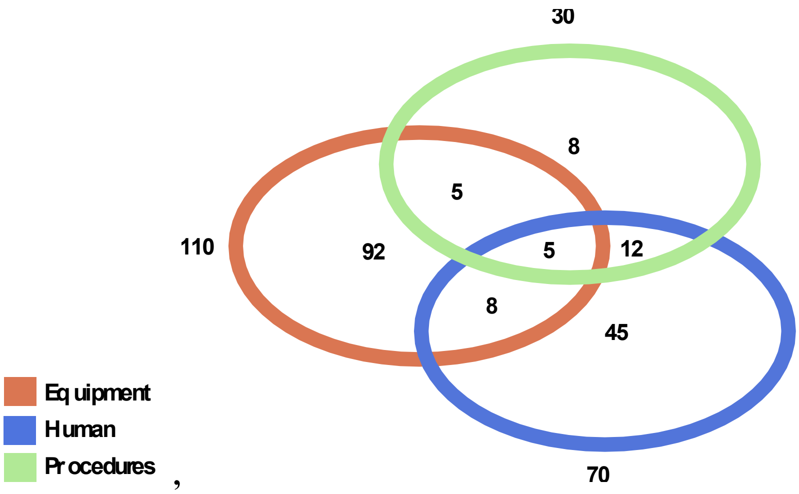

Figure 5: Identified and confirmed root causes of 175 fire events in [3] having occurred during low-power and shutdown POS

The most recent Database version OECD/NEA FIRE 2024:01 [11] with a total of 648 events until the end of 2024, already covers fourteen fires recorded so far from nuclear power reactors under decommissioning. Although this most recent version of the FIRE Database has not yet been used for quantitative analyses, a first preliminary result is that during the different stages of decommissioning and dismantling activities, some technical causes have been observed which had not been expected by the personnel in charge. As a lesson learned, several procedures have been adapted accordingly to prevent recurrence. Twelve different root causes of the root cause category “equipment” were identified in ten of the fourteen fire events from four member countries having reported fire events from nuclear power plant units under decommissioning and dismantling (Canada, Germany, Spain, and the United Kingdom) so far to the Database. Root causes of the category “human” were involved in six of the fourteen events. Another remarkable contribution to the root causes for plants under decommissioning comes from the root cause category “procedure” with eight different causes in eight of the fourteen events. recorded so far.

These first results indicate that there is a need for successfully preventing incipient fires as far as reasonably practical, considering the sometimes quite different boundary conditions compared to plants in commercial operation. In addition, the awareness of the personnel involved in the decommissioning and dismantling activities should be trained and suitable corresponding procedures been provided. Corrective actions have often already been taken or at least initiated in the affected plant. However, sharing the information on the root causes and potentially resulting improvements in fire protection for nuclear installations under decommissioning with the expert community could be beneficial.

Already Started Database Extensions

Extensions of the Database to include fire events in research, demonstration and other FOAK reactors and to better cover fire events in installations under decommissioning and dismantling have also been started. The FIRE Coding Guidelines have already been modified and extended to consider the more unique boundary conditions in such types of reactor facilities with a lower level of structural separation, number of redundant trains, or activities specific to the (e.g. experimental, medical, etc.) purposes of these reactors. For reactors in the decommissioning and dismantling phase the coding needs to consider the different, mainly manual activities and the associated variation of fire loads and ignition sources over time.

3. CONCLUSIONS AND OUTLOOK

The insights gained so far for Hazards PSA, particularly Fire PSA, have already been considered in further extensions and advancements of the FIRE Database which have been started or are planned for the near future.

One of such possible extensions resulted from the European Nuclear Safety Regulators Group (ENSREG) second Topical Peer Review (TPR II) on “Fire Protection“. A total of 22 member countries from the European Union (EU), but also from other non-EU countries, such as Switzerland, Turkey, Ukraine and the United Kingdom, participated in this international self-assessment providing national reports on (deterministic and probabilistic) fire safety assessment as well as the fire protection means implemented in the country- and plant-specific fire protection concepts for the three levels of fire-specific defense-in-depth: fire prevention, passive and active fire protection. The reports were reviewed by experts from the participating countries, and two workshops were held, the first being a thematic workshop comparing the approaches in the participating countries for the different fire protection aspects in the different types of nuclear installations investigated under the Nuclear Safety Directive (NSD) of the EU. The second workshop was a country-specific one. Each participating country gave a presentation highlighting the areas of good fire protection performance but also areas where improvements are needed compared to state-of-the art. The results of the assessment were summarized in 22 Country Reports and a final Summary Report [14], pointing out strengths and weaknesses in the fire protection of nuclear installations of the different participating countries as well as good practices that can be adopted b*y* the other participating countries.

Some challenges affecting different thematic issues and various installations with the need to address these in all participating countries as far as applicable were identified. From a Fire PSA viewpoint, the following challenge was identified: “*A need for a unique repository for sharing information on fire* *safety related events for all types of nuclear installation, based on defined criteria for categorisation and reporting*". This challenge results from the fact that the available information on fire events and even more on events with failures and/or deteriorations of fire protection provisions is not collected in a unique manner in a common nuclear database, but spread over various different data repositories (e.g. IAEA databases such as INES and IRS by the IAEA, FIRE by the OECD/NEA, or national fire event databases such as the U.S. FEDB (*F*ire *E*vents *D*ata *B*ase). Not all these databases are made for specific purposes of fire safety assessment and do not always contain the level of detail needed, particularly not for Fire PSA. This often makes their use by nuclear operators worldwide challenging. In order to suitably address this challenge, the need for a unique international repository for sharing and assessing events from nuclear installations related to fire safety and protection with sufficient and pertinent detail was identified.

A recently conducted experts workshop jointly by the OECD/NEA CSNI Working Group on Risk Assessment (WGRISK) and the OECD/NEA Database Projects ICDE, FIRE and CODAP on "Applicability and Applications of Operating Experience from the OECD/NEA Database Projects to Probabilistic Risk Assessment (PSA)" provided several arguments that the FIRE Database – supported by other experts – might enable the analysts in the future to overcome this challenge by developing clear guidance including common reporting criteria, ensuring consistency in fire safety related event reporting, instructions for coherent coding of fires as well as of failures/deteriorations of fire protection features, ensuring consistent type and level of detail of the required information to be collected and sufficient information for direct use by other countries. In the frame of the Database Project, it should be possible to provide a suitable definition of the data repository structure based on more than two decades of data collection experience, enabling the experts participating in the longer term to consolidate fire safety related events and lessons learned (e.g. corrective actions, improvements) from all types of nuclear installations.

Last but not least, the existing Database should be extended and advanced to such a unique repository, including lessons learned from the recorded operating experience will support experts from regulators, TSOs (*T*echnical *S*afety *O*rganisations), and the plant operators, not only for implementation of corrective actions but also for further improvements in the plant design and modifications in the plant operation, e.g. procedures.

Although the Database itself is available to Project member countries only, various publications with insights of the Project outcomes and generic data are available, which can be useful also for non-participants. Detailed information can be found on the OECD/NEA FIRE Database Project website (www.oecd-nea.org/jcms/pl_24954/fire-incidents-records-exchange-fire-project).

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