Master Thesis

Enhancement of the ETHZ Nuclear Events Database and Preliminary Trend Analysis

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Abstract

The nuclear power community has long recognized the importance of safety. Operational experience in nuclear power facilities has increasingly been recorded over the years in the quest for ever improving regulatory compliance and safety monitoring. With the goal of more intensively learning from experience and supporting the continued safe operation of nuclear power plants, the team at the chair of entrepreneurial risks at the ETH Zurich has been collecting and analyzing operational events from the nuclear power industry with the goal of constructing the most comprehensive open nuclear events database in the world, titled "ETHZ curated nuclear events database". The database contains information assimilated from different sources such as annual reports from national regulators, published IAEA INES events, open access official reports, operating experience databases, academic publications, serious newspaper articles, and others. In this thesis, the enhancement of the database will be presented, detailing the new features that were implemented, as well as the changes made to the already existing ones. Currently, the database contains around 1040 events, out of which 930 from the commercial nuclear sector. These events were analyzed by our team and classified with regards to their origin, cause, type, failure sequence, contributing factors, operating reactor mode, significance of the event, etc. The resulting effort provided us with the data necessary for conducting detailed statistical analyses relevant to the safety of nuclear power plants, as well as a preliminary trend analysis in order to help us identify the behavior of events sharing certain similarities. The results indicate of a stable decrease in the number of significant events over time, especially of incidents and accidents, while the number of anomalies and events with no safety significance tends to be increasing. Surprisingly, the number of events originating from boiling water reactors (BWRs) is larger than that of pressurized water reactors (PWRs), when compared to the total number of reactors of that type. An important trend is the general decline in the number of reported initiating events over time, while the share of system/component failures is increasing, especially potential/hidden failures (latent errors).

Keywords**:** Nuclear incidents and accidents, database, nuclear safety, statistical analysis, trend analysis.

Contents

Chapter 1. Introduction

With more than 15’000 reactor years of cumulative operating experience at commercial nuclear power plants (NPPs), nuclear power is considered a mature technology. Nevertheless, the safety of nuclear power plants is a recurring discussion, thus continuously improving the safety standards and the safety levels are vital for the future exploitation of nuclear power. With the goal of more intensively learning from experience and supporting the continued safe operation of nuclear power plants, the team at the chair of entrepreneurial risks at the ETH Zurich has been collecting and analyzing operational events from the nuclear power industry around the world [1]. This thesis is a continuation and enhancement of that work, introducing new events, concepts and features, as well as detailing and further developing the already existing ones. Many of the previously existing features have undergone a revision process in order to make them more consistent. The immense efforts have culminated in the development of the world’s most comprehensive open “curated[1]” nuclear events database focused on safety significant events, titled “ETHZ curated nuclear events database” (access link: http://er-nucleardb.ethz.ch/).

The idea of building a database of nuclear events is not new, as there are many existing databases from different organizations around the world. However, most of these are not publicly available and have different motivations and scopes. These databases include:

- The International Reporting System for Operating Experience (IRS) from the International Atomic Energy Agency (IAEA). The objective and scope of the IRS is to “promote and motivate the sharing of operating experience” between the 33 participating countries [2]. The focus of the IRS are mainly precursors of serious events and other safety related events/issues in currently operating power plants. Unfortunately, the IRS database is not publicly available and access can be only granted to regulators and research institutions.
- Additionally, the IAEA along with the Nuclear Energy Agency of the Organization of Economic Cooperation and Development (OECD/NEA) and World Association of Nuclear Operators (WANO) operates the Nuclear Events Web-based System (NEWS) which publishes minor, as well as significant events from participating countries [3]. This information is published online and is removed after one year. The majority of events are of minor safety significance and are related to radiation exposure of workers or minor releases to the environment.
- WANO additionally operates a database containing events from the operating experience of consenting member utilities. These events are understood to be very detailed, but unfortunately are not available to the general public.
- The European Commission Joint Research Centre (JRC) “Clearinghouse on Operating Experience Feedback” database contains around 55’000 events, the majority of which are from LERs from the United States of America. The database has filtering options and certain classification criteria which are implemented on around 1’000 of these events [4]. The database contains events starting from 1979 and access to it is available upon request. The scope of the database is very general as it attempts to include all events, meaning events are rarely discarded if they contain no safety-relevant information, while only a relatively small number of serious events are contained in the database. Around 1500 events in the database contain an INES rating, out of which: only 33 events are rated as INES 2, one event is INES 7 and the remaining events (941) are rated as INES 1. Only 59 events in the database are rated as events with “high safety relevance”.

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[1] Curated refers to the thoughtful presentation of events in the database, where every event is carefully analysed and classified using outlined classification criteria.

Aside from global organizations, national regulators also have databases built upon their operational experience. Databases of this type which are open-access include: The USA NRC LER database (which contains tens of thousands of reports since 1980) [5], the USA NRC Accident Sequence Precursor (ASP) Program reports (which include serious events) [6], The Korean KINS OPIS Nuclear Event Evaluation Database (containing events with general information, which are easy to search and filter) [7], the German BfE (which publishes events online in yearly and monthly reports) [8], etc. Although, the NRC published the largest number of reports, navigating through them is very challenging as most of the reports have no indication regarding the severity of the event. The ASP program reports tend to contain serious events with a respective precursor analysis which are published only as yearly reports.

As mentioned, many of the existing databases have different purposes and scopes, and most of them are not focused exclusively on safety relevant events. Those who are, however, are usually not publicly available. This resulted in the lack of available comprehensive information regarding the operating experience of nuclear power plants, which was the primary motivation behind the construction of our database. The main focus of the database is the inclusion of safety relevant events and our purpose is: building a curated nuclear events database which is publicly available, providing data to our team and experts around the world for further scientific research. Additionally, we envision the database to be used as a communication tool for the general public in order to increase awareness of the safety of nuclear power plants and actual severity of events.

The database contains information assimilated from different sources such as annual reports from national regulators, published IAEA INES events, open access official reports, operating experience databases, academic publications, serious newspaper articles, and others. The collected events (more than 1000) were analyzed, and each is given a set of features to explain its major aspects such as origin, failure sequence, contributing factors, operating reactor mode, significance of the event, and many others to facilitate the database navigation and utilization and highlight major elements. Additionally, important and/or interesting events are selected and analyzed in order to shed light on information which might be overlooked. The analyzed events aim to support the construction of generic data-driven PSA models and to be used in precursor analysis [9][10]. All listed events in our database have a reference, the majority of which come from official sources.

Reportable events happen quite often ranging from anomalies to events with varying severity. In order to screen out events which are of less importance, we have implemented the following acceptance criteria:

- We strive to include all reportable events of interest to our cause. Special attention is given to commercial nuclear power plants, which are included in the main section of the database. Events from fuel fabrication plants, reprocessing plants, storage facilities, experimental reactors, research reactors and military facilities are included in a separate section of the database.
- In absence of access to a single complete official source, we strive to be complete in including all events which have an INES rating of 2 or above. For these events we try to be as detailed as possible in analyzing them.
- Events which have a lower INES (0 or 1) or no official INES rating are very numerous, and we neither strive nor claim to be complete for this category. Nevertheless, we included some of these events, for which we have reliable information, and which are of core-safety relevance or of general interest to our work.

The included events are subjected to multiple classification criteria that will be covered in the following section. The remainder of the thesis will be structured as follows:

- Structure and Features of the Database – The database will be presented and compared to the previous version [1], along with its most important features such as the general information and classification criteria.

- Statistical Analysis – Data obtained using the classification criteria will be used for statistical analysis, as well as a preliminary trend analysis. The results from the analysis will be displayed and commented.
- Conclusions and Future Work – where the conclusions made within the previous two chapters will be summed up and the future plans for the database will be outlined.

The proposal for this thesis containing the outlined goals of the project are presented in the Annex.

Chapter 2. Structure and Features of the Database

The current version of the database contains around 1040 events, 90% of which come from the commercial nuclear power plant sector, making it the most comprehensive curated database for safety significant events in the nuclear sector in the world. In order to properly classify the events, many new features have been added or further developed from the previous version of the database. Each event contains general information which includes:

- Short description of the event

A short version of the event report, containing the most important information, such as: operating mode of the plant, initiating event, contributing factors and mechanisms, sequence development, outcome and consequences of the incident/accident, downtimes, etc.

- Date of the event and location of the unit

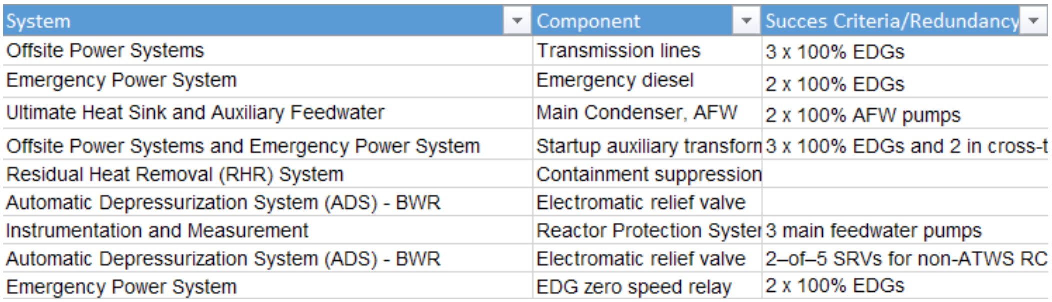
The date and location are usually given by the publisher of the event report.

- Plant type

The plant type is provided by the publisher of the report, or is determined using official reactor information databases. In the ETHZ curated database, for the most part, information for the plant type was obtained from the official IAEA Power Reactor Information System (PRIS) database [11]. Every entry in our database contains the reactor type (PWR, BWR, etc.), manufacturer (GE, Westinghouse, etc.) and additional information such as number of loops (in PWRs) and type of containment, when such information is available.

- Description of the affected system

The newly included description of the affected system contains information only about the most important system affected during the event, which is inferred from the report of the event. Additionally, it contains information about the components that failed during the event and the number of redundant trains of the system. The information regarding the redundant trains is usually obtained from the report or from an official governmental institution, such as the NRC for the United States of America [12] (**Figure 1**).



System	Component	Succes Criteria/Redundancy
Offsite Power Systems	Transmission lines	3 x 100% EDGs
Emergency Power System	Emergency diesel	2 x 100% EDGs
Ultimate Heat Sink and Auxiliary Feedwater	Main Condenser, AFW	2 x 100% AFW pumps
Offsite Power Systems and Emergency Power System	Startup auxiliary transforn	3 x 100% EDGs and 2 in cross-t
Residual Heat Removal (RHR) System	Containment suppression	
Automatic Depressurization System (ADS) - BWR	Electromatic relief valve	
Instrumentation and Measurement	Reactor Protection Syster	3 main feedwater pumps
Automatic Depressurization System (ADS) - BWR	Electromatic relief valve	2–of–5 SRVs for non-ATWS RC
Emergency Power System	EDG zero speed relay	2 x 100% EDGs

Figure 1. Description of the affected system (excerpt from the database)

- Official or assessed INES rating

The International Nuclear Event Scale (INES) was introduced by the IAEA in 1990 in order to effectively convey information regarding nuclear accidents to the general public. The main focus of the INES rating is to quantify the amount of radiation exposure or release in any event associated with the transport, storage and use of radioactive material and radiation sources [13]. There are 7 levels on the INES scale ranging from events with no safety significance (INES 0), to anomalies (INES 1) and incidents (INES 2 and 3) and finally accidents with varying degrees of severity (INES 4-7). The scale is presented in **Figure 2**.

The INES score of an event is either provided by the IAEA, by a regulatory institution of the country where the event occurred, or by independent observers. However, the majority of obtainable events do not have an official INES rating, as many countries (such as the USA) have different methods to determine the severity of an event and use INES only when communicating with the public. Therefore, an assessed INES rating has been given in the database for most of these events, following the IAEA guidelines provided in [13]. The assessed rating is sometimes also used to re-evaluate the official INES rating for events that we consider to be unjustifiable. As the majority of events of interest to our work originate from the commercial nuclear sector, the INES rating can be severely flawed due to its focus on the radiation release/exposure and not on core damage probability. For that reason, a Core Only INES rating has been implemented in the database that will be covered in section **2.2**.

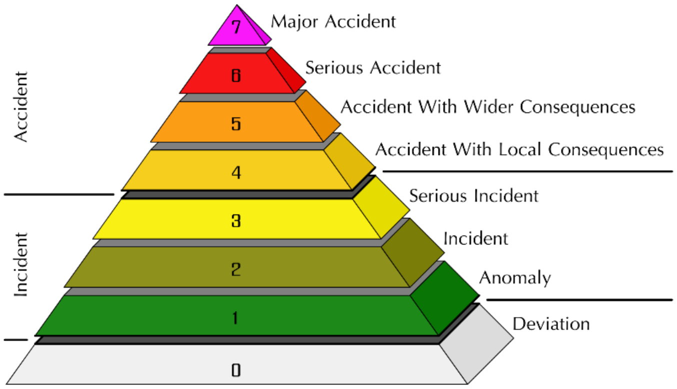


Figure 2. The International Nuclear and Radiological Event Scale (INES) [13]
Source: https://en.wikipedia.org/wiki/International_Nuclear_Event_Scale

Additionally, the events were analyzed by our team using more detailed classification criteria which will be separately covered in the following sections. These criteria include:

- Event details
- Event significance
- Contributing factors
- Failure sequences, including initiating events

It is worth mentioning that, in our database, these criteria are designed and applied only to events originating from commercial nuclear power plants.

2.1 Event details

Providing details for an event is often challenging due to common lack of official information as well as the different reporting style used by countries or organizations. As a continuation to the approach presented in [1], the details of the event are explored by taking into account the origin, cause and type of the event, as well as the operating mode of the plant. In the latest version of the database, these features have been further detailed in order to increase the consistency in their application.

2.1.1 Origin of the event

The origin refers to the physical location where an initiating event originally occurred or a system was affected. In order to retain consistency, three boundaries where the event can originate from have been drawn out (**Figure 3**):

- Events affecting the nuclear island directly - Initiating events or failures of systems/components located within the primary containment:
    - Loss of coolant accidents (LOCAs), steam generator tube rupture, reactivity induced accidents (RIA), loss of feedwater (for BWRs), etc.
    - Actual or potential failures of the following systems/components: Instrumentation, measurement and control, emergency core cooling systems (ECCS), automatic depressurization system, steam isolation system, atmospheric dump valves, etc.
- Secondary part events - Initiating events or failures of systems/components located in the “secondary” non-nuclear part of the plant or withing the plant boundary:
    - Internal floods and fires in the turbine building or auxiliary buildings, loss of main feedwater (PWR), loss of service water, internal fires, internal floods, loss of offsite power (LOOP) events originating in the plant/switchyard, etc.
    - Actual or potential failures of the following systems/components: auxiliary feedwater, emergency power system, service water system, offsite power systems, ultimate heat sink, lubrication system etc.
- External events – Initiating events originating from outside of the plant boundaries:
    - External floods, external fires, storms, earthquakes, plane crashes, blocking of the water intake system (e.g. from the river), loss of offsite power (LOOP) events originating in the grid (far-away transmission lines), etc.

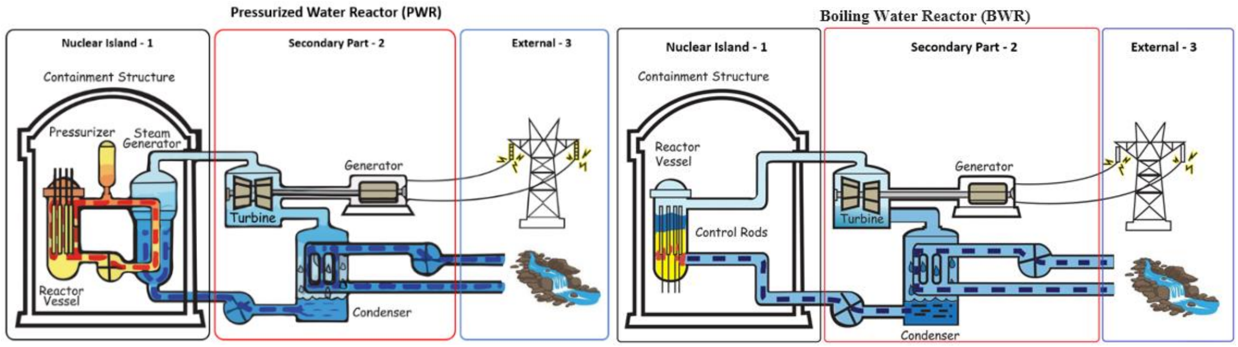


Figure 3. Boundaries for determining the origin of the event, shown on the most common reactor types: pressurized water reactor (PWR) and boiling water reactor (BWR)
Source: NRC “Animated Images of Plants PWR and BWR”. https://www.nrc.gov/reading-rm/basic-ref/students/multimedia/animated-images-plants-pwr-bwr.html

Example: If a degraded condition exists which makes the emergency diesel generators susceptible to external flooding, the origin of the event is still categorized as a secondary part event.

When discussing the origin of events which have a chain of multiple system failures and/or an initiating event, the origin of the initial occurrence is considered to be the origin of the event.

2.1.2 Cause of the event

The cause of the event defines the root cause behind the system failure or initiating event, which can be attributed to:

- Plant Personnel Errors - Where actions performed or omitted by the plant staff directly caused or contributed to an event which undermines the safety of the plant. Additionally, the staff’s lack of training or failure to mitigate a potential design-basis event can sometimes be treated as a plant personnel error. Usual plant personnel errors include: operator error, component failure due to testing and maintenance error, safety culture deficiency, etc.

- Technical Errors - Where a component failure or a design flaw (due to lack of knowledge, revision etc.) is the leading cause of the event and the staff contribution to the occurrence is minimal. Typical technical errors include: arbitrary or causal component failures, design residuals, faulty components provided by vendors, etc.
- Both technical and plant personnel errors - Where both types of errors had comparable contributions to the cause of the event.

In the ETHZ Curated Database, only plant personnel errors originating from within the plant boundaries presented in **Figure 3** are considered as such, i.e. from the staff of the plant, contractors currently operating within the plant boundaries or is the consequence of organizational/safety culture deficiencies. Plant personnel errors originating from outside of said boundaries are considered as technical errors, as it is presumed that the staff of the plant could not be aware or have the necessary training in diagnosing or preventing these errors.

Example: A failure of an Emergency Diesel Generator due to a flawed/wrong bearing provided by a vendor will be considered as a technical error, even though the root cause might be a human error in the vendor manufacturing process.

When discussing the cause of events which have a chain of multiple system failures and/or an initiating event, the cause of the initial occurrence is considered to be the cause of the event.

2.1.3 Type of the event

The type of the event describes the circumstances under which the event was discovered:

- Actual events – Events which cause noticeable acute problems and force an immediate response from the plant safety systems. Usually caused by: initiating events, frontline and support system failures, inadvertent system actuations, etc.
- Potential failures – Latent errors which may potentially result in failures of systems or redundant trains and can greatly reduce the reliability and availability of the plant safety systems. These events are usually the result of: design residuals, improper testing and maintenance and/or subsequent actions/leftovers, aging, inadequate procedures, etc.
- Both actual and potential failures – Events with both an actual and potential component. Usually these are actual events which also revealed a more serious latent error in the same or related safety system. **Example:** Failure of an emergency diesel generator (EDG) during testing, revealing a more serious problem with the cooling water system for all EDGs.

Actual events are generally regarded as more serious due to the immediate response required by the plant safety systems and personnel. As such, they are usually well analyzed by experts in the attempt to prevent their recurrence. These actions ideally should result in the decrease of actual events and increase of potential failures over the years, which will be discussed in **Chapter 3**.

In order to maintain consistency, when classifying the origin of potential failures, only the directly affected/deficit system is taken into account, and not the postulated event which might impact the safety of the plant due to the said deficiency.

2.1.4 Operating mode of the reactor

In the database, three operating modes are taken into account:

- Stable power state - when the reactor is in a steady state, whether that state is operating with nominal or reduced power. Stable power always refers to the thermal power level of the reactor instead of the

electrical power level of the plant - operating in hot standby mode is still considered as stable power operation.
- Transitory state – when the reactors is in the process of increasing or decreasing power and has not reached a steady state. Transitory modes include: startup, power increase/decrease and hot shutdown.
- Cold shutdown state – when the reactor is subcritical, bellow the coolant temperature threshold value of 100°C and depressurized at one atmosphere. This mode is also used to describe the fuel unloading and refueling modes.

This information is of upmost importance in determining the severity of an event, as reactors which operated in stable nominal power prior to the event have higher decay heat, compared to reactors which were under cold shutdown.

2.2 Significant core relevant events

The significance of an event is qualitatively assessed to segregate events which are more severe or give light to potential weaknesses in nuclear power plants. The primary assessment takes into account the core relevance of the event. In the database, every initiating event with the potential to cause core damage or every event that will, or has the potential to, degrade the function of a safety system needed to avoid or mitigate core damage is considered a core relevant event.

As briefly mentioned in **Chapter 1**, a Core Only INES rating has been implemented to further analyze core relevant events. This newly included rating is inspired, yet separate from the official INES rating. The rating uses the same INES scale, the main difference being the explicit focus on core relevant events, in contrast to the standard INES rating where the main focus is the radiation release/exposure. An event which is not considered core relevant will always receive a Core Only INES 0 rating. The core relevant events are then analyzed in detail in order to assess their Core Only INES rating, although experience has shown that for most of these events, the rating is often identical to the normal INES rating. Most common situations where the Core Only INES rating differs from the normal rating is when an event has very limited core relevance, while receiving a high INES score due to environmental radioactive release or worker injury.

Not all events which are considered to be core relevant are of equal significance. For that reason, a new feature has been included which highlights significant core relevant events. In general, significant events are considered to be events which had caused or had the potential to cause serious degradation to the safety of the nuclear power plant. In the database, the risk significance of the event is assessed based on experts' judgment and qualitative analysis. For an event to be considered significant, one of the following criteria should be fulfilled, which are similar to the US ASP screening criteria [6]:

- The event resulted in the unavailability, or potential unavailability of a major safety system, loss of a major safety function or one redundant safety train for longer than technically specified.
- The event simultaneously affected, or had the potential to affect two or more safety-relevant systems or components.
- The event was an initiating event which can result in core damage or a general transient with complications.
- The event was an initiating event followed or preceded by a failure of a safety system.
- The event resulted in a complete loss of a support system – service water, plant electrical systems (DC, low voltage AC), lubrication system, etc.

In the database, a system being affected refers to an error which caused of might cause a partial or complete failure of a system. A partial failure always refers to the failure of at least one redundant train, however, the system could still fulfil its function. This will be further explored in section **2.4**. The redundancy refers to the addition of multiple identical equipment items/systems required to perform a specific safety function, which are divided into multiple independent trains. When referring to redundant trains in the database, we always consider the trains to be fully independent from each other, unless information about the contrary is provided.

Based on experience, exceptions can be made for events that do not fulfil the criteria but to still be considered as significant core relevant events. When debating such an event, the following aspects are taken into account:

- Provision of new information regarding potential vulnerabilities in operating nuclear power plants
- Highlighted organizational or communicational deficiencies
- Frequency of occurrence of the event
- Operating mode of the power plant (full power, transition state or cold shutdown)
- General readiness of the staff to prevent or mitigate safety system failures

2.3 Contributing factors

The contributing factors have the goal to quantify the importance of specific factors that have caused or in some way contributed to the event occurrence. This information will be then used for statistical analysis and building comprehensive fault trees. As a general rule, complete loss of DC power or other support systems (component cooling/service water systems) - i.e. losses that affect the whole plant systems and are not specific to a train or system - are not part of the modeled contributing factors, and are modeled as separate initiating events. Aside from helping quantify system failures, the contributing factors feature can be also used to analyze causes of initiating events, which will be covered in section **2.4**.

Two types of contributing factors are taken into account: system level and train level contributing factors [9].

2.3.1 System level contributing factors

System level contributing factors are used to quantify the importance of factors which contributed to the actual or potential unavailability of a whole safety system. The term “unavailability of a system” refers to the simultaneous unavailability of all redundant trains of the system. These contributors include:

- Actuation system failure (automatic or manual), including operator error of omission or the failure to manually --duly-- recover a failed system.
- The independent failure of all redundant trains.

Common cause failures of all redundant trains, which cover major dependent failure causes and are explicitly modeled in the Fault tree (**Figure 4)**:

- Design residuals, which include initial design issues, construction errors, assumptions and lack of knowledge, incorrect systems actuation/trip logic, vendor/manufacturing errors, improper supply (lubrication oil, fuel, equipment, etc.), regardless whether the design deficiency was related to a frontline or a support system.
- Organizational/regulatory deficit and lack of safety culture contributions, cost-cuts, etc. regardless whether the deficit was related to a frontline or a support system.
- Inadequate procedures, which encompass both inadequate operator procedures and inadequate maintenance/testing procedures. The procedures can be defined by the regulatory body and/or the plant operator (utility), and the scope of their impact on safety can vary: inadequate plant operator procedures can adversely impact one or even more plants owned by the same company, while inadequate procedures by the regulatory body have the potential to adversely impact all plants under its supervision and control.
- Common cause residuals which cover remaining dependent failure causes, which are design dependent and cannot be explicitly modeled in a generic fault tree.

Currently, the design residuals and organizational/regulatory deficit and lack of safety culture are considered to be contributors at a system level only. This impression could be modified or further validated if such indications are uncovered.

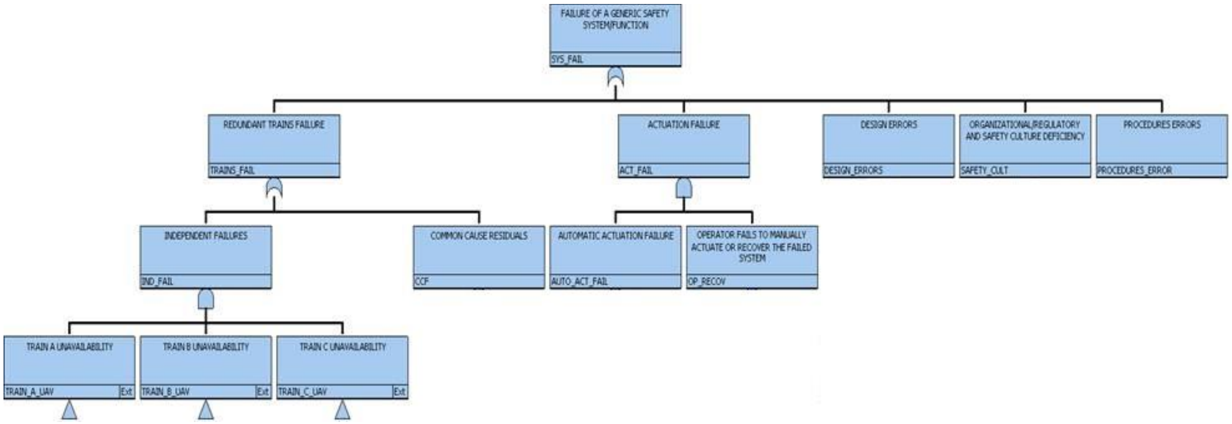


Figure 4. Fault tree of the system level contributing factors. The train unavailability blocks continue with the train level contributing factors [9].

2.3.2 Train level contributing factors

Train level contributing factors are used to quantify the importance of factors which contributed to the actual or potential unavailability of one or more redundant trains of a safety system. The cause of the unavailability of a train can either be of technical or human nature.

The technical factors are decomposed into four groups while having a train-level/super-component modeling philosophy:

- Frontline systems failures - Failures of major safety system components that affect the functionality of the whole train (suction valves, emergency diesel generators, breakers, pumps, injection valves, etc.).
- Local support systems failures - Failures in the support systems that render a single train of a safety system unavailable. Local support systems include: “local” part of component cooling systems and components (valves, pumps, heat exchangers), power supply system and components (breakers, voltage regulators), control systems, local lubrication system, etc. which are independent and dedicated to a single train.
- Global support systems failures - Failures in the support systems rendering multiple trains of different safety systems unavailable. Global support systems include: component cooling systems, power supply systems and components (breakers, voltage regulators), lubrication system, etc. which can be shared between multiple trains of different systems.
- Frontline or local support systems unavailability due to planned testing and maintenance[2] actions.

Typical causes for the technical train level failures include: normal wear, ageing, the influence of the operating conditions (stress, pressure, loads, etc.) and the immediate surroundings (moisture, radiation, etc.). The difference between what is considered a frontline and a support system will be presented on a schematic (**Figure 5)** of an emergency diesel generator (EDG) [14]. In this example, a frontline system component is every component which is required for power production or is on the flow path of the output

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[2] Testing and maintenance actions refer to the scheduled and intentional disabling of a safety system train in order to perform maintenance on the comprising components and/or testing of the functionality of the train/components. The allowed outage time and conditions for performing these actions is determined by the regulatory body, however, the success criteria for the system in question must be met during that outage time.

by the EDG. These components include the: fuel oil supply system, diesel engine, generator and EDG breaker. The local support systems include all other components in the EDG system boundary. Global support systems originate from outside of the boundaries, and in this case include: electric power for the control and protection system and cooling water supply system. On some occasions the lubrication system can also be considered as a global support system if the same lubrication system is shared between multiple trains of different safety systems.

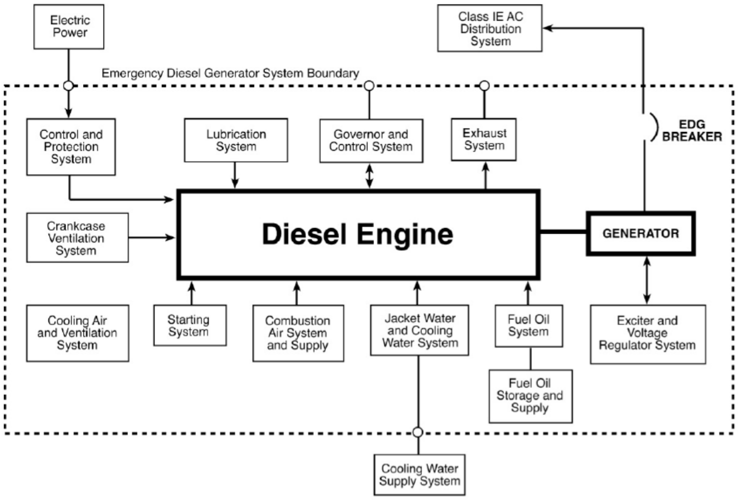

Figure 5. Schematic on an emergency diesel generator system boundary with all of the necessary components [14].

Human factors contributing to the actual or potential unavailability of a redundant train include:

- Operator and technical staff errors[3] - Errors committed by the plant operators regardless whether the error was related to a frontline or a support system. These errors include: error of commission, tripping a functional train, failure to follow correct procedures, failure to properly assess the situation, etc.
- Maintenance crew errors - Errors committed by the maintenance team regardless whether the error was related to a frontline or a support system. These errors include: errors during testing and maintenance actions, errors during operation or revision including leftovers, wrong arrangements, failure to follow correct maintenance procedures, failure to detect or report apparent degraded conditions, etc. Maintenance errors can be intra-system errors (contained within one system) or inter- systems errors (maintenance crew errors in one system affecting the availability of another system).

The fault tree of the train level contributing factors is presented in **Figure 6**.

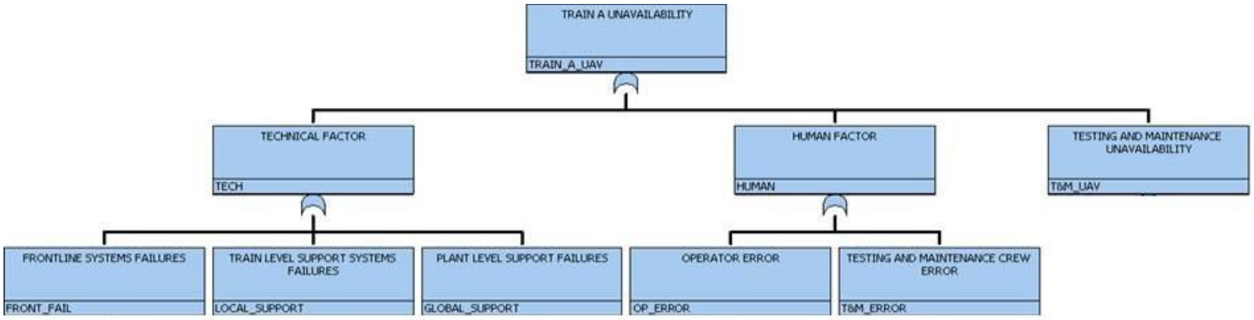

Figure 6. Fault tree of the train level contributing factors [9].

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[3] Technical staff refers to the plant personnel tasked with calculations regarding the safe operation of the reactor (e.g. neutronics team experts).

2.3.3 Recovery of a system

The recovery of a system is a separate factor that is used to highlight events where the staff of the plant managed to recover a safety system or a train, needed to avoid or mitigate core damage, for the duration of the event. This information can be important for precursor analysis, as it can be helpful in calculating the conditional core damage probability (CCDP) of an event. This factor will be used only when the recovery of a safety system is explicitly mentioned in the report. For all other events, we consider a safety system failure to be throughout the duration of the event, i.e. the recovery is never credited unless explicitly mentioned. Additionally, only the recovery of previously failed safety systems/trains by the operators or maintenance/repair team is defined by this factor, and not systems which failed to automatically to actuate and were manually actuated by the operators. This action is already defined in the system level contributing factors by the "Automatic actuation failure" factor.

2.4 Failure sequences

The failure sequences feature of the database highlights the chronological order in which plant safety systems were affected during an event. The original motivation behind introducing this feature was to give light to potential similarities between events at different plants which have experienced similar chains of events. Compairing these events can provide valuable information why some plants have experienced more severe consequences than others, when similar failure sequences occurred. Over time, the feature was further developed to resemble a simplified version of an event tree, in which the main focus is on the systems that were unavailable/affected during the event. This information is presented in a user-friendly manner and can be effectively used for statistical analysis and building event trees for precursor models.

The greatest strength of this feature turned out to be the scale at which it is applied: currently the failure sequences of all of our 930 events from the commercial nuclear sector have been modelled in the database. Furthermore, it works in synergy with the contributing factors feature covered in the previous subsection, which highlights the intiating event and/or system failure contributors. The visual representation of this feature is given in **Figure 7**.

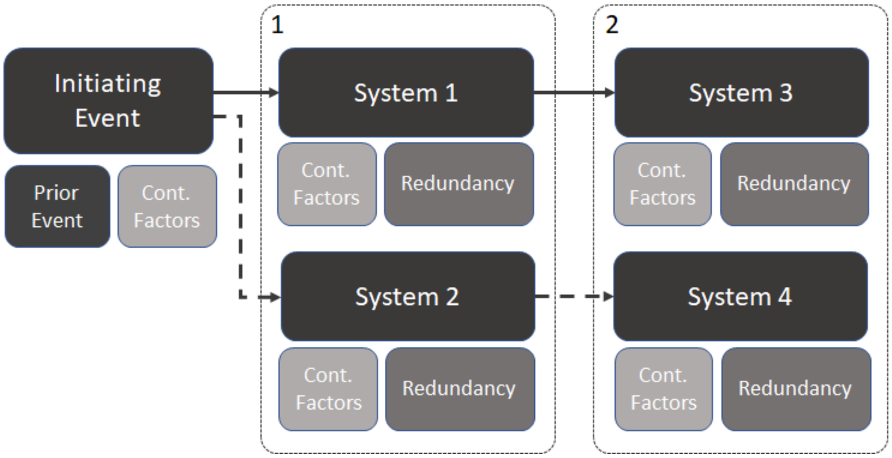


Figure 7. Representation of the failure sequences. The initiating event and systems are presented with main blocks, while the other elements are called descriptive blocks, which contain important information for their respective main block.

The initiating event block is straightforward and contains the initiating event if one occurred in the event under investigation. This main block has two descriptive blocks: prior event and contributing factors. The prior event refers to the event or conditions that occurred before the main initiating event, which are relevant for the analysis. An example of this would be the earthquake that preceded the tsunami at Fukushima

Daiichi, or a non-typical prior event. The second block details the factors that contributed to the initiating event, as described in subsection 2.3.

The system main blocks represent the affected safety systems during the event. They are always placed in groups in chronological order (groups 1 and 2 in the figure), indicating that all systems in one group were affected approximately at the same time. The system blocks also contain two descriptive blocks: contributing factors and redundancy. The contributing factors block serves the same purpose as discussed before, while the redundancy block contains information regarding how severely a safety system was affected during the event. Three levels of severity are used to describe the system:

- System affected - No significant failure of the system was observed, but the potential for a failure existed.
- Partial system failure - The failure did not encompass the whole system and was limited to one or more redundant trains which may limit the operability of the system. The number of affected redundant trains is always mentioned if this information is available.
- Complete system failure - The system failed to actuate or could not fulfil its safety function.

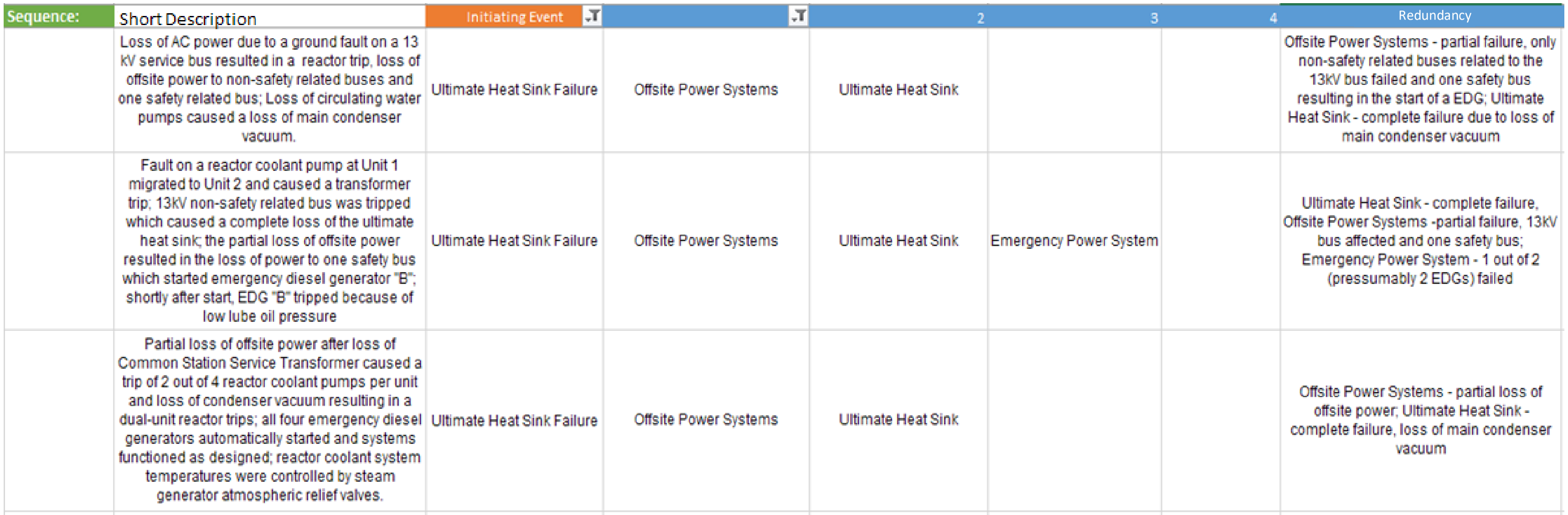
An additional trait of the failure sequences is the ability to demonstrate causality between system failures and the initiating event or preceding failures. In **Figure 7**, this feature is demonstrated with a solid line in the following failure sequence: **Initiating Event–System 1–System 3**, where each successive failure was caused by the preceding event. In the sequence shown with the dashed line there is no causal relationship between the failures of systems 2 and 4, although they occurred around the same time as the failures of systems 1 and 3, respectively. The causality is indicated in the short description of the event. It is worth mentioning that in some cases the initiating event is not the start of the chain, as initiating events themselves can be caused by system failures. However, this approach was developed as it can be efficiently applied for the majority of the events.

The sequences can be followed to map out similarities between events and show which particular factors led to different outcomes for the comparable events. Information obtained from this research can be used to further deepen our understanding of the correlations between certain safety systems, as well as the impact of plant personnel actions. This feature is envisioned to help us uncover the existence of latent design and organizational errors, as well as causal factors that might affect currently operating nuclear power plants. The usage of the feature is presented in **Figure 8**.

In the example presented in the figure, events which have the same initiating event (ultimate heat sink failure) were filtered to observe potential similarities between them. These events are presented in **Figure 8a**. It can be observed that in some of these events, the ultimate heat sink was not the first system to be affected, as a failure in the offsite power systems preceded it. By filtering out these events, a clear similarity between the failure sequences of these events can be observed (**Figure 8b**). The sequence for all of them started with a partial loss of offsite power, which then caused the loss of power to the recirculation pumps of the ultimate heat sink, finally causing the ultimate heat sink failure. One event included an additional failure in the emergency power system, which can be easily observed. The information for the extent to which the systems were affected is presented in the “Redundancy” block. The contributing factors blocks are not presented in this example due to the way they are structured in the database. This demonstrates the ability of this feature to highlight events which follow similar failure sequences and provide information regarding why some of these events result in different outcomes.

Sequence:	Short Description	Initiating Event	1	2	3	4	Redundancy	1	2	3	4	Redundancy
	Frazil ice blockage cau	Ultimate Heat Sink Failur	Ultimate Heat Sink				the very limited water intake					
	Loss of main condens	Ultimate Heat Sink Failur	Ultimate Heat Sink				failure; TDAFW pump was tripped					
	During a storm, debris	Ultimate Heat Sink Failur	Ultimate Heat Sink	uxiliary Feedwater			recoverable failure; Auxiliary					
	Loss of AC power due	Ultimate Heat Sink Failur	Offsite Power Systems	ltimate Heat Sink			failure, only non-safety related					
	Reactor trip due to swi	Ultimate Heat Sink Failur	Ultimate Heat Sink				water intake					
	Fault on a reactor cool	Ultimate Heat Sink Failur	Offsite Power Systems	ltimate Heat Sink	Emergency Power System		failure, Offsite Power Systems -					
	Manual reactor scram	Ultimate Heat Sink Failur	Ultimate Heat Sink	njection (HPCI) BWR			failure; HPCI - tripped, then		Cooling (RCIC) - BWR			restarted succesfully
	Massive infow of debri	Ultimate Heat Sink Failur	Ultimate Heat Sink				failure					
	Partial loss of offsite p	Ultimate Heat Sink Failure	Offsite Power Systems	ltimate Heat Sink			loss of offsite power; Ultimate Heat					

a)



Sequence:	Short Description	Initiating Event		2	3	4	Redundancy
	Loss of AC power due to a ground fault on a 13 kV service bus resulted in a reactor trip, loss of offsite power to non-safety related buses and one safety related bus; Loss of circulating water pumps caused a loss of main condenser vacuum.	Ultimate Heat Sink Failure	Offsite Power Systems	Ultimate Heat Sink			Offsite Power Systems - partial failure, only non-safety related buses related to the 13kV bus failed and one safety bus resulting in the start of a EDG; Ultimate Heat Sink - complete failure due to loss of main condenser vacuum
	Fault on a reactor coolant pump at Unit 1 migrated to Unit 2 and caused a transformer trip; 13kV non-safety related bus was tripped which caused a complete loss of the ultimate heat sink; the partial loss of offsite power resulted in the loss of power to one safety bus which started emergency diesel generator "B"; shortly after start, EDG "B" tripped because of low lube oil pressure	Ultimate Heat Sink Failure	Offsite Power Systems	Ultimate Heat Sink	Emergency Power System		Ultimate Heat Sink - complete failure, Offsite Power Systems -partial failure, 13kV bus affected and one safety bus; Emergency Power System - 1 out of 2 (pressumably 2 EDGs) failed
	Partial loss of offsite power after loss of Common Station Service Transformer caused a trip of 2 out of 4 reactor coolant pumps per unit and loss of condenser vacuum resulting in a dual-unit reactor trips; all four emergency diesel generators automatically started and systems functioned as designed; reactor coolant system temperatures were controlled by steam generator atmospheric relief valves.	Ultimate Heat Sink Failure	Offsite Power Systems	Ultimate Heat Sink			Offsite Power Systems - partial loss of offsite power; Ultimate Heat Sink - complete failure, loss of main condenser vacuum

b)

Figure 8. Demonstrating the use of the failure sequences function (excerpt from the database): a) filtering only the events with the same initiating event; b) filtering the events that follow the same failure sequence

2.5 Summary of changes and achievements

The ETHZ curated nuclear events database is the enhanced version of the database described in [1]. As such, many notable changes compared to the previous version can be observed. These changes include:

- Increased number of events (by 160 new events): The current version contains around 1040 events, out of which 930 are from the commercial power plants, while the previous version contained 884 total events, with 770 events originating from the commercial power plants.
- Addition of the description of the affected system feature
- Further development on the event details features: The existing origin, cause and type of the event, as well as the operating mode of the reactor features have been reviewed and updated in order to maintain consistency when classifying events according to their criteria.
- Further development of the core relevance criterion: The existing core relevance criterion was further defined in order to maintain consistency when applying said criterion to the events.
- Addition of the Core Only INES rating
- Addition of the significant safety relevant events feature
- Addition of the contributing factors feature
- Addition of the failure sequences feature
- Revision of all formerly included events
- Classification of every event, both formerly and newly included, using the features of the database
- Increased number of references for the events where more information could be uncovered

It should be noted that the classification criteria presented in this chapter have been reviewed and altered multiple times over the course of the project using feedback from the processed data.

As multiple criteria are used to classify every event, the data obtained from this classification can be used in performing different types of statistical analyses, which will be presented in **Chapter 3**.

Chapter 3. Statistical Analysis

The results will be presented in a manner similar to the criteria used, starting from analysis of the data obtained from the general information, and ending with the data obtained from the failure sequences. A trend analyses will be also performed and presented for some of the criteria. The list of events originating from each sector is presented in Table 1. The following statistical analyses will be performed only on events originating from the commercial nuclear sector.

Table 1. List of events per nuclear sector

Nuclear sector	Number of events	Percentage [%]
Commercial power plants	930	89.1
Reprocessing plants	62	5.9
Research reactors	21	2
Experimental reactors	9	0.9
Fuel fabrication plants	7	0.7
Others	15	1.4

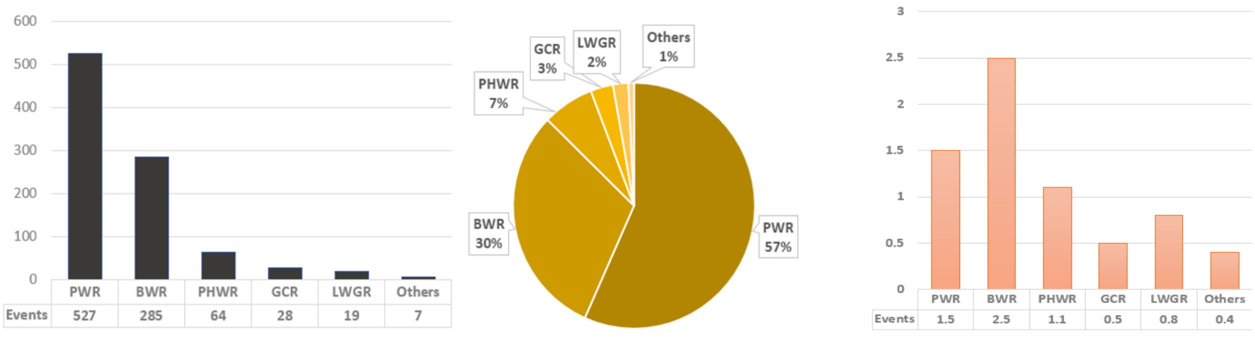
It should be noted that the data shown in this section is only performed for the events that we have included in the database. This data should not be used for predictions of the future behavior of events, but to observe tendencies in certain areas or rough estimates relevant to the safety of nuclear power plants.

3.1 General statistical analysis

The general statistical analysis is based on the general information available for every event in the database, i.e. plant type, location, year of the event and INES score.

3.1.1 Analysis of the reactor types

According to the data, the most common reactor types from the events in the database are pressurized water reactors (PWRs– presented in **Figure 50** in the Annex) with 527 events, or 56.7% of the total events, followed by boiling water reactors (BWRs) with 285 events, or 30.65% of the total events. The complete list is presented in **Figure 9a**.



a) b)

Figure 9. Number of events and shares per reactor type: a) events in the database; b) normalized by the total number of reactors of the same type

Comparing the number of events per reactor to the total number of reactors of that type gives a slightly different result (**Figure 9b**), as events originating from BWRs are the most common with 2.5 events per reactors, followed by PWRs with 1.5 events per reactor and pressurized heavy water reactors (PHWRs) with 1.1 events per reactor. The total number of reactors includes both currently operational and reactors in permanent shutdown.

3.1.2 Geographical location based statistical analysis

Currently, the largest contributor of events is the United States of America with 565 events, or 54.1% of the total events, followed by Germany and France. The list is presented in **Figure 10**.

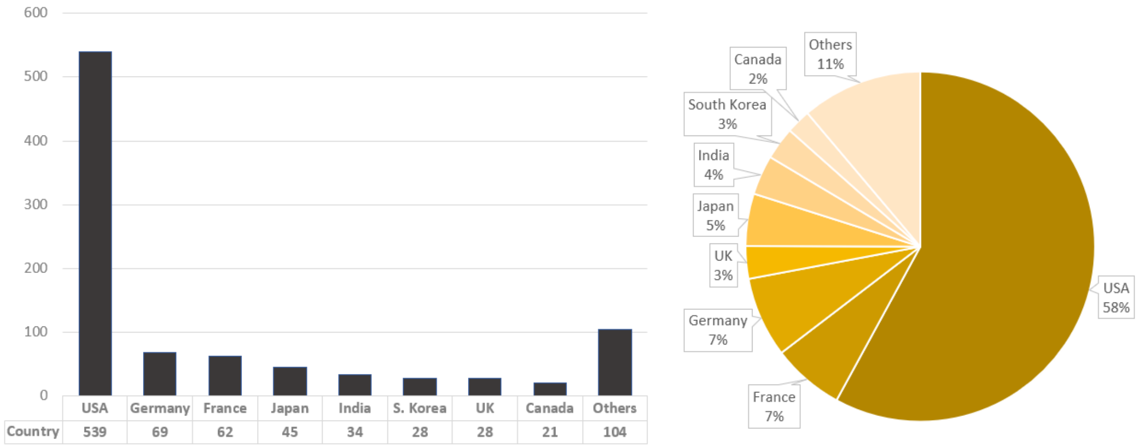


Figure 10. Number of events per country

The reason for the large number of events originating from the USA is due to the largest number of historically operating reactors (133) and due to their transparent information policy, which unfortunately is not shared by every country. To provide a more reliable information regarding the number of events originating from one country, the data is normalized based on the number of historically operating reactors in the said country. The normalized data for some of the highest contributing countries is presented in **Figure 11**.

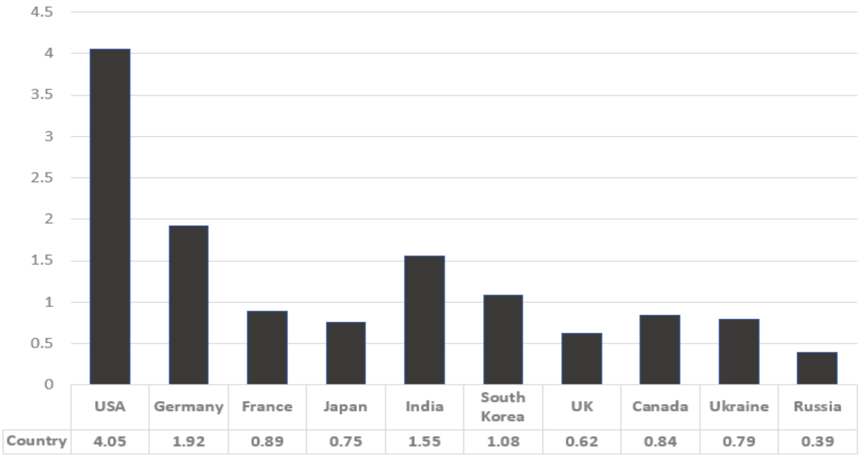


Figure 11. Number of events per country per reactor. The events from Russia and Ukraine include events in their respective reactors when they were part of the USSR.

From the figure, it can be concluded that the highest contributing country is the United States of America (USA) with 4.05 events per reactor in their 62 years of exploiting nuclear power, followed by Germany (58 years) and India (50 years) with 1.92 and 1.55 events per reactor respectively. However, this data should not be taken as an indication of the safety of operating plants in a specific country, due to the fact that not all countries share events publicly. As mentioned earlier, the USA has a shared information policy, meaning that all of their events are public; Germany follows a similar policy, where they publicize most of their events in yearly and monthly reports.

However, some countries are very restrictive towards sharing information from this sector, especially countries from the former eastern bloc. That would explain the rather low number of events per reactor originating from Russia and Ukraine, in which events from the former USSR are included. Out of all countries that currently exploit nuclear power and have a significant number of reactors, only events from China (with 48 reactors) are not included in the database, as we have difficulties in obtaining official and reliable information regarding such events.

3.1.3 Analysis of the number of events based on the year of occurrence

The first event entry in the database is from the fast breeder reactor FERMI-1 in the USA from 1966. Since then the number of reported events has drastically increased from just one event in 1966 to the all-time high of 40 events in 2001. The main reason behind this trend is the increase in the number of operating reactors over the years, although the increase in transparency of the countries exploiting nuclear power also plays a certain role. The majority of events are of low and very low safety significance, as it will be shown in the following section. The trend of reportable events over the years is presented in **Figure 12**.

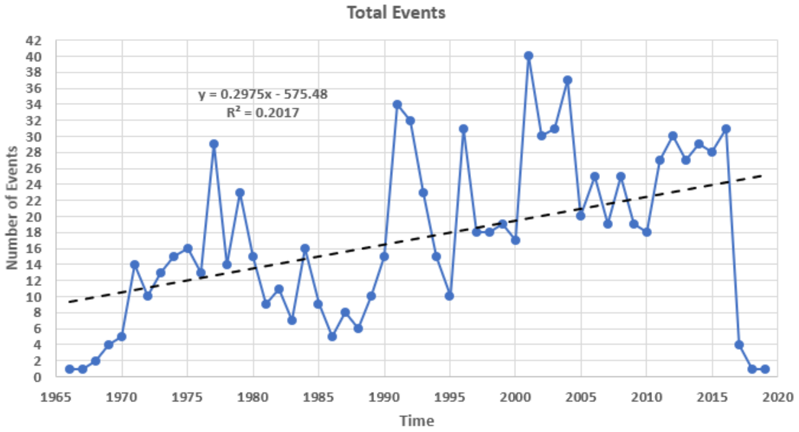


Figure 12. Number of events per year. A stable increase is predicted by the linear trendline, despite the multiple oscillations in the number of events.

Although multiple oscillations can be observed, the general trend is that the number of events per year is steadily increasing. In **Figure 13** the number of events per decade are presented. The decade with the highest number of events is the 2000s with 28% of the total events, while the decade with the lowest number of events is the 1960s with less than 1% of the total events. The similar oscillations can be observed, along with the stable increase of reportable events from the 1980s until the 2000s. Information regarding the complete number of events for the 2010s should be considered as unreliable due to the low number of currently included events from 2016 onwards. The real trend for the 2010s will be observed when these events are included in the following weeks.

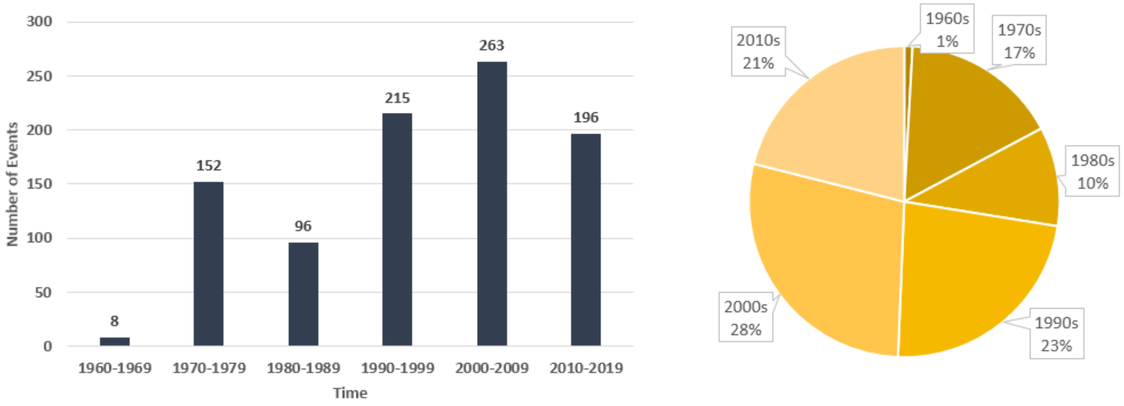
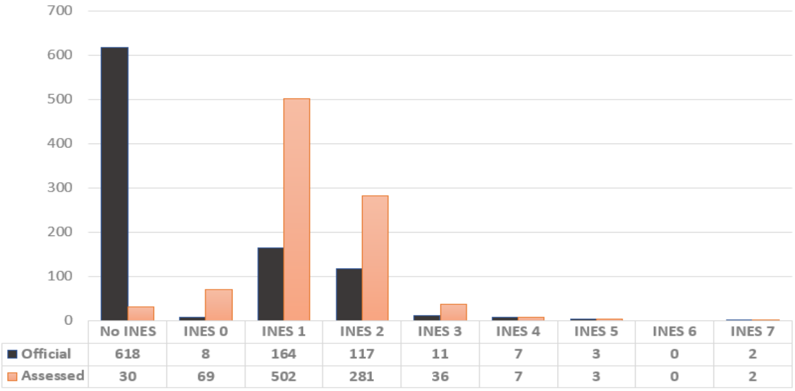


Figure 13. Number of events per decade.

3.1.4 Analysis of the number of events based on their assessed INES score

The attractiveness of the INES rating was discussed in **Chapter 1** and we strive towards providing a rating for every entry in the database. Out of the captured 930 events from commercial nuclear plants, only 312 (34%) have an official INES rating. This score is either provided by the IAEA, national regulators or independent observers. The distribution of these events based on their INES score is presented with the black graphs in **Figure 14**.



	No INES	INES 0	INES 1	INES 2	INES 3	INES 4	INES 5	INES 6	INES 7
■ Official	618	8	164	117	11	7	3	0	2
■ Assessed	30	69	502	281	36	7	3	0	2

Figure 14. Comparison between the number of events with official and assessed INES rating.

Furthermore, every entry in the database was subsequently analyzed by our team using the official INES guidelines in order to provide an INES score for the remaining events, as well as to re-evaluate certain debatable official scores. Thus, the number of events without an INES score was reduced to only 30 events (3.2%), while some events had their scores altered. The comparison between the official and assessed INES rating is presented in the same figure. As the events with assessed INES score are more numerous, they will be used for all of the consecutive analyses.

In the previous sub-section, the number of events per decade was presented. This data is broken down by the events' INES rating and presented in **Figure 15**. It can be observed that historically the biggest contributor to the number of events are INES 1 events, which have been on the rise since the 1980s, until a drop is observed in the 2010s, due to the high number of events which are not yet included in the database. The only exceptions to this trend are the 1970s when INES 2 events were the most numerous. The number of serious incidents (INES 3) appears to be decreasing over the decades, while the number of accidents (INES 4 or higher) are very rare, and there were no observed accidented for more than two decades, until Fukushima Daiichi in 2011.

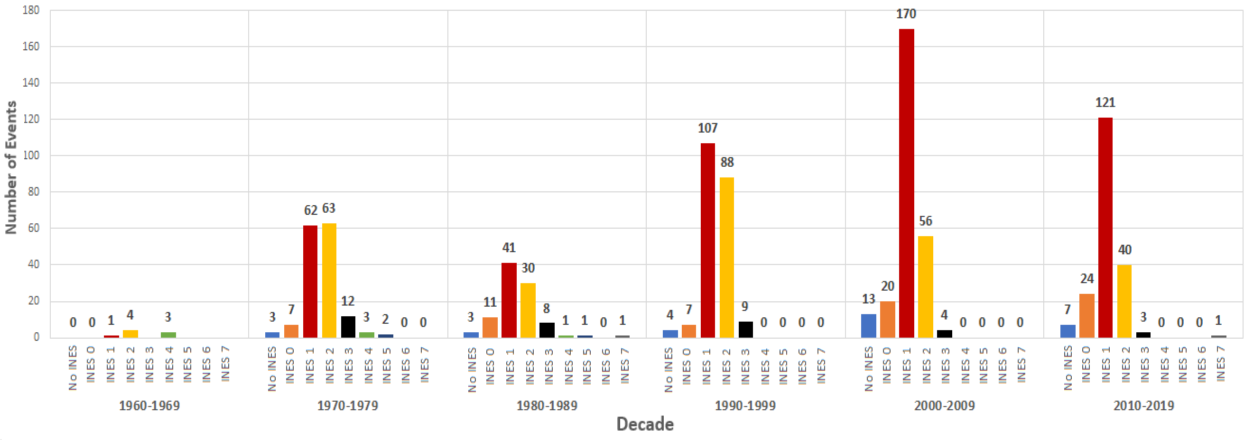


Figure 15. Breakdown of the number of events per decade according to their assessed INES score.

Another perspective of the behavior of the events based on their INES score over the decades is presented in **Figure 16.**

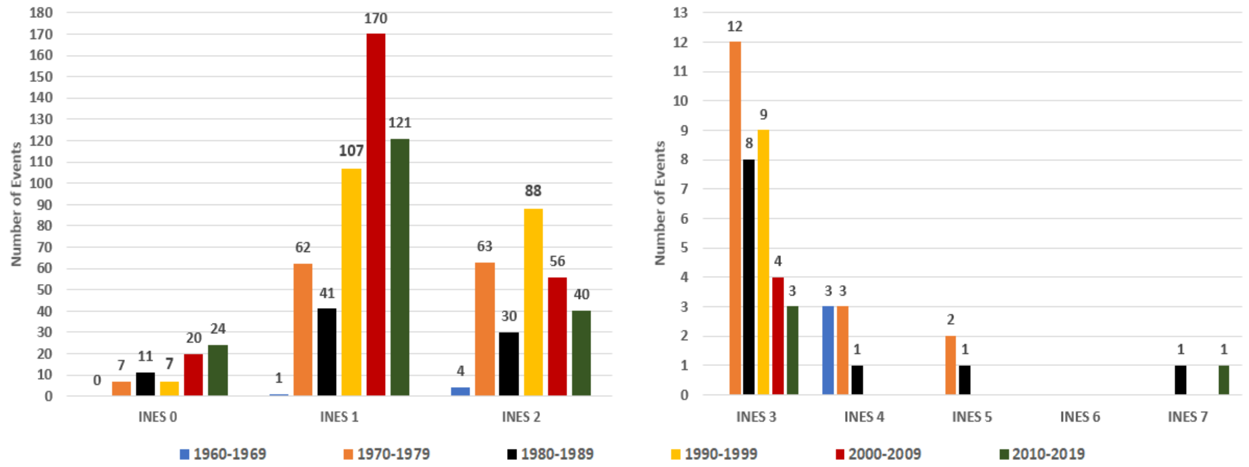


Figure 16. Behavior of events based on their assessed INES score over the decades.

To better understand the behavior of events based on their assessed INES score over the years, a trend analysis was performed. The trends for the most numerous events (INES 0 to 3) are presented in **Figure 17**. The number of events is displayed for every INES rating over the years, as well as their normalized values, which are represented as percentage of the total number of events for that year. The trendlines shown in the plots are meant to give an indication of the trend that the data is following, and should not be taken as accurate predictions or extrapolated to demonstrate future behavior.

As shown before, the general trend is that the number of reported events is increasing over the years. INES 0, or events which have no safety significance, are the third most numerous group of events. A stable increase of these events is observed in their total numbers, which is in line with the general increase of the number of reportable events. Although their normalized values are oscillating over the years, a trend of slight increase can be observed. INES 1 events (anomalies) are the most numerous, and their number is continuously increasing over the years, both in total numbers and normalized values.

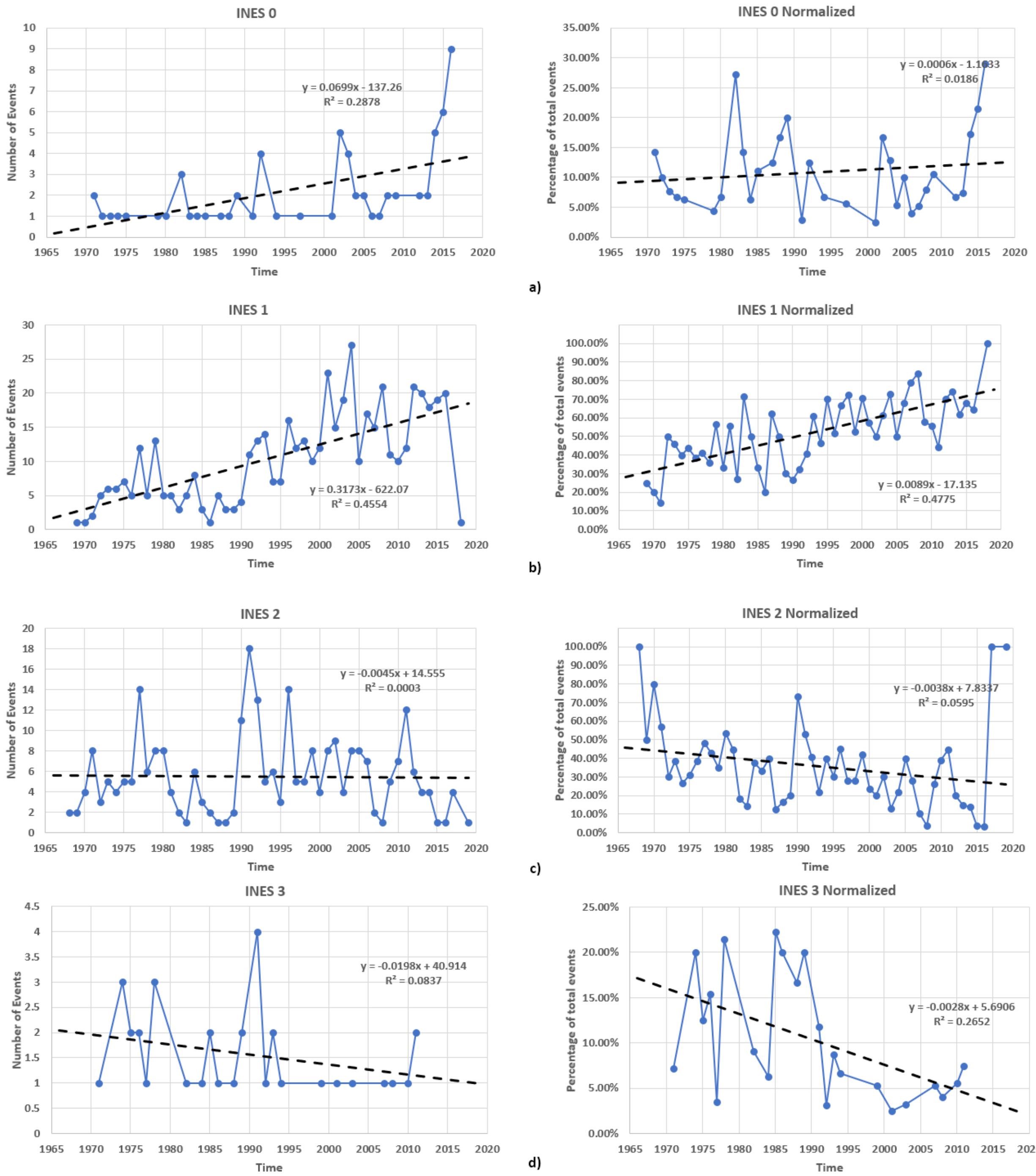


Figure 17. Trend analysis of events based on their INES scores. a) events with a score of INES 0; b) events with a score INES 1; c) INES 2 events; d) INES 3 events.

The second most numerous group, the INES 2 events are observed to be slightly decreasing in terms of total numbers, while their percentage on the total events per year is steadily decreasing. The sudden increase in the last 2 years is due to the currently low number of included events from these years. INES 3 events are the most severe of the discussed groups in **Figure 17**, as they represent serious incidents. They occur less frequently compared to the other groups, and their numbers show a trend of a steady decline both in terms of total events and normalized values. It can be observed that only 9 INES 3 events have been recorded in the past 25 years, while their percentage in the total events has declined from an all-time high of 22% in 1985 to just 7% in 2011. Regarding the nuclear accidents (INES 4 to 7), there is little incentive in doing a standard trend analysis due to the very low number of events recorded. All accidents currently in the database are unique for the year they have occurred, so they will be plotted on the same plot as shown in **Figure 18**.

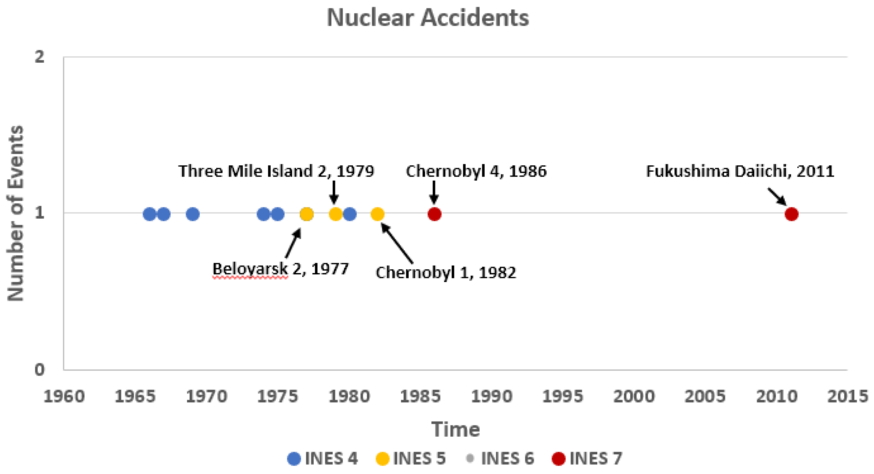


Figure 18. Recorded number of nuclear accidents per year

Unlike the incidents, nuclear accidents are fortunately very rare and their prevention is the highest priority of the countries exploiting nuclear power. INES 4 events represent accidents with local consequence, and these usually include events where a minor fuel damage was observed accompanied with a radiation release in the primary circuit or facility. Most of these events were observed in the early days of nuclear power, with the last INES 4 event recorded in our database being from 1980.

INES 5, or accidents with wider consequences, are usually events where a significant core melting is observed and/or larger amount of radiation is released within the plant, followed by a minor release outside of the plant boundaries. Only 3 INES 5 events have been observed so far, most of them occurring in the period from 1977 to 1982. The most important INES 5 event is Three Mile Island 2 in 1979. INES 6, or serious accidents, are events where a core meltdown has occurred, and larger amounts of radiation have been released to the environment. There have not been observed INES 6 events in commercial nuclear power plants.

INES 7, or major accidents, are events where a core meltdown has occurred and significant amounts of radioactive substances have been released to the environment, including large atmospheric release of short- and long-lived radioisotopes. Only two accidents in recorded history have received an INES 7 score: Chernobyl 4 in 1986 and Fukushima Daiichi in 2011. It should be noted that the reason for the INES 7 score of Fukushima Daiichi was due to the fact that all units involved were considered as part of one event. The acute consequences and release of radioactive substances from each individual unit were not severe enough to be considered an INES 7. Before Fukushima Daiichi, which was caused by a beyond design basis earthquake and tsunami, there was no occurrence of a nuclear accident for almost 25 years.

The data presented indicates that the safety improvements and backfits in commercial power plants are reflected in the decreasing trend of accidents and incidents, as well as the increasing number of anomalies and events of low safety significance. However, even in this state of nuclear safety, beyond design basis events (like in Fukushima Daiichi) always have the potential to severely undermine the plant safety systems, resulting in serious consequences.

3.2 Statistical analysis based on the event details

The event details classification criteria were presented in section **2.1** and they include: origin, cause, type of the event and operating mode of the reactor. Using the information obtained with these criteria, a statistical analysis can be performed on the 930 events from the commercial nuclear sectors.

The plant boundaries presented in **Figure 3** were used to determine the origin and cause of the events. The data shows that majority of the events originated from the nuclear island with 484 events, or 52% of the total events, followed by events originating in the secondary part with 346 events (37.2%). External events accounted for 76 events, or 8.2% of the total events, while 13 events (1.4%) had shared boundaries. The origin of the remaining 11 events, or 1.2%, could not be determined (**Figure 19a**).

Regarding the causes of the events, the leading cause was technical errors with 605 events, or 65% of the total events, followed by plant personnel errors with 251 events (27%) and both types of error were shared for 55 events, or 6% of the events. The causes for the remaining 19 events, or 2% of the total events, could not be determined due to lack of information (**Figure 19b**).

The processed data showed that distribution of the event type was as follows: 684 events, or 73.6% of the total events, were actual events, 233 events, or 25%, were potential failures and 7 events, or 0.8% of the total events, had indications of both actual and potential failures. The remaining 6 events, or 0.6% could not be classified due to the lack of information (**Figure 19c**).

The operating mode of the reactor is used to describe the power of the reactor during the event. The data shows that out of the 930 events, the reactors in 529 events, or 56.9% of the total events, were operating at stable power, 93, or 10%, were in a transitory state and 138 events (14.8%) were under cold shutdown. The operating mode of the remaining 170 events (18.3%) could not be determined due to lack of information (**Figure 19d**).

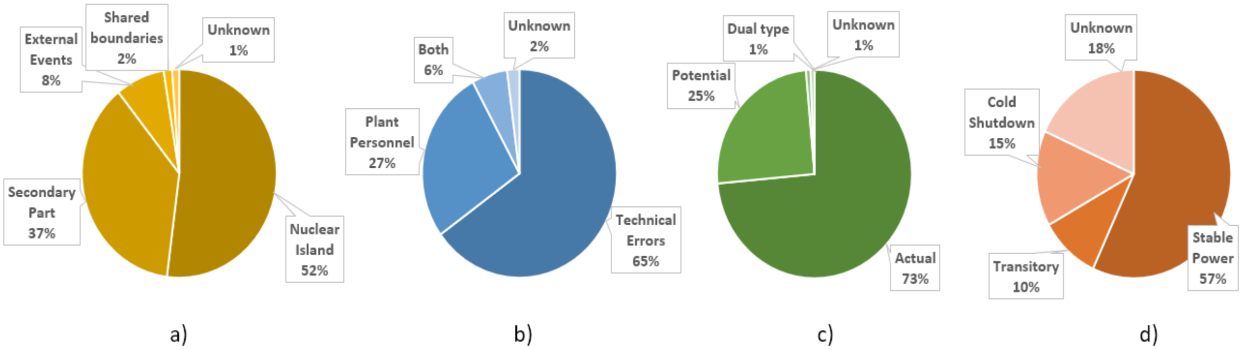
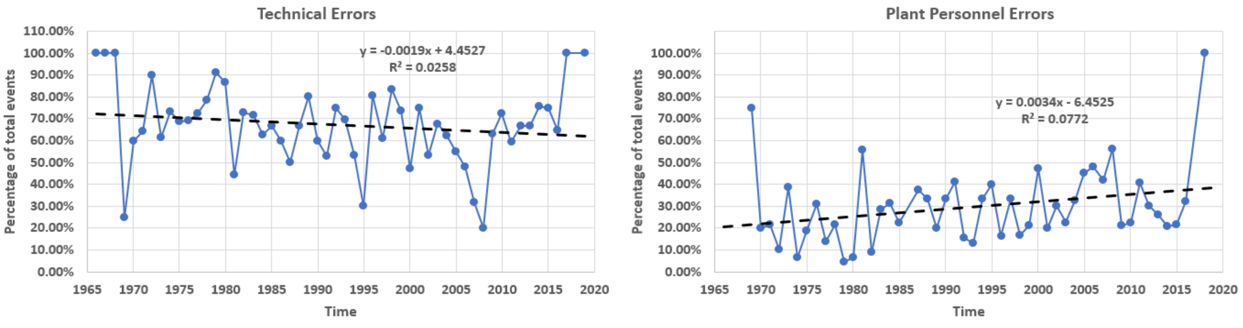


Figure 19. Statistical data for the event details: a) origin of the events; b) causes behind the events; c) type of the events; d) operating mode of the reactors for the duration of the events.

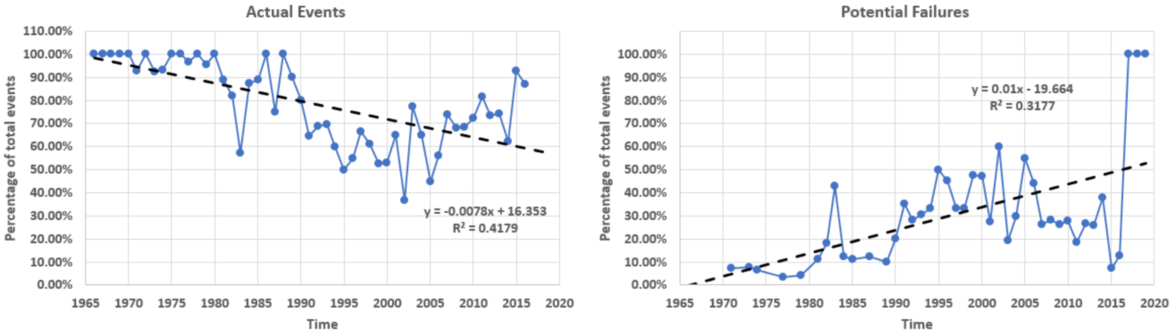
The trend analysis will only be performed for the cause and type of the event, as it can provide important information related to the safety of nuclear power plants. The behavior over time of the other criteria is not of such importance. The trend of the cause of the events if presented in **Figure 20**, where only the behavior of technical and plant personnel errors is of interest. Only the normalized values are presented in the plots, as we are not interested in the absolute number of events per year due to the general increase of reportable events. It can be observed from the figure that even though technical errors are generally the dominating factors, their percentage from the total events is slightly declining over the years, and their average representation in the last two decades is around 65-70% of total events. As expected, the percentage of plant personnel errors appear to be steadily increasing over the years, and this trend will most likely continue. The reason for the decline of technical errors is most likely due to the implementation of lessons learned from operating experience such as: stricter standards for components in NPPs, modification of inadequate designs, providing proper protection of components against operating/external factors, etc.



a) b)

Figure 20. Trend analysis of the causes of events over time: a) contribution of technical errors; b) contribution of plant personnel errors.

The behavior of events based on their type is presented in **Figure 21**. Only the normalized values are presented in the plots due to the aforementioned reasons. We can observe that the percentage of actual events from the total events is sharply decreasing, reaching an all-time low of 36% in 2002. The increase of the share of potential failures is most likely due to the conservation of the total number of events. The reason for the decline of actual events is linked to the increase in operating experience and heightened safety measures, inspections, improved performance of testing and maintenance teams, and information sharing within and between countries. The sudden peak of potential failures in **Figure 21b** is due to the low number of currently included events for those years.



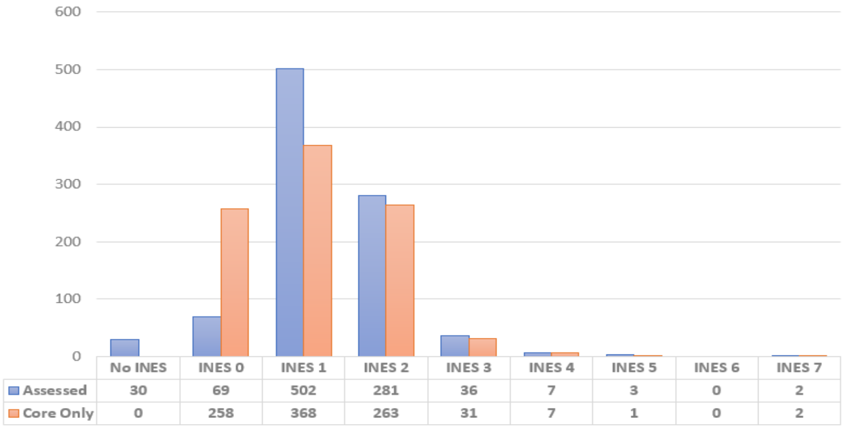
a) b)

Figure 21. Trend analysis of the type of events over time: a) contribution of actual events; b) contribution of potential failures.

3.3 Statistical analysis based on the significance of the event

The significance of the events was discussed in section **2.2**. By using the core relevance and significant core relevant criteria, the following data was obtained:

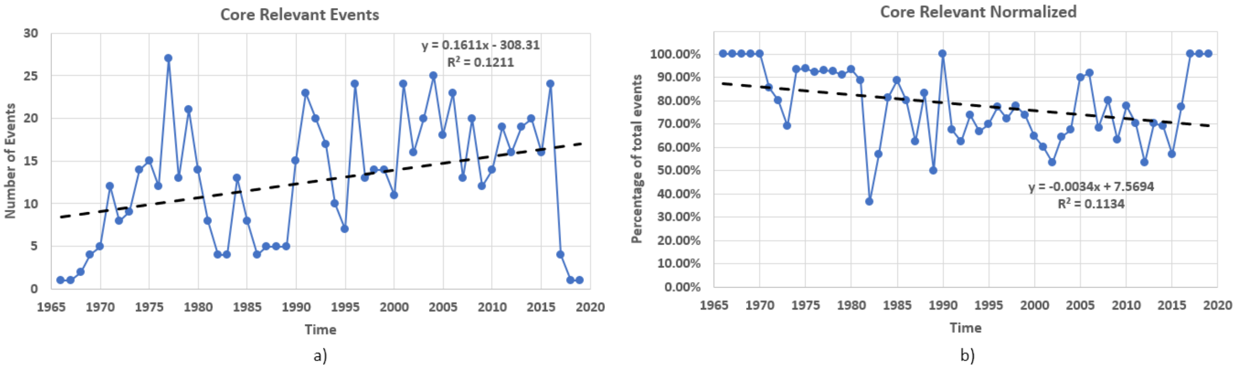
Out of the 930 events from the commercial nuclear power plant sector, 687 events are considered to be of core safety relevance, or 73.9%. The remaining 243 events, or 26.1%, are considered to have no core relevance. It should be noted that core relevant events are more readily reported by organizations and are preferred to be included in the database, which would explain their rather high percentage of the total events. The core relevant events were given a separate Core Only INES rating to account for their real core damage related severity. As a general rule, events which have no core relevance were given a rating of 0. A comparison between the core relevant INES rating and the normal rating of the events is presented in **Figure 22**.



	No INES	INES 0	INES 1	INES 2	INES 3	INES 4	INES 5	INES 6	INES 7
▨ Assessed	30	69	502	281	36	7	3	0	2
▨ Core Only	0	258	368	263	31	7	1	0	2

Figure 22. Comparison between the assessed INES rating and the Core Only INES rating.

It can be deduced from the figure that many events which were previously INES 1, have been rescaled to INES 0 due to their core safety irrelevance. Most of these events are instances of acute radiation exposure of workers, failure of non-safety relevant systems or release of radioactive substances to the environment. The majority of events with a score of INES 2 or higher have retained their score, with the exception of two INES 5 events, which will be discussed in the following paragraphs. The behavior of core relevant events over the years is presented in **Figure 23**. Plot **a)** portrays the total number of core relevant events per year, while plot **b)** portrays the percentage of core relevant events of the total events per year. Although the total number of core relevant events is increasing, this is mainly due to the general increase of reported events, the normalized values indicate that core relevant events have been steadily decreasing over the years.



a)

b)

Figure 23. Behavior of core relevant events over the years: a) number of events per year; b) contribution of core relevant events to the total events per year.

As mentioned before, the values for the events after 2016 should be taken as unreliable due to more recent events which are yet to be included.

A detailed trend analysis of the number of events based on their Core Only INES score is performed, similar to the one for the normal INES rating. The results are presented in an identical manner in **Figure 24**. A trend analysis of core relevant events has already been conducted for the previous version of the database (before the enhancement), which was presented in [15] and [1], therefore a comparison will be drawn between the results obtained using the two versions of the database.

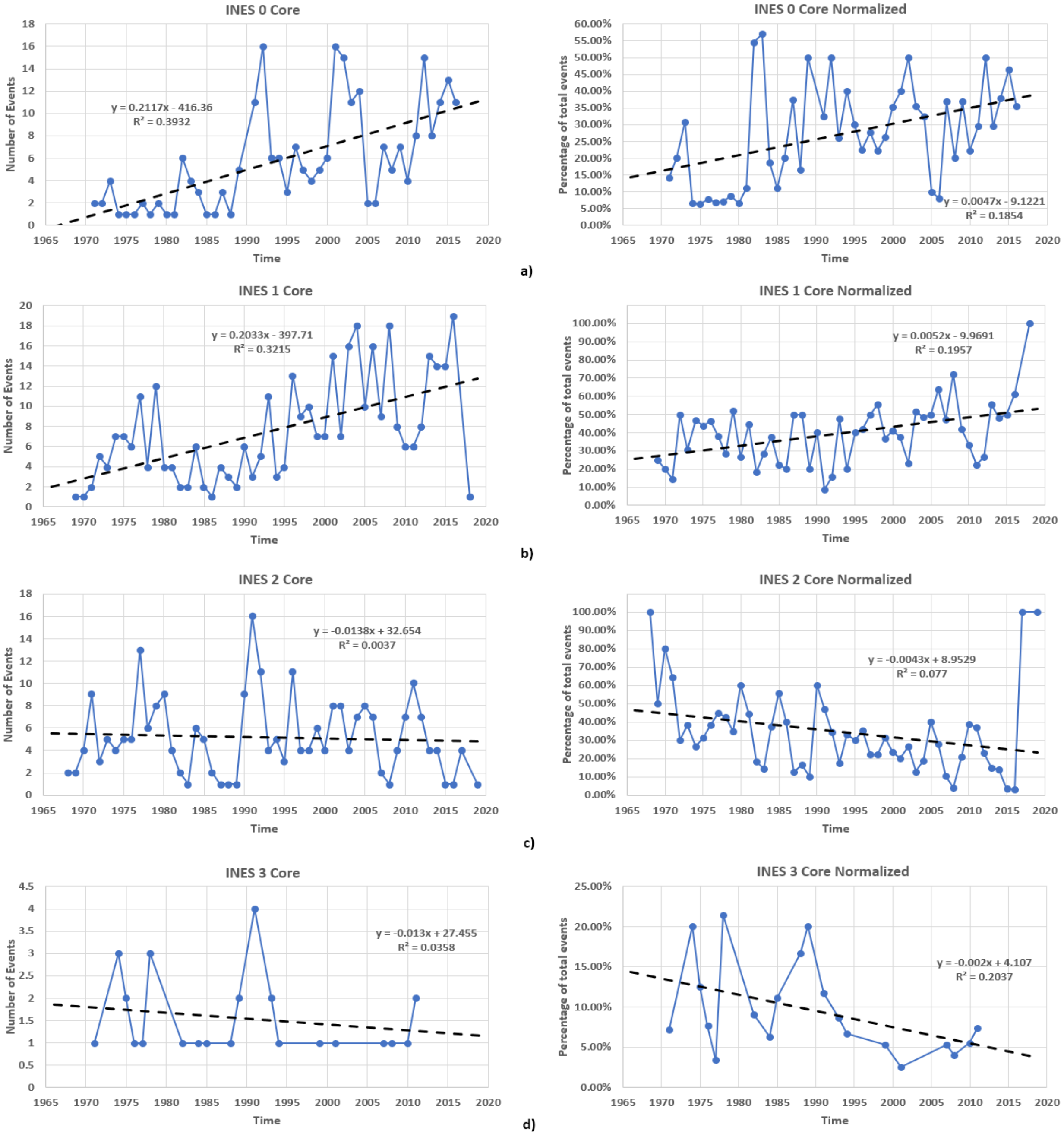


Figure 24. Trend analysis of events based on their Core Only INES scores. a) events with a score of INES 0; b) events with a score INES 1; c) INES 2 events; d) INES 3 events.

In [15] and [1], the results showed that the number of core relevant anomalies (INES 1) is increasing over time, while the number of serious incidents (INES 2 and 3) and accidents (INES 4-7) is declining. The conclusions for Core Only INES 2 and 3 events are identical, as the trends for both types of incidents steadily decline over time. Many INES 1 events have been rescaled to INES 0, which is reflected in the normalized values for these events, as INES 0 events contribute by as much as 20% more in recent years, compared to the same time for the assessed rating, while the contribution of INES 1 events to the total events is reduced. The trendline for INES 0 events indicates that the contribution of these events to the total events is steadily increasing over time, while INES 1 events are also on the rise, albeit with a slightly lower intensity. These results are also in line with the previous statements presented in [15] and [1], even though the number of processed events is higher.

Regarding the nuclear accidents, their behavior is identical to the one discussed before and in [15] and [1] (**Figure 25)**. What is important to discuss is the number of INES 5 events, which was reduced from three events to one. This is due to the fact that the accident in Chernobyl 1 in 1982 was rescaled to INES 2, as only one pressure pipe out of 1640 suffered a meltdown, which was quickly replaced. The reason for the high rating was the radiation exposure of the workers and leak to the environment, however those factors are not as highly valued when assigning a Core Only INES score. The accident in Beloyarsk 2 in 1977 was reduced to INES 4 score due to the fact that the accident did not result in the complete meltdown of the core, the affected pressure tubes were replaced in the following year and the reactor resumed operation. Likewise, in this accident the biggest factor in receiving the high official score is the radiation exposure of workers. However, this accident is still shrouded in mystery as information is very scarce, so the Core Only INES score might be reassessed if new information comes to light.

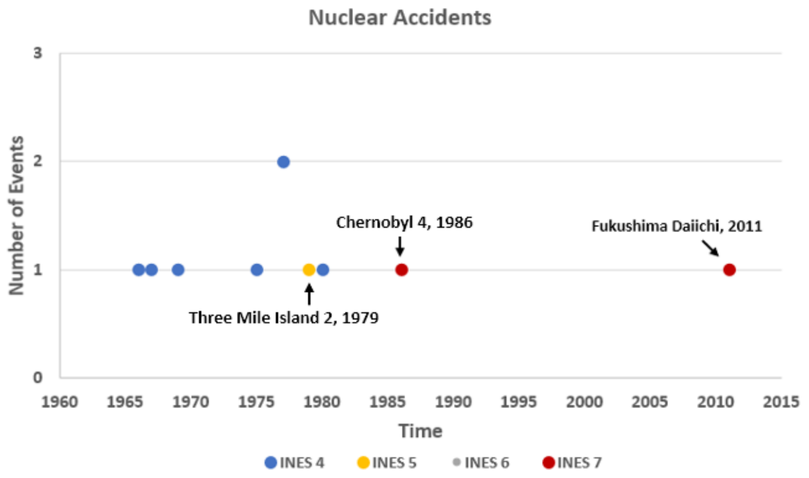


Figure 25. Recorded number of nuclear accidents per year based on their core relevance

The distinction between significant events and other core relevant events was discussed in section **2.2**. Out of the 687 core relevant events, 573 events (83.4%) are considered to be significant, while the remaining 114 events (16.6%) are of low safety significance. Out of all significant events, 315 events (or 55%) contain an initiating event, while the remaining 258 events (45%) are safety system failures (**Figure 26**).

The trend analysis of significant events in depicted in **Figure 27**. Similar to the analysis for core relevant events, plot **a)** portrays the total number of significant events per year, while plot **b)** portrays the percentage of significant events of the total events per year. The total number of significant events appears to be increasing due to the general increase of reported events. However, the normalized values indicate that significant events have been steadily decreasing over the years.

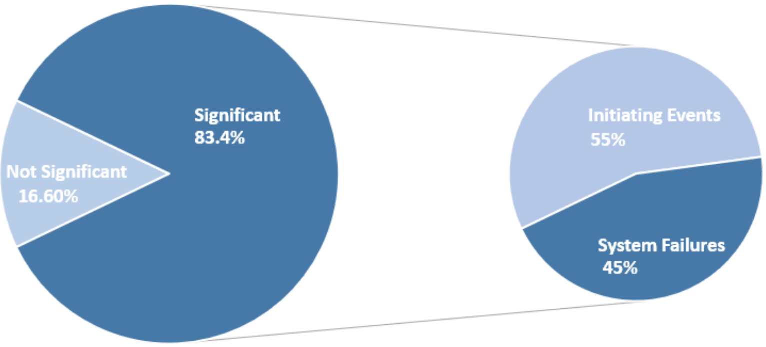
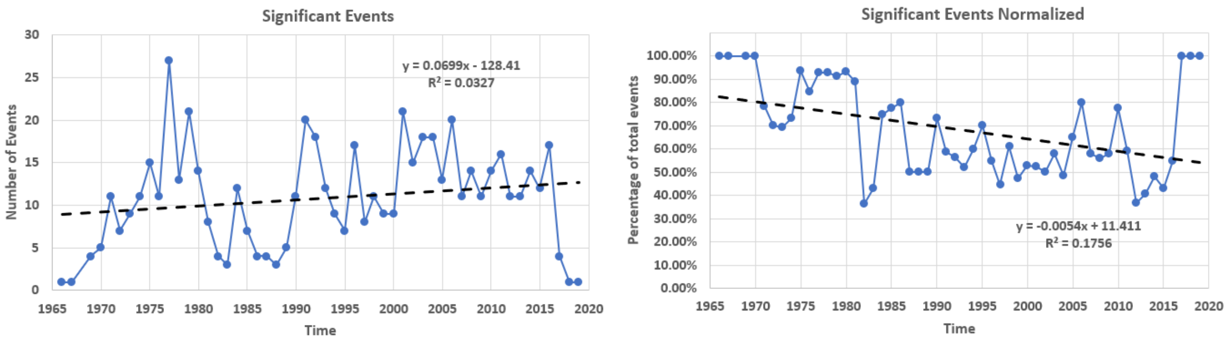


Figure 26. Breakdown of the significant events from the core relevant events.



a) b)

Figure 27. Behavior of significant events: a) total number of events per year; b) contribution of the significant events to the total number of events per year.

When it comes to the origin of safety significant events, out of the 573 significant events, 260 events (45.4%) originated from the nuclear island, 230 events (40.1%) originated from the secondary part and 72 events (12.6%) were external events. The remaining 11 events (1.9%) shared their origin between two boundaries (**Figure 28a**).

Regarding the causes behind the significant events, technical errors accounted for 372 events (64.9%), plant personnel errors for 157 events (27.4%), while a combination of both errors was the cause for 40 events (7%). The causes for only 4 events (0.7%) could not be determined due to the lack of information (**Figure 28b**).

The type of the significant events is dominated by the actual events, which amount to 460 events (80.3%), followed by potential failures with 108 events (18.8%). The remaining 5 events (0.9%) were both actual and potential failures (**Figure 28c**).

Regarding the operating mode of the plant when a significant event has occurred, 353 (61.6%) of the 573 significant events occurred while the plant was operating at stable power, while 60 (10.5%) occurred while the plant was in a transitory state. The remaining events include: 59 events (10.3%) where the plant was in cold shutdown and 101 events (17.6%) for which the operating mode could not be determined (**Figure 28d**).

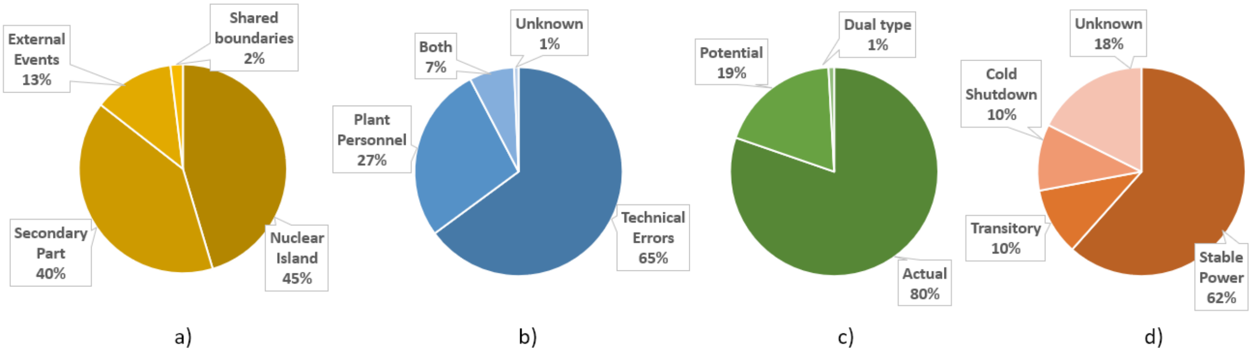


Figure 28. Statistical data for the significant events: a) origin of the significant events; b) causes behind the events; c) type of the events; d) operating mode of the reactors for the duration of the events.

3.4 Dominating initiating events

Initiating events were involved in 371 events (39.9%) out of the 930 events from commercial nuclear power plants. The remaining 559 events (60.1%) did not have an involved initiating event and were purely caused by a system failure. From here onwards, these events will be referred to only as system failures. As mentioned in subsection **3.3.1**, 315 events containing initiating events (84.9%) are considered to be of safety significance, while the remaining 56 events (15.1%) are of lower significance. Of the system failures, 258 events (46.2%) are considered to be of safety significance, while the remaining 301 events (53.8%) are of lower significance (**Figure 29**).

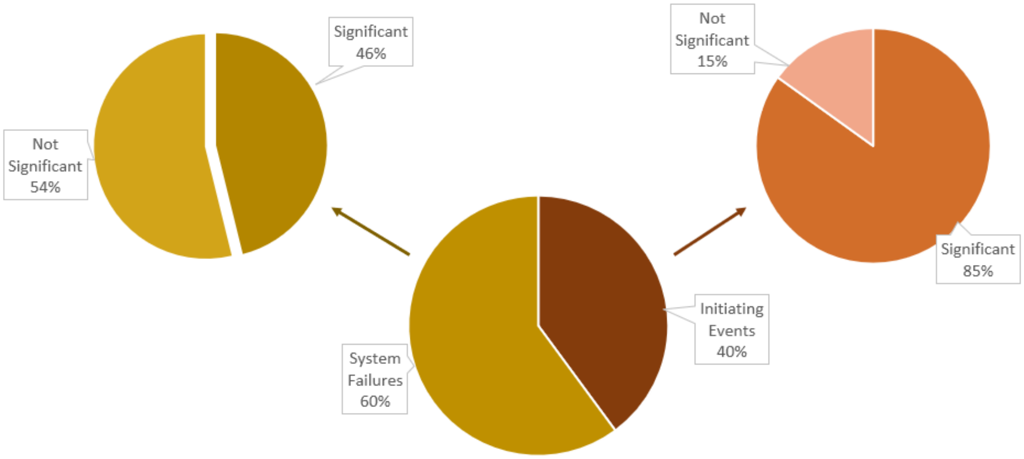
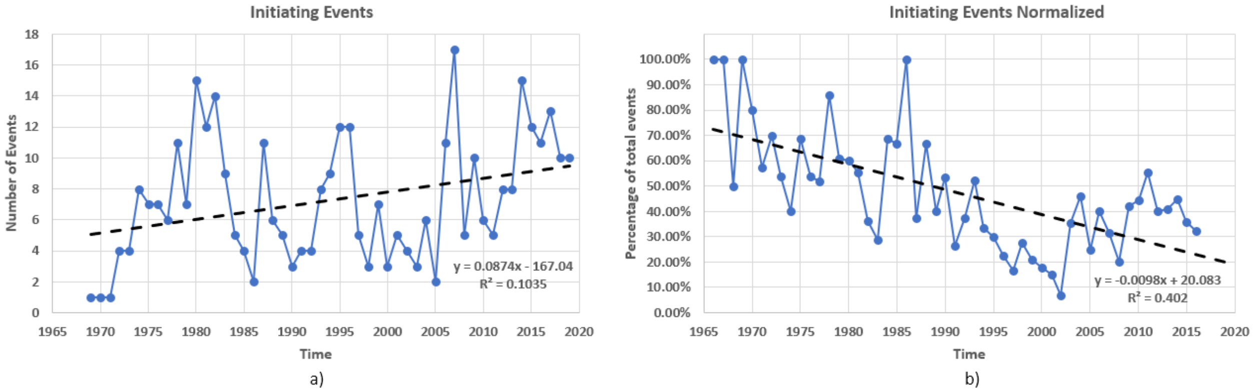


Figure 29. Breakdown of the percentage of initiating events and system failures

The total number of initiating events is increasing over the years, which is in line with the general increase of reported events (**Figure 30**). However, the contribution of initiating events to the total events has been steadily decreasing for the past 30 years, with some oscillations. As mentioned before, the trendlines in these graphs should only be considered as an indicator of the increasing/decreasing trend of the initiating events, and not as a tool for predicting the future number of initiating events per year.

The complete list of initiating events currently modelled in the database is presented in **Table 3** in the Annex.



a) b)

Figure 30. Behavior of initiating events: a) total number of initiating events per year; b) contribution of the initiating events to the total number of events per year.

The statistical analysis shows that the leading initiating event is loss of offsite power with 110 occurrences, or 29.6% of the total initiating events, followed by general transients with 104 occurrences (28.6%) and small break loss-of-coolant accidents (SBLOCAs) with 31 occurrences (8.4%). The complete list is presented in **Figure 31**. The three most common initiating events are responsible for more than 66% of the total initiating events, and for that reason they will be the focus in the subsequent analysis. The system failures which occurred during these events will not be explicitly analyzed in this thesis. This analysis is expected to be included as part of the future work on the database.

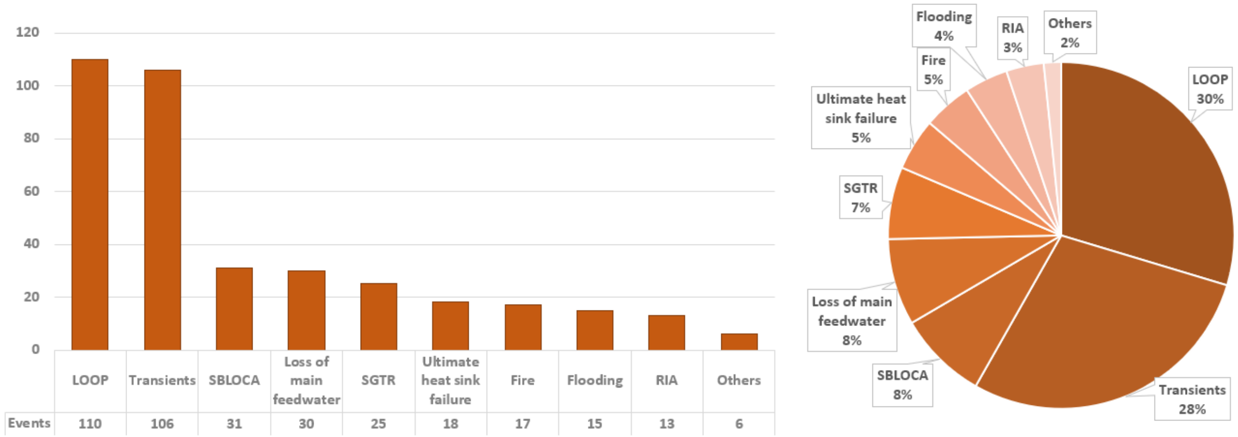


Figure 31. Breakdown of the number of initiating events. The fire and flooding initiating events are comprised of both internal and external occurrences.

3.4.1 Initiating event: Loss of Offsite Power (LOOP)

Loss of offsite power (LOOP)[4] events are very serious events which can significantly degrade the safety of the plant, as most of the important safety systems require electricity to properly fulfil their function. It is difficult to determine the trend for the total number of LOOP events per year as major oscillations can be observed, even though the trendline in **Figure 32a** points to a decreasing trend. The normalized data for the

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[4] Loss of offsite power (LOOP) refers to an event in which power is lost from all main and auxiliary offsite power sources, such as the transmission grid. The normal response to a LOOP event is the transfer of all safety systems to the emergency diesel generators (EDGs) of the plant. Also referred to as loss of preferred power (LOPP) in some literature.

number of LOOP events from the total number of initiating events **(Figure 32b)** also indicates that the number of LOOPs compared to the total number of initiating events is steadily decreasing, even though similar oscillations can be observed.

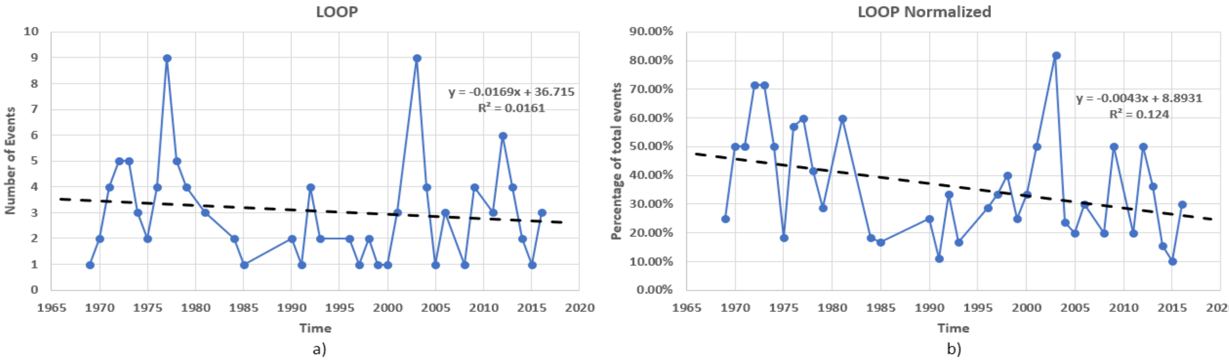

Figure 32. Number of loss of offsite power (LOOP) events per year: a) total number of LOOP events; b) contribution of LOOP events to the total number of initiating events per year.

When discussing the origin of LOOP events, 61 events (55.5%) originated from the secondary part (switchyard), while 48 (43.6%) were events caused by external factors. Only 1 event[5] (0.9%) originated from the nuclear island and migrated to the switchyard, leading to a LOOP event (**Figure 33a**). Regarding the causes of the LOOPs, 79 events (71.8%) were caused by technical errors, 25 events (22.7%) by plant personnel errors, while both errors accounted for 6 events (5.5%) (**Figure 33b**). Out of the 110 LOOP events, 89 (80.9%) occurred while the plant was at stable power, 6 (5.5%) while the plant was in a transitory state and 15 (13.6%) while the plant was in cold shutdown (**Figure 33c**).

Classifying the LOOPs based on their Core Only INES scores yields the following results: Out of the 110 LOOP events, 55 (50%) have an INES 1 score, which is the minimum for a LOOP, while 50 events (45.5%) have an INES 2 score. Only 5 events (4.5%) have an INES 3 score, which are the highest recorded LOOP incidents. As of the time of writing of this thesis, there has never been a recorded nuclear accident caused by a LOOP (**Figure 33d**).

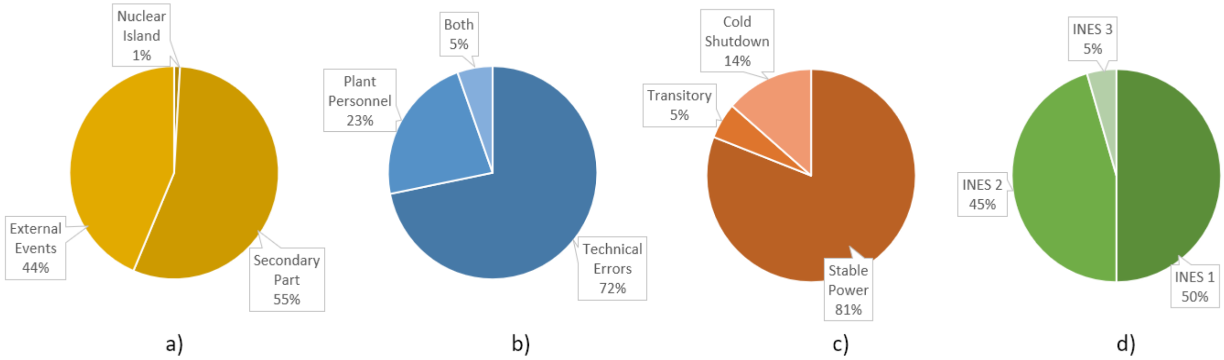

Figure 33. Figure 34. Statistical data for the loss of offsite power events: a) origin of the events; b) causes behind the events; c) operating mode of the reactors for the duration of the events; d) Core Only INES rating of the events.

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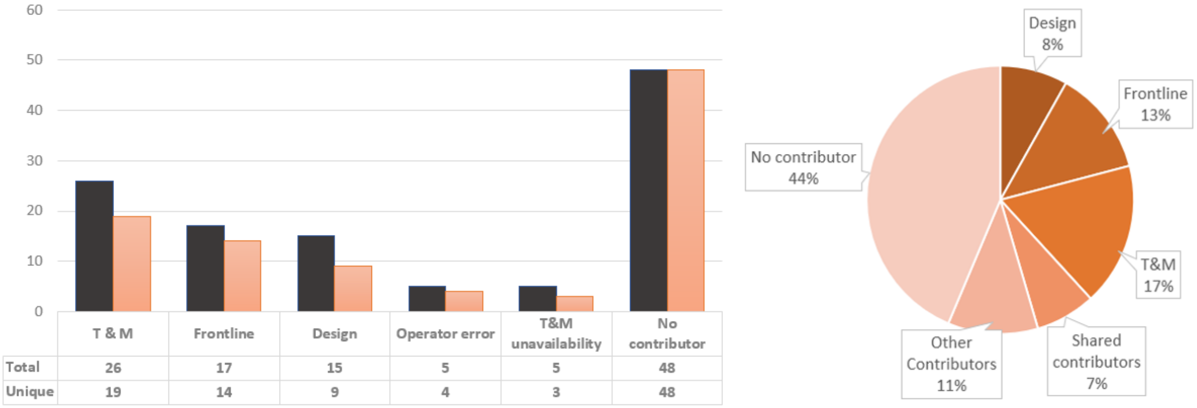
[5] The event occurred at Indian Point 2, USA in 1999. Errors in the reactor trip logic resulted in the sudden trip of the reactor, which caused a consecutive turbine trip. During the transfer of power to the station auxiliary transformer, a fault in the transformer tap changer triggered the station black out logic, which disconnected all the breakers in the offsite power system, resulting in a LOOP.

It should be noted that the type of the event and event significance classification are omitted from further analysis here as all LOOP events are actual failures and are considered to be of safety significance.

The contributing factors discussed in **2.3** can be used to highlight all factors which have in any way contributed to the occurrence of a LOOP. It should be noted that the contributing factors are not always equivalent to the cause of an event. Two groups of contributing factors are discussed: shared and unique contributing factors. Shared contributing factors describe situations where multiple factors contributed to an event or a system failure, while unique factors describe situations where there was only one contributing factor. The contributing factors for LOOPs are presented in **Figure 35**.

From the figure it can be concluded that design residuals contributed to 15 events in total, and were the unique factor in 9 (8.2%) of them. Testing and maintenance errors contributed to 26 events of the total LOOP events, and were the unique factor in 19 events (17.3%), while frontline failures contributed to 17 of the total events and were the unique factors for 14 (12.7%) of them. A total of 48 events (43.6%) did not have any factor contributing to the event, while 8 events (7.3%) had shared contributing factors.



a)

b)

Figure 35. Contributing factors for loss of offsite power events: a) comparison of the total and unique contributing factors; b) breakdown of the contribution of different factors in the occurrence of these events.

3.4.2 Initiating event: General Transients

General transients[6] are the second most frequent initiating event and they account for 106 events, or 28.6% of all initiating events currently present in the database. General transients refer to all transient events which are currently not specifically modeled as other initiating events. The total number of transients appears to be increasing over the years as it is indicated by the data presented in **Figure 36a**. The behavior of their contribution to the total number of initiating events is difficult to determine as the transients frequently change their share from less than 10% of all initiating events for the year, to more than 50% (**Figure 36b**).

When discussing the origin of general transients, 56 events (52.8%) originated from the nuclear island, 44 (41.5%) from the secondary part and 6 events (5.7%) had an external origin (**Figure 37a**).

The majority of general transients, or 64 events (60.4%), were caused by technical errors, 32 events (30.2%) by plant personnel errors, while shared errors accounted for 10 events, or 9.4% (**Figure 37b**).

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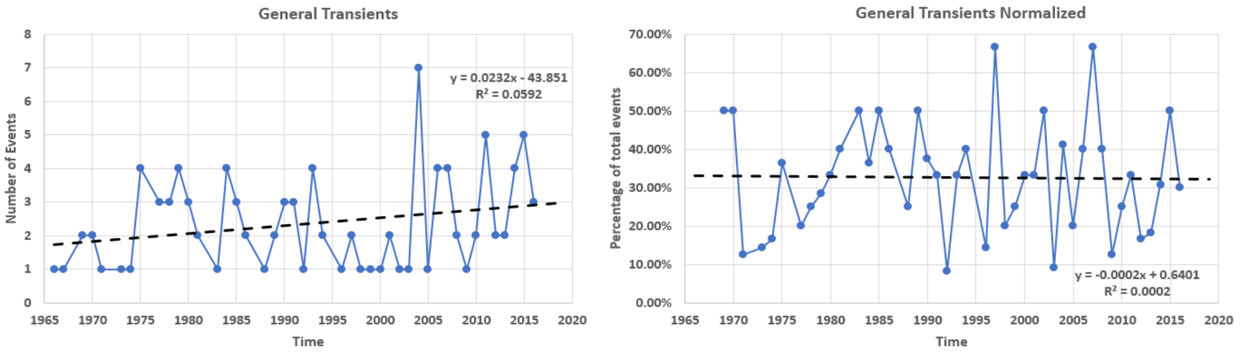
[6] General Transients refer to the disbalance of the thermal power produced by the reactor and the thermal power transferred to the secondary circuit.



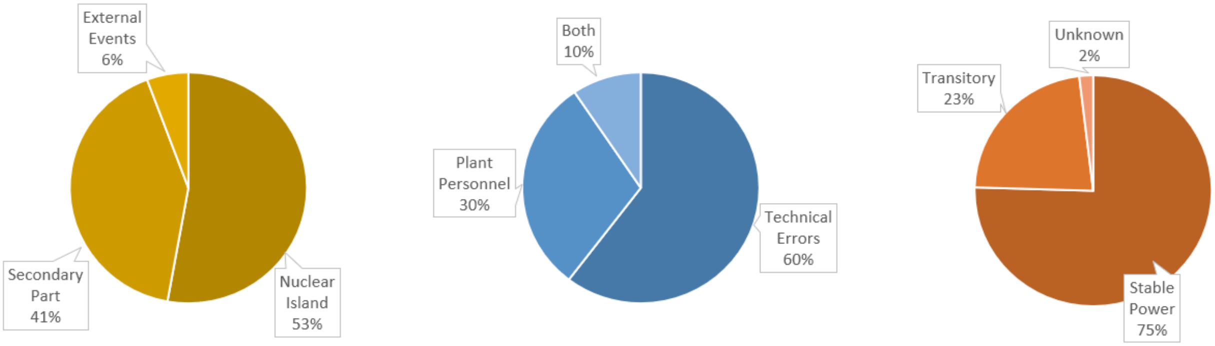
a)

b)

Figure 36. Number of general transient events per year: a) total number of events; b) contribution of LOOP events to the total number of initiating events per year.

Out of the 106 transients, 80 (75.5%) occurred while the plant was at stable power, 24 (22.6%) while the plant was in a transitory state and for 2 events (1.9%) the mode of the plant could not be determined (**Figure 37c**).

It should be noted that the type of the event classification is omitted from further analysis here as all general transient events are actual failures and are considered to be of safety significance.



a)

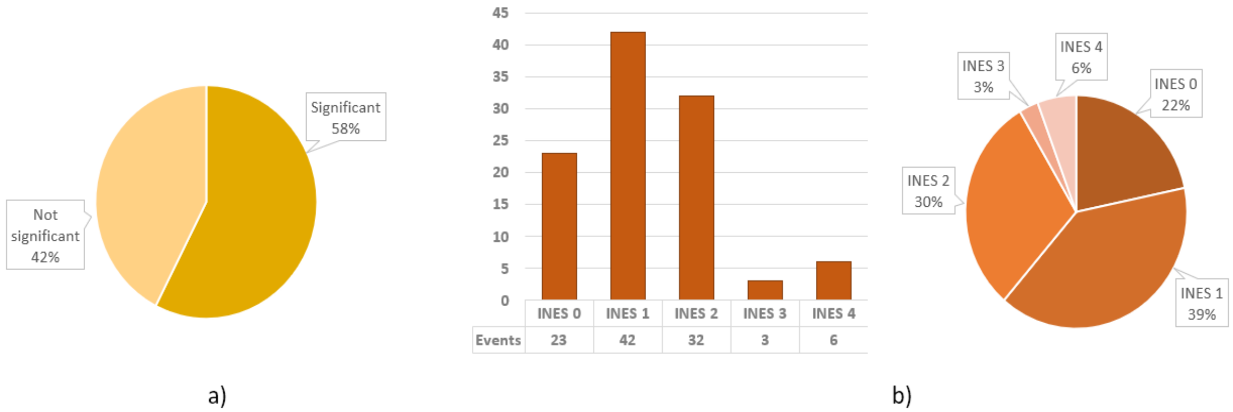
b)

c)

Figure 37. Statistical data for the general transient events: a) origin of the events; b) causes behind the events; c) operating mode of the reactors for the duration of the events.

General transients can have varying degrees of severity, from minor incidents to real accidents. In fact, transients have been the cause for 6 out of the 7 INES 4 events in the database. When discussing the safety significance of these events, the criteria from section **2.2.1** is used, according to which general transient events with complications (e.g. simultaneous unavailability of a safety system) are considered to be significant events. The total number of these events in the database is 61, or 57.5% of total general transient events. The remaining 45 (42.5%) were transients without complications, and as such had limited safety significance (**Figure 38a**). The classification of general transients according to their Core Only INES criterion is presented in **Figure 38b**.

The contributing factors for general transients will not be covered in this section due to the fact that these events can be caused by many different system failures, so identifying all of the contributing factors can be very challenging. This kind of analysis is expected to be included as part of the future work on the database.



a)

b)

Figure 38. Significance of general transient events: a) percentage of significant events; b) breakdown of general transient events according to their Core Only INES scores

3.4.3 Initiating event: Small break loss-of-coolant accident (SBLOCA)

Small break loss-of-coolant accidents (SBLOCAs) are the third most numerous type of initiating event, and they account for 31 events, or 8.4% of all initiating events in the database. These events can have very severe consequences, therefore preventing or mitigating them is of the upmost importance. The number of events over time is presented in **Figure 39**. As these events are rare in recent years, there was no incentive in doing a plot of normalized values. From the figure, it can be observed that the majority of SBLOCAs have occurred before 1995, as there has been only one recorded event in the last 24 years. The most probable reasons for this decreasing trend are the increased durability of components, piping, improved designs and revised procedures based on operating experience. Additionally, a very important factor is the Three Mile Island 2 accident of 1979, which triggered a series of revisions and updates across the operating reactors in the world.

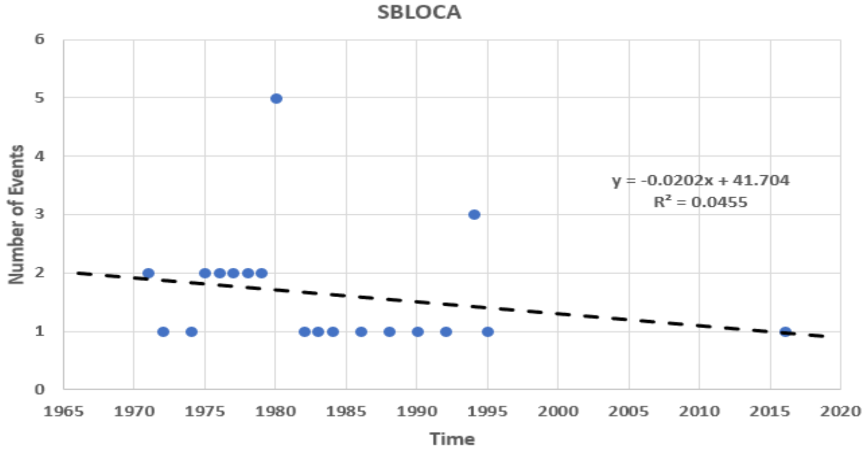


Figure 39. Number of events resulting in a small break loss-of-coolant accident over time.

When discussing the origin of the events which resulted in a SBLOCA, 24 events (77.4%) originated from the nuclear island, while 7 (22.6%) from the secondary part (**Figure 40a**). The causes of these events were classified as follows: 24 events (77.4%) were caused by technical errors, 4 events (12.9%) by plant personnel errors, while both errors accounted for 3 events (9.7%) (**Figure 40b**). Out of the 31 events resulting in a SBLOCA, 26 (83.9%) occurred while the plant was at stable power, 2 (6.45%) while the plant was in a transitory state, 2 (6.45%) while the plant was in cold shutdown and for 1 event (3.2%) the mode of the plant could not be determined (**Figure 40c**).

The type of the event and event significance classification are omitted from further analysis as all events resulting in a SBLOCA are actual failures and are considered to be of safety significance.

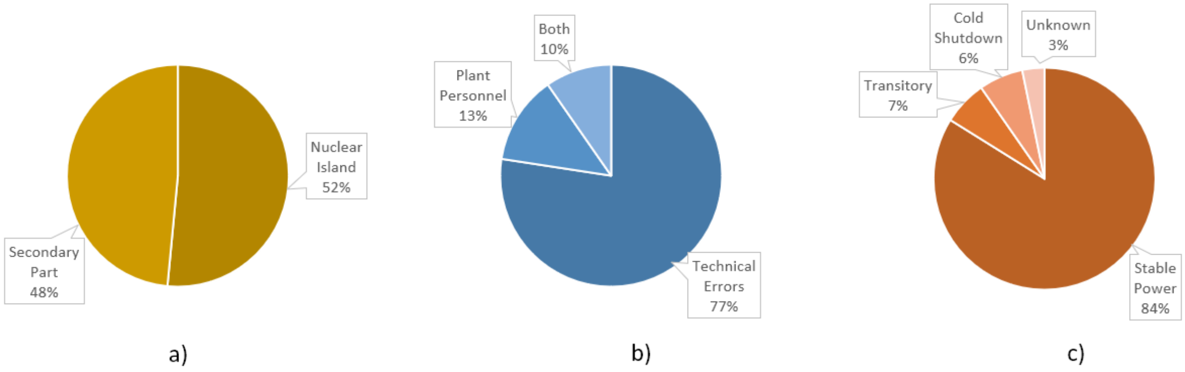


Figure 40. Statistical data for events resulting in small break loss-of-coolant accidents: a) origin of the events; b) causes behind the events; c) operating mode of the reactors for the duration of the events.

SBLOCAs are regarded as very serious events, which can result in severe consequences. The classification of these events based on their Core Only INES scores is presented in **Figure 41**.

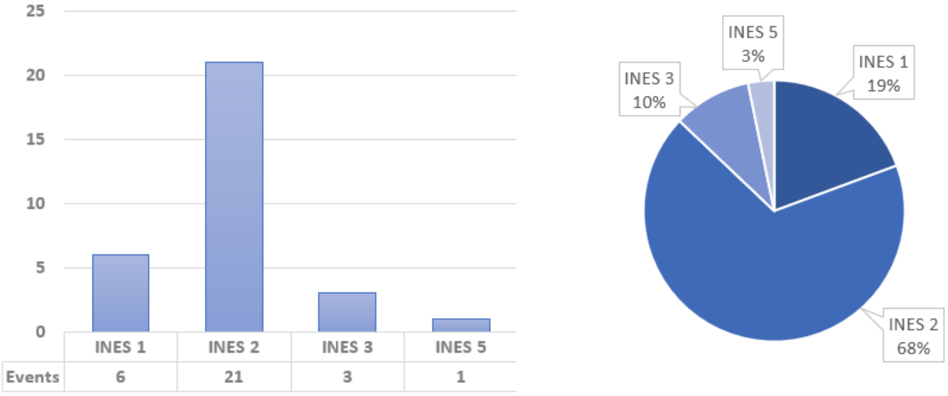


Figure 41. Small break loss-of-coolant accident events based on their Core Only INES scores.

In order to properly determine the contributing factors, the most common component failures leading to SBLOCAs need to be identified. Out of the 31 events currently in the database, stuck open pilot operated relief valves (PORVs) at PWRs were the reason for 10 events (32.3%), stuck open safety relief valves (SRVs) at BWRs were the cause for 7 events (22.6%), pressure pipe cracks occurring mostly at PHWR reactors contributed to 7 events (22.6%) and liquid relief valve (LRVs) failures at the same reactor types contributed to 3 events (9.7%). The remaining 4 events (12.9%) were caused by failures of other components, such as cold/hot leg piping, chemical and volume control system, etc. (**Figure 42a**).

The factors that have in any way contributed to the occurrence of the events include: frontline failures which contributed to 16 events (51.6%), testing and maintenance errors contributed to 5 events (16.1%), design residuals to 4 events (12.9%) and support system failures which contributed to 2 events (6.5%). The remaining 4 events (12.9%) had other contributing factors (**Figure 42b**).

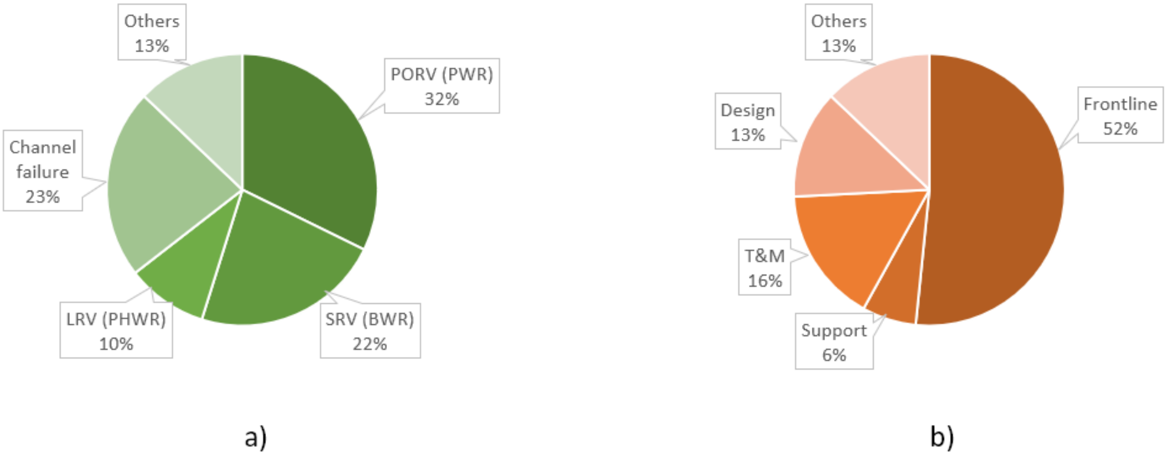


Figure 42. Contributing factors for small break loss-of-coolant accident events: a) number of events based on the component failures; b) breakdown of the contribution of different factors in the occurrence of these events.

3.5 Dominating safety system/component failures

As mentioned in **3.4**, pure system/component failures (which do not contain an initiating event) are the dominating group, with 559 events, or 60.1% of the total 930 events. The number or recorded system failures per year and the normalized values are presented in **Figure 43**. It can be observed that the number of system/component failures has been steadily increasing over time. The reason for the increase is the general increase of reportable events in the database.

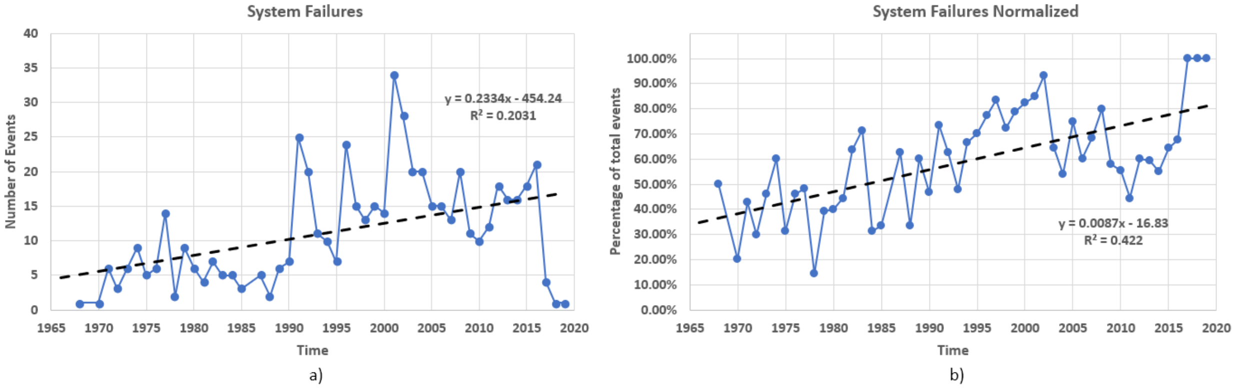


Figure 43. Number of system/component failures over time: a) number of events per year; b) contribution of system failures to the total number of events per year.

When discussing the origin of pure system/component failure events, 352 events (63%) originated from the nuclear island, 186 (33.3%) originated from the secondary part, 2 (0.3%) were events caused by external factors and 8 events (1.4%) had a shared origin between two boundaries. The origin of the remaining 11 events (2%) could not be determined (**Figure 44a**).

The causes of the system/component failure events are distributed as follows: 350 events (62.6%) were caused by technical errors, 170 events (30.4%) by plant personnel errors, while both errors accounted for 21 events (3.8%). The causes for the remaining 18 events (3.2%) could not be determined due to the lack of information (**Figure 44b**).

The type of the event for the system/component failures include: 318 (56.8%) actual events, 229 (41%) potential failures, and 6 (1.1%) what had a dual type of event. The type could not be determined for the remaining 6 events (1.1%) (**Figure 44c**).

Out of the 559 system failures, 242 events (43.3%) occurred while the plant was at stable power, 45 (8%) while the plant was in a transitory state and 116 (20.8%) while the plant was in cold shutdown. The mode of the plant for the remaining 156 events (27.9%) could not be determined (**Figure 44d**).

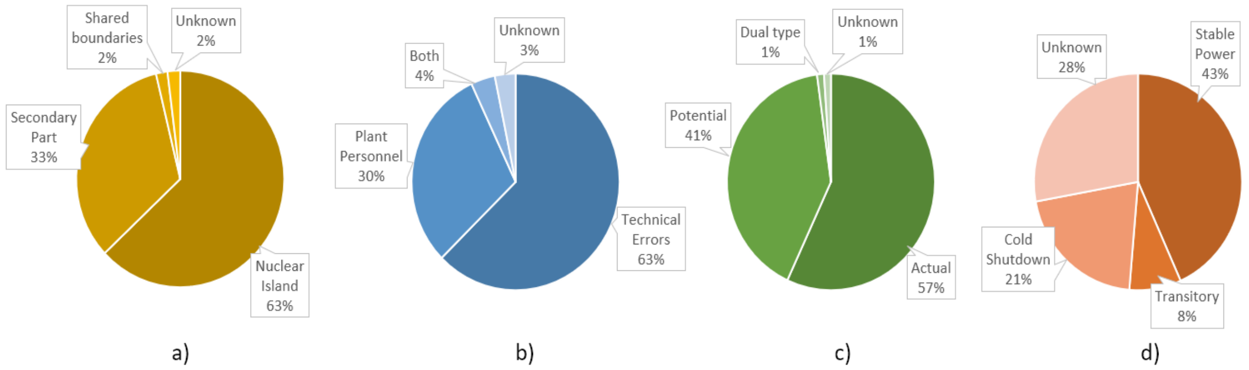


Figure 44. Statistical data system/component failure events: a) origin of the events; b) causes behind the events; c) type of the events; d) operating mode of the reactors for the duration of the events.

The significance of the system/component failures was depicted in **Figure 29**, where it was presented that 258 events (46.2%) are considered to be significant, while the remaining 301 events (53.8%) are not safety significant. The number of events based on their Core Only INES scores is presented in **Figure 45**.

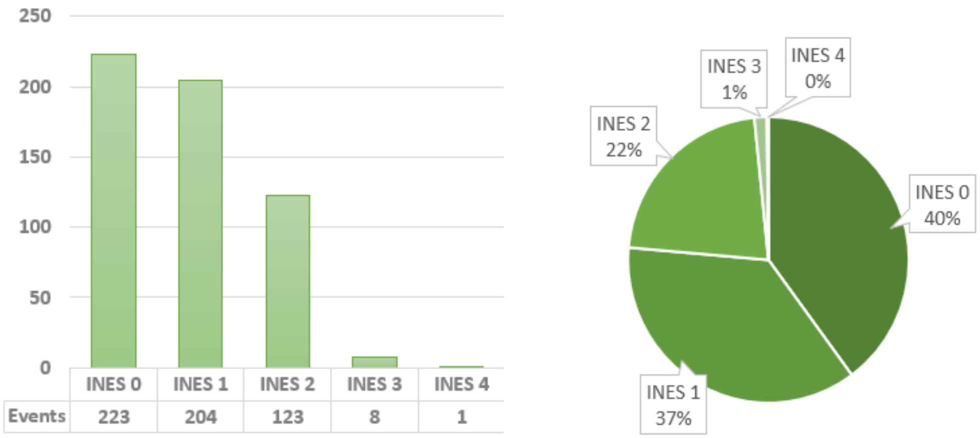


Figure 45. Number of system/component failures based on their Core Only INES scores.

It can be concluded that the majority (more than 77%) of system/component failures are anomalies (INES 1) or events with no safety significance (INES 0). Incidents (INES 2) are fairly common, while serious incidents (INES 3) and accidents are extremely rare (approximately 1%). There has only been one accident attributed to a system failure – the Beloyarsk accident of 1977 which was previously mentioned. It should be stated that information for this accident is scarce, and in light of new information this classification might be altered.

3.5.1 Contributing factors of safety system/component failures

The contributing factors discussed in **2.3** can be used to highlight all factors which have in any way contributed to a system or a component failure event. As stated before, the contributing factors are not always equivalent to the cause of an event. In this section, the contributing factors will be presented based on the number of occurrences in the events. Two types of occurrences will be discussed: total and unique occurrences. The total occurrences of a contributing factor refers to the absolute number of times the discussed factor has occurred in all of the discussed system failure events. One system failure can have multiple contributing factors, meaning that they are not mutually exclusive. Unique occurrences refer to the number of times one factor was the only contributor to the event. The complete list of these factors is presented in **Table 2**.

It can be observed that the total occurrences are always compared to the total number of events, as they are not mutually exclusive (they will not sum up to 100%), while the unique occurrences are mutually exclusive. The overlapping of factors in the unique occurrences is presented with the number of shared factors. From the table, it can be concluded that the factor with the highest contribution are design residuals with 148 unique occurrences (26.5%) and 182 total occurrences, followed by testing and maintenance errors with 82 unique (14.7%) and 119 total occurrences. A total of 144 events (25.7%) did not have any contributing factor, while 72 events (12.9%) had shared contributing factors.

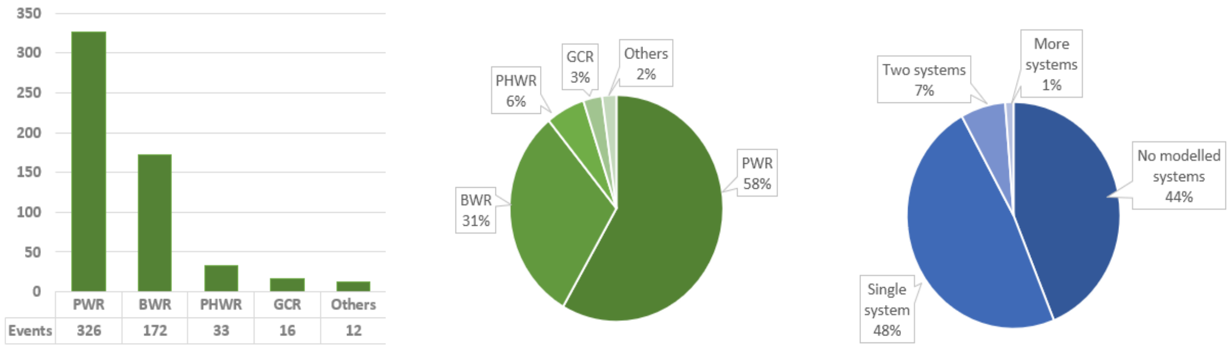
Table 2. Contributing factors in system/component failure events.

Contributing factor	Total occurrences	Percentage [%]	Unique occurrences	Percentage [%]
No contributing factor	144	25.7	144	25.7
Shared factors	72	12.9	72	12.9
System level				
Design residuals	182	32.6	148	26.5
Safety culture	44	7.9	11	2
Common cause residuals	21	3.8	21	3.8
Procedural errors	20	3.6	12	2.1
Automatic actuation failure	5	0.9	5	0.9
Unavailability due to T&M	18	3.2	1	0.2
Train level				
T&M errors	119	21.3	82	14.7
Operator errors	21	3.8	10	1.8
Frontline failures	65	11.6	41	7.3
Support system failures	28	5	12	2.1

3.5.2 Most commonly affected safety systems/components

The most common system failures will be discussed with regards to the reactor type of the plant. The distribution of events based on their reactor type is presented in **Figure 46a**.

The system failures are modeled with the failure sequences feature presented in section **2.4**. One event can have multiple system failures, meaning that an overlapping of system failures can occur which will further complicate the counting of system failures. For that reason, a similar approach to the counting of contributing factors will be presented, in which the system failures will be counted based on their total and unique occurrences. Primarily, the events will be filtered out based on the number of system failures which occurred.



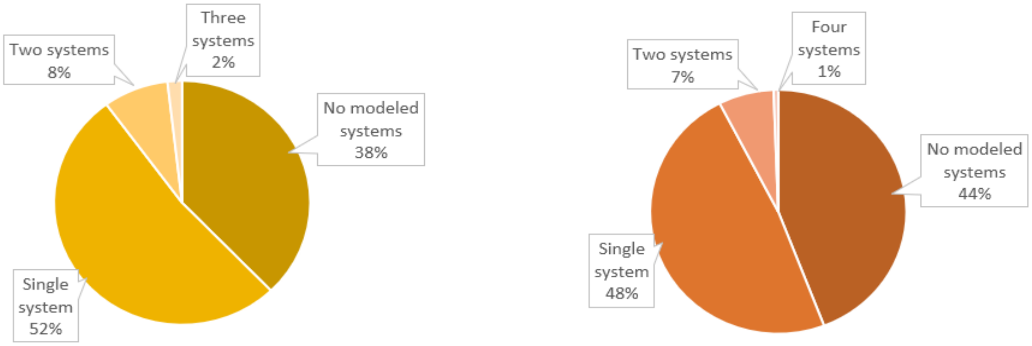
a) b)

Figure 46. Number of safety system/component failure events based on: a) the reactor type; b) number of affected systems.

Out of the 559 system/component failure events, in 269 events (48.12%) only one safety system/component was affected, while in 38 (6.8%) two systems/components were affected. Events in which three systems were affected are rare, with only 6 (1.1%) of the total recorded events, while only 1 event (0.2%) has been recorded with four affected systems. The remaining 245 events (43.8%) had no modelled affected systems/components (**Figure 46b**). Due to the fact that different reactor types have different safety systems, we will only discuss the most commonly affected safety systems in PWRs and BWRs, as they are the most common reactor types in the world.

It should be noted that systems that are currently modeled in the database are presented in **Table 3** in the Annex. Other systems which are affected during the events are taken into account, but they will always appear in the statistics as "No modelled systems". These systems include: service water system, plant electrical systems, DC power, etc. However, a complete loss of some of these systems is taken into account and they are modelled as initiating events.

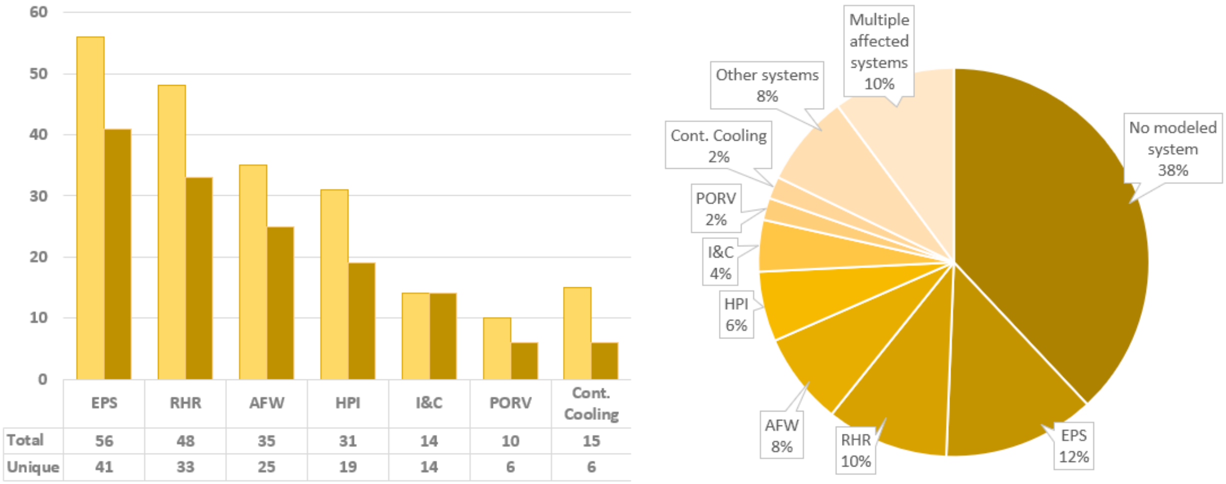
A total of 326 events, or 58.3% of the safety system failure events have occurred at PWRs. Out of these, in 171 events (52.5%) only one safety system/component was affected, in 27 events (8.3%) two systems or components were affected, while in 6 events (1.8%) three systems were affected (**Figure 47a**). No systems were affected in 124 events (38%).



a) b)

Figure 47. Number of affected safety systems/components in the events occurring at: a) pressurized water reactors (PWRs); b) boiling water reactors (BWRs).

The data shows that the most commonly affected systems/components in PWRs is the emergency power system (EPS) with 56 total occurrences and 41 unique occurrences (12.6%), followed by the residual heat removal system (RHR) with 48 total and 33 unique occurrences (10.1%). The complete list is presented in **Figure 48**.



	EPS	RHR	AFW	HPI	I&C	PORV	Cont. Cooling
Total	56	48	35	31	14	10	15
Unique	41	33	25	19	14	6	6

Figure 48. Most commonly affected safety systems/components in PWRs.

It should be noted that for this analysis, large systems such as the emergency core cooling system (ECCS) which contain multiple sub-systems (high-pressure injection, RHR, etc.) are considered to be very broad and are therefore broken down to their comprising components (simplified schematic presented in **Figure 51** in the Annex, while a more detailed schematic is presented in **Figure 52**). If the ECCS was considered as one system, it would be the most commonly affected system in PWRs.

The number of safety system/component failure events that have occurred at BWRs is 172, or 30.8% of the total failures. Out of these, in 83 events (48.2%) only one safety system/component was affected, in 12 events (7%) two systems or components were affected, while in 1 event (0.6%) four systems were affected. In the remaining 76 events (44.2%) no modeled systems were affected (**Figure 47b**). Similar to the data for PWRs, the most commonly affected system in BWRs is the emergency power system (EPS) with 29 total and 27 (15.7%) unique occurrences, followed by the RHR system with 20 total and 18 (10.5%) unique occurrences. The complete list is presented in **Figure 49**.

The same argument can be made regarding the emergency core cooling system (ECCS) in BWRs. If the ECCS is considered as one system comprised of the RHR and high-pressure coolant injection (HPCI) system, it would be the most commonly affected system. Additionally, the safety relief valves (SRVs) which technically are part of the automatic depressurization system (ADS) can be considered in the statistics for this system, leading to a total number and unique number of 13 events (7.6%). The reason why the SRVs are considered separately is to increase the level of detail when modeling these components, as they are of high importance for the safety of the plant.

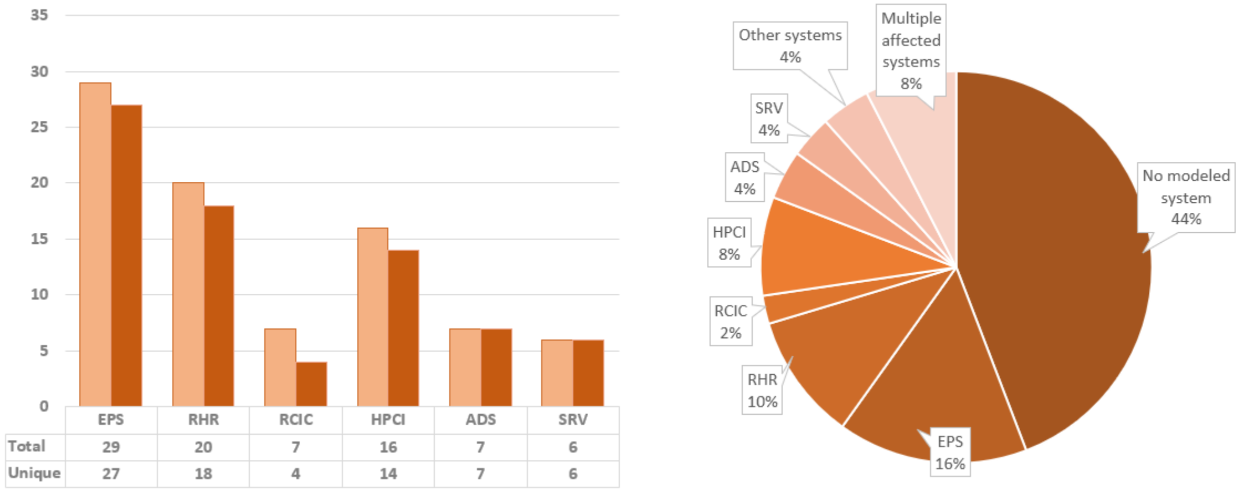


Figure 49. Most commonly affected safety systems/components in BWRs.

Abbreviations for safety systems used in this section which were not explained in the text include:

AFW – Auxiliary feedwater system

I&C – Instrumentation and control system

PORV – Pilot operated relief valve

Cont. Cooling – Containment cooling system

RCIC – Reactor core isolation cooling system

Chapter 4. Conclusions and Future Work

In this thesis, the motivation behind the "ETHZ curated nuclear events database" was presented, along with its structure and features. With more than 1000 events, we strive towards building the most comprehensive open nuclear events database in the world, that can be used as an invaluable source of information of practical use and for future scientific work worldwide, as well as an information tool for the general public (access link for the database: http://er-nucleardb.ethz.ch/). The database is an enhanced version of the one presented in [1], where many old features were revised, new features were added, and more than 160 new events were included. Each currently included event is analyzed using the classification criteria outlined in **Chapter 2** and the data is presented in an accessible manner. Analyzing this large number of events from the database supported the existing PSA philosophy of reductionism and causal chains proving that the methodology is robust enough to describe a huge set of different operational experiences.

Using this data, a general statistical analysis was performed and presented in the previous section where multiple topics were explored such as: determining the number of events per country, determining the origin, cause, type and reactor mode of the events, the INES scores, significance and the number of significant events over time, determining the dominating initiating events and system failures etc. From this analysis, multiple conclusions were drawn and presented, the main being that:

- The number of reported events is increasing over time mainly due to the increased number of operating reactors as well as the more transparent exploitation of nuclear power by the majority of countries.
- The reactor type with the highest number of events per reactor are BWRs with 2.5 events per reactor, followed by PWRs with 1.5 events per reactor.
- The country with the highest number of included events is the USA with 4.05 events per reactor in 62 years of exploiting nuclear power.
- The number of significant events is steadily decreasing over time, indicating the increase of the general safety of nuclear power plants.
- The number of nuclear accidents has been greatly reduced, however, beyond design basis events can still challenge the modern nuclear plants and have severe consequences.
- Technical errors are the dominating cause of events, although they have been on the decline in recent years, while the contribution of plant personnel errors appears to be increasing.
- There is a general decline in the number of reported initiating events over time, while the share of system/component failures is increasing, especially potential/hidden failures (latent errors).

The information presented in this thesis and the trends which were discussed should be considered as rough estimates used to observe tendencies in certain areas of importance for the safety of nuclear power plants. The analysis is performed only on events which are included in the database, and we do not claim to be complete in including all publicly available events. Upgrading of the database, including inputs/comments from the future users, is a continuing effort and additional events will be constantly included.

In addition to the inclusion of new events, the future work will include: further developing the contributing factors and failure sequences features, mapping out the contributing factors for all initiating events, identifying the contributing factors for each system (currently only unique contributing factors are identified), trend analysis of the contributing factors, detailed analysis of the failure frequency of every safety system both in initiating events and system failures as well as uncertainty analysis, precursor analysis using the features of the database, etc.

ANNEX

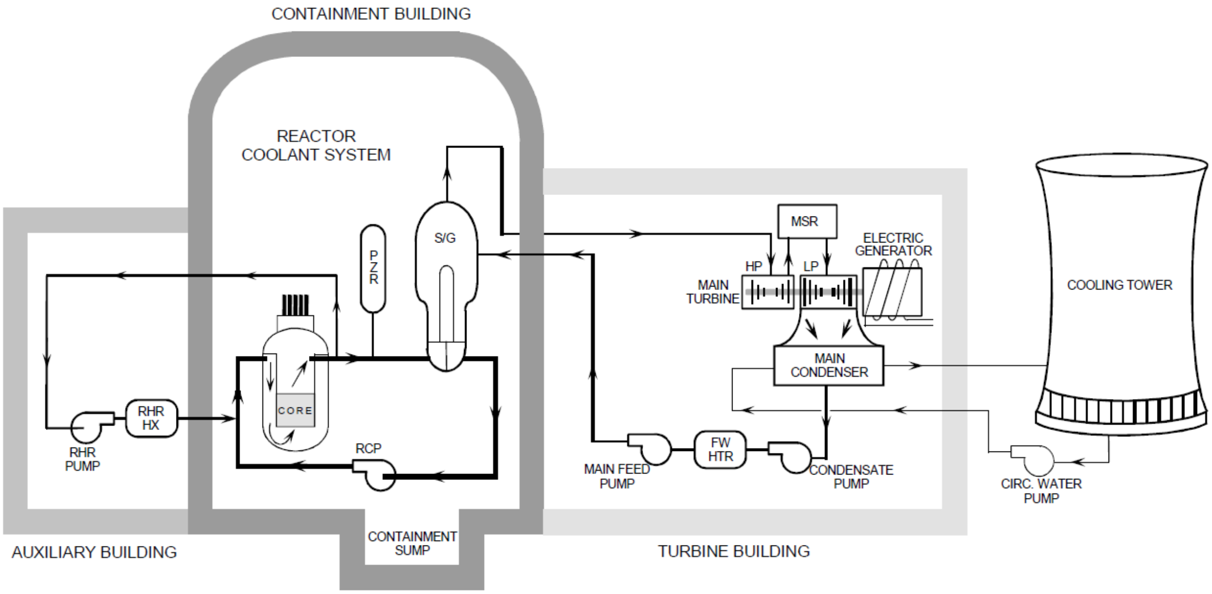


Figure 50. Schematic of a pressurized water reactor (PWR) [16]

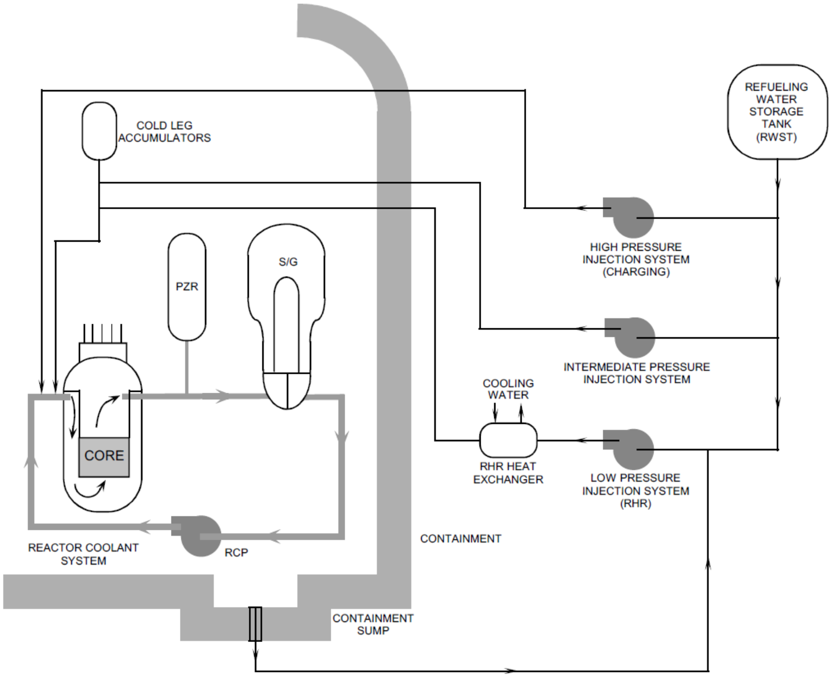


Figure 51. Simplified schematic of the emergency core cooling system (ECCS) of a PWR [16].

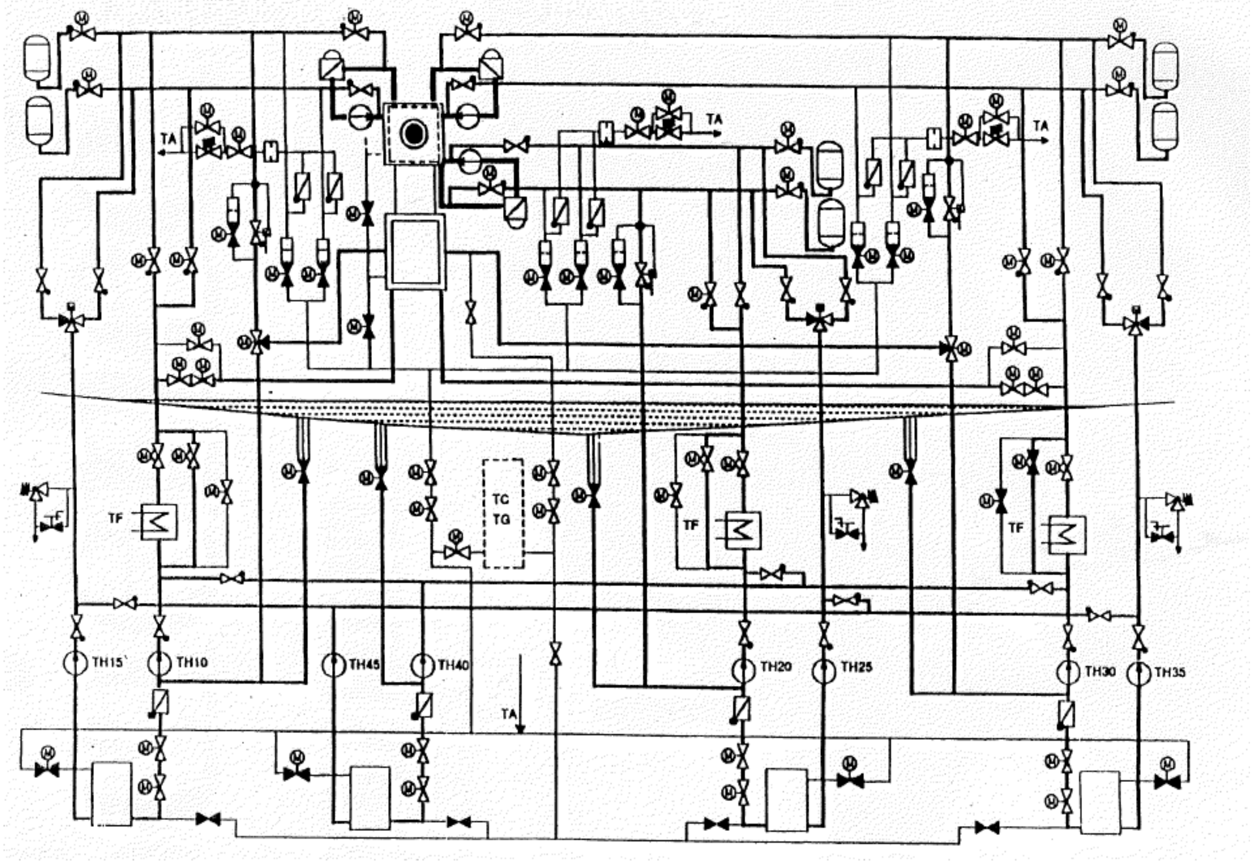


Figure 52. Detailed schematic of the emergency core cooling system (ECCS) of a PWR with 4 redundant trains [17].

Table 3. Modeled initiating events and safety systems in the ETHZ curated nuclear events database

Initiating Events	Safety Systems	Non-safety related system
Large Break Loss-of-Coolant Accident (LBLOCA)	Instrumentation and Measurement	Main feedwater
Medium Break Loss-of-Coolant accident (MBLOCA)	Auxiliary Feedwater	Ultimate Heat Sink
Small Break Loss-of-Coolant accident (SBLOCA)	Pilot Operated Relief Valve (PORV)	Offsite Power Systems
Loss of Offsite Power (LOOP)	High-Pressure Injection (HPI)	
Steam Generator Tube Rupture (SGTR)	Residual Heat Removal (RHR) System	
Steam Line Break	Emergency Power System	
Ultimate Heat Sink Failure	Containment Cooling	
Fire Internal	Boration (PWR)	
Fire External	Liquid Control (BWR)	
Flooding Internal	Reactor Core Isolation Cooling (RCIC) - BWR	
Flooding External	Isolation Condenser	
Earthquake	High Pressure Coolant Injection (HPCI) BWR	
Loss of Service Water	High Pressure Core Spray (HPCS) BWR	
Loss of Feedwater (BWR)	Safety Relief Valve (BWR)	
Transient	Primary Containment Suppression Pool (BWR)	
Airplane Crash	Steam Isolation System	
Loss of Main Feedwater (PWR)	Turbine Bypass System	
DC Power Loss	Reactor Trip System	
Reactivity Induced Accident (RIA)	Automatic Depressurization System (ADS) - BWR	
Loss of Component Cooling Water	Containment Depressurization System	
	Atmospheric Dump Valves	
	Maintenance Cooling System (PHWR)	
	Safety Shutdown System (PHWR)	
	Liquid Relief Valve (PHWR)	
	Emergency Core Cooling System (LWGR)	

Proposal for a Master Student's Thesis

Intensively **learning from experience** is an important goal to verify and improve the level of safety of any industrial facility, and of nuclear power plants in particular. To support this critical endeavor the Chair or Entrepreneurial Risks has established a **comprehensive open access database** on incidents and accidents in nuclear facilities worldwide, from early days until recently. The database comprises roughly 1'000 events and includes information about the power stations involved such as the power level (full power or non-full power), the experienced chain of events and underlying mechanisms, the origin: either primary or secondary circuit/either inside or outside the plant, and the type of the triggering events: either technical, human, or organizational.

We have started to use the database for trend analyses, gaining more general insights, and notably, for precursor analysis to complement traditional probabilistic safety analysis (PSA). By doing so we have realized that the hitherto existing characterization of the initial power level, the origin of the events, the type of trigger, and maybe others are by far too general and need to be broken down into further details. For example, the distinction between "inside" (primary or secondary circuit) and "outside" the plant does not sufficiently capture the crystalized importance of sufficient electric power supply, i.e. loss of offsite and/onsite power (island operation after disruptions) and loss of emergency AC and DC power.

Therefore, scientific efforts are needed to **make the existing characterization of events more precise** and ease the evaluation of the information compiled. Specific tasks are foreseen and are as follows:

1. Make initial power level more precise (important for decay-heat removal requirements), e.g., by distinguishing different kinds of non-full power operations: before and after shut down for revision.
2. Scrutinize the origin of the event and make it more detailed, e.g., primary or secondary circuit, which system/train, started outside and moved in, electric fault, etc…
3. Check and categorize if the component that failed in the database is safety relevant, or part of the safety mitigation systems? Or is normal operation component? Or what?
4. Understand the specific role/layout of AC and DC power supply for safety systems including instrumentation and control.
5. Characterize the type of initiating event or failure (e.g., technical real or anticipated, human during operation, maintenance, re-start after shut down, organizational at different levels, all).
6. How to deal with hidden failures (degraded safety systems) during operation, identified during maintenance, false adjustment of system after revision or testing. Are they precursors if coupled with other events?
7. Group similar events, and match subsequences of events, e.g., see if for the same sequences plants have arrived to different states. Why at one plant the consequences were mitigated while at another not, what did go wrong in one and not in another?

The candidate is expected to be interested in -and knowledgeable of- basics of electrical and mechanical engineering and will become integrated into a small team and supervised by respective experts.

Contact person:
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PhD researcher, Entrepreneurial Risks Lab

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