Transactions of the SMiRT 27
Yokohama, Japan, March 3-8, 2024
Division VII

SAFETY ASSESSMENT OF NUCLEAR INSTALLATIONS AGAINST EXTERNAL EVENTS BASED UPON INNOVATIVE EVENT ANALYSIS AND A NEW SET OF METRICS FOR ROBUSTNESS AND RESILIENCE

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ABSTRACT

Natural hazards such as earthquakes, floods or wildfires may seriously challenge nuclear installation safety. Therefore, it is crucial not only to predict such events and calculate their magnitude, but also to evaluate the response of nuclear installations to those events. Lessons learned through studying the response of installations to real hazards can provide insights into previously unknown failure mechanisms and can lead to improved safety of nuclear installations worldwide. To this end, the IAEA has launched the External Events Notification System (EENS). The EENS provides real time alerts on natural phenomena hazard events that may impact nuclear installations worldwide. It provides a quick look at the damage potential to nuclear installations and supports the IAEA Emergency Centre with these data. The data are collected in a database which can be used for further assessment and lesson learnt analysis. The EENS provides the foundation for a proactive event analysis program, based on accident reports, but primarily focused on the analysis of records of near-misses collected everywhere in the world and of all types (meteorological, hydrological, fire-related, earthquakes, etc.). This paper presents the results of recent efforts by the IAEA on the analysis of external events supported by the EENS, oriented to the development of hazard evaluation and design methods (risk informed performance based) for evaluating the impact of beyond design basis events and human-induced events on plant safety, its robustness and resilience.

INTRODUCTION

Natural hazards such as earthquakes, floods or wildfires may seriously challenge nuclear installation safety. Therefore, it is crucial not only to predict such events and calculate their magnitude, but also to evaluate the response of nuclear installations to those events. Lessons learned through studying the response of installations to real hazards can provide insights into previously unknown failure mechanisms and lead to improved safety of nuclear installations worldwide. To this end, the IAEA has launched the External Events Notification System (EENS). The EENS is based on a multi-hazard monitoring and early warning platform and has been developed in collaboration with the University of Hawaii's Pacific Disaster Centre (PDC). It is a system that is permanently available to provide 24/7 support to the IAEA. Data collected by EENS will be placed in a database which can be used for additional analysis.

The data collected by EENS provides a basis for investigating what can fail during natural phenomena hazards. Design provisions today are largely based on past experiences. Structures, systems, and components are designed for loads and load combinations that may occur, but there may be some load combinations or effects that are overlooked. An in-depth examination of what can possibly go wrong, based on the response of structures, systems, and components to real events provides insights into what can possibly go wrong. Design and evaluation for these rare occurrences will help to prevent or mitigate accidents in the future.

In the aftermath of the Fukushima Daichi accident, appropriate mitigation measures have been implemented in many countries, reducing the likelihood of core damage and radiological releases. However, it was highlighted on many occasions that learning from accidents has to be associated with learning from near-misses in a much more proactive mindset in order to develop a generic approach to the assessment of the inherent safety features of operating and licensed plants.

The newly available EENS at the IAEA provides an excellent basis for a proactive event analysis programme, still based on accident reports, but primarily focused on the analysis of records of near-misses collected everywhere in the world and of all types (meteorological, hydrological, fire-related, earthquakes, etc.).

This paper presents the results of recent efforts by the IAEAon the analysis of external events supported by the EENS, oriented to the development of hazard evaluation and design methods (risk informed performance based) for evaluating the impact of natural phenomena hazards and human-induced events on plant safety, its robustness and resilience. The post Fukushima effort in many nuclear power plant operating countries highlighted the interest to calculate the safety margin available in structures, systems and components in relation to beyond design basis events. That safety margin to failure (or inoperability) is essential to assure the operating organization that cliff-edge effects are "far" from the operating conditions and that enough margin is available to accommodate for unanticipated scenarios. The current practice suggests an assessment of such margin, but only in a few cases is an acceptable limit provided, and the practice is quite uneven. In addition to that, a consolidated approach to a suitable metric for safety margin is not available in the engineering community. The paper discusses recently developed definitions for concepts such as "robustness" and "resilience" and provides an overview of the experience in operating countries in the margin assessment, also on the basis of the feedback of experience from recent events.

THE EXTERNAL EVENT NOTIFICATION SYSTEM

The EENS provides real-time (not later than 30 minutes) Event Notification Reports (ENR) pertaining to natural events to the EESS and IEC of the IAEA for immediate action on event review, assessment on possible damage to nuclear installations and major population centres (with more than 50k inhabitants). The reports may also be provided to the affected operators, regulators and communities.

The ENRs include information on the external event (severity, location, date\time, etc.) and the estimation of the potential damaging effects on nuclear installations (Nuclear Power Plant (NPP), Research Reactor (RR) and Fuel Cycle Facilities (FCF)) and major population centres where nuclear sources may be hosted.

Overall Architecture of EENS

The EENS is composed of two main modules, namely the Alert System (AS) and the External Event Damage Forecast (EEDF). The EENS collects data and reports on the most challenging external event scenarios, such as: earthquakes, volcanoes, high winds, tsunamis, coastal flooding, river flooding and wildfire.

The AS module is expected to watch the whole globe in real time to record the onset of significant external events, with trigger values on their severity and destructive potential. The EENS architecture is described in Fig.1.

The AS module is expected to hand over to the EEDF the following information:

– Characteristics of the external event (e.g. earthquake magnitude, epicentre, etc.)

– Hazard map of the external event in space and time (e.g. intensity map for earthquake, wave propagation map for tsunami, etc.)

Based on the information from the AS module, the EEDF module produces a preliminary prediction of the hazard levels and potential damage on nuclear installations and major population centres due to external events, generates an ENR and sends it timely to the EESS/IEC of the IAEA.

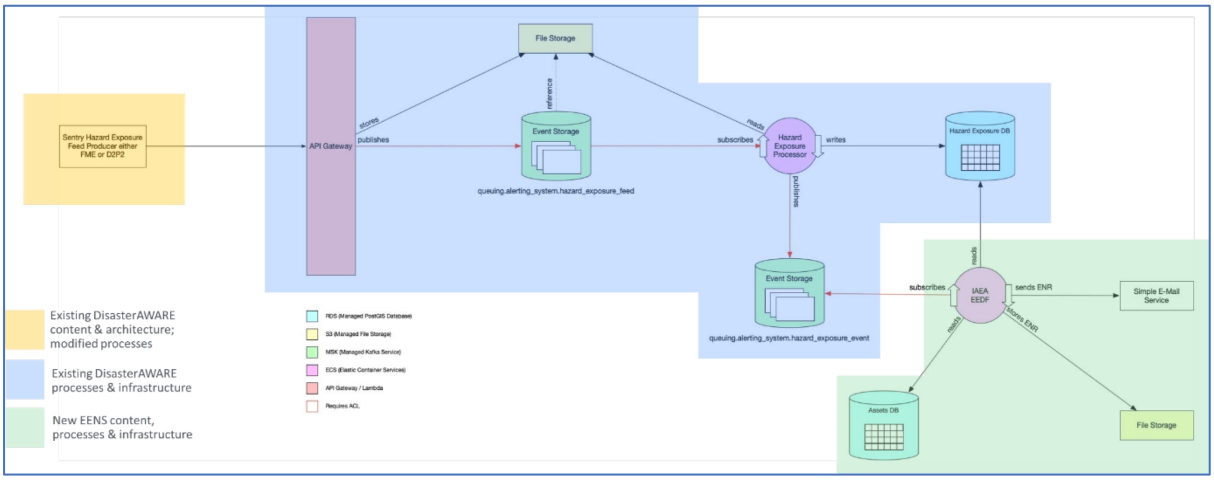

Figure 1. EENS Cloud-hosting Architecture (Amazon Web Services, AWS) depicting the two main components:1) existing Alert System (AS) hosted and operated by PDC, and 2) customized External Events Damage Forecast (EEDF) module hosted by IAEA. The two AWS environments are securely accessible by each other.

All external events modules, namely earthquake module, volcano module, high wind module, tsunami module, river flooding module and wildfire module are provided in both AS and EEDF modules for the respective functions.

The locations of all nuclear installation sites are available in the EENS, together with the location of major population centres.

Overall Functional Requirements of EENS and External Event Modules

In the following subsections, the specific functional and performance requirements for each external event module are described.

Earthquake module

When an earthquake occurs, the EENS generates a notification report which includes earthquake information, earthquake shake map with scale, list of nuclear installations located in in the region of the earthquake, epicentral distance to nuclear installations and an estimation of peak ground acceleration (PGA) and peak ground velocity (PGV) at the relevant/affected nuclear installation sites. The notification report also presents exceedance ratio of the design basis ground motion of nuclear installation.

The EENS sends a notification report to EESS, if the following criteria are satisfied;

–PGA ratio is greater than or equal to 0.5 at any nuclear installation site (Ratio of the predicted PGA at nuclear installation site to design basis PGA of the nuclear installation),

or

–Modified Mercalli Intensity (MMI) intensity is greater than VII for major population centre (population centre with more than 50k inhabitants). Those criteria are subject to change and can be modified as needed. More specifically, the notification report includes the following:

–Earthquake information (location, time, depth etc.),
–Image of ShakeMap and its scale,
–Name of installation sites,
–Epicentral distance (km),
–Estimated PGA (g),

–Estimated PGV (cm/s),
–MMI,
–Design basis ground motion exceedance ratio.

Volcano module

When a volcano eruption happens, the EENS generates a report with information on the volcanic activity maps including ash cloud polygons (geographic boundaries representing current and 6, 12, and 18 anticipated ash clouds, based on VAAC (Volcanic Ash Advisory Center) forecasts), volcano exposure polygons (geographic boundaries representing areas under a volcano watch or warning or exposed to the volcano) and location of the affected nuclear installation sites. EENS sends a notification report to EESS/IEC if any nuclear installation or major population centre fall within the volcano exposure areas for volcano events.

Tsunami module

When a tsunami is expected, the EENS generates a report which includes information on the tsunami source, tsunami propagation map, tsunami exposure area and tsunami travel time contours, location of the nuclear installation sites and estimated arrival time to nuclear installation sites. EENS sends a notification report to EESS/IEC, if any nuclear installation or major population centre fall within the tsunami exposure area for a tsunami event.

River flooding module

When a river flooding occurs, the EENS generates a report which includes information on the flooding sources and basin, flood propagation map, flood exposure areas, and the location of the nuclear installation sites. EENS sends a notification report to EESS/IEC, if any nuclear installation or major population centre falls within the flood exposure area for a flood event.

High winds (Tornado, hurricane, cyclone, and typhoon) module

When a rotational wind event occurs, the EENS generates a report which includes information on the high wind event, maps, wind speeds, high wind exposure areas and location of the nuclear installation sites. EENS sends a notification report to EESS/IEC, if any nuclear installation or major population centre falls within the high wind exposure area for a high wind event.

A sample of event notification report (only the AS module) is provided in Figure 2.

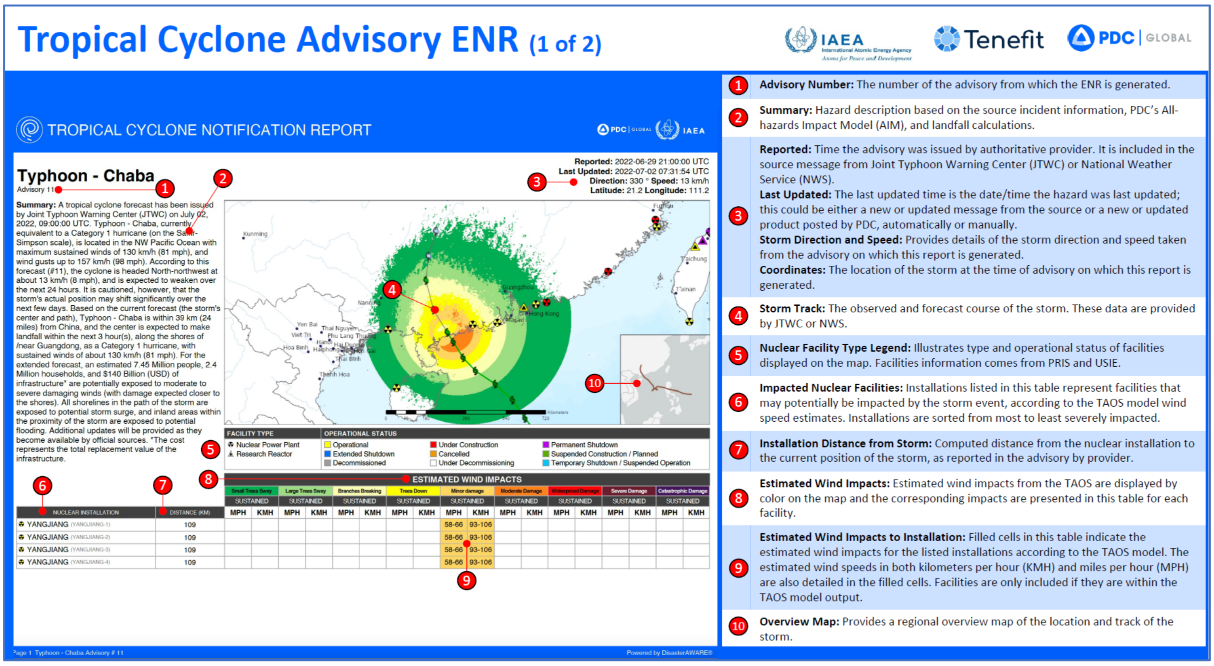

Figure 2 – Sample ENR for Tropical Cyclones

Wildfire module

When a wildfire occurs anywhere, the EENS generates a report which includes information on wildfires, a map of the wildfire exposure areas, the duration of time that the wildfire incident has been observed within the exposure polygon (fire perimeter), and the location of the nuclear installation site and fire intensity at the installation. EENS sends a notification report to EESS/IEC, if any nuclear installation or major population centre falls within the wildfire exposure area for a wildfire event.

PRELIMINARY LESSONS LEARNED

The EESS is actively advancing the framework for external event analysis, drawing insights from events recorded in the EENS system. A preliminary analysis of the lessons learned was carried out on the basis of the ENRs collected in the timeframe of 1 September 2022 to 31 May 2023, and it is presented in the following.

Cyclones

The EENS database recorded 95 instances of nuclear facilities affected by 8 cyclones, with 39 instances of operational or under construction NPPs and 56 instances of research reactors affected, as presented in Figure 3.

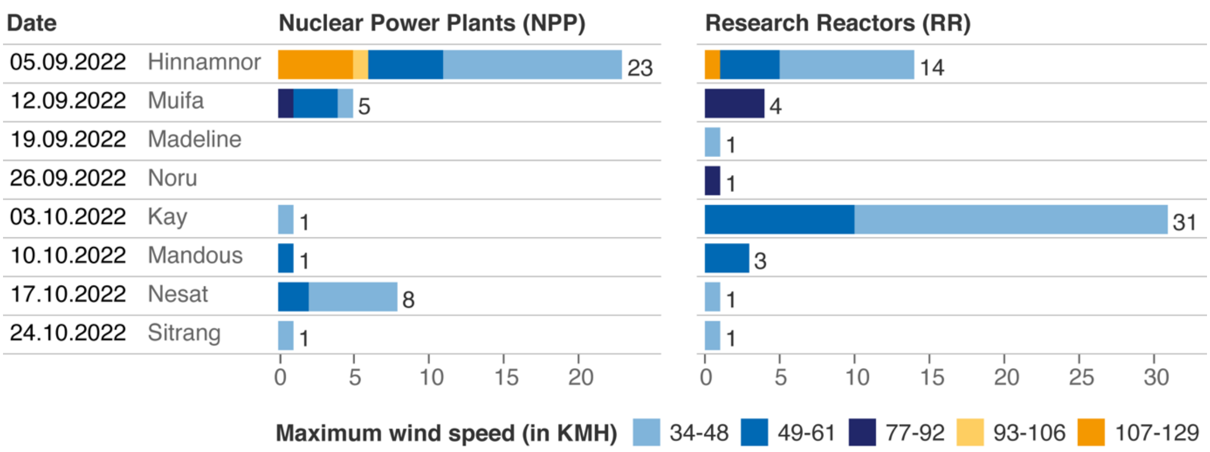

Figure 3. Nuclear Power Plants (NPPs) and Research Reactors (RR) in the active path of cyclones

One cyclone can affect many facilities at once: Cyclone "Hinnamnor", which occurred in September 2022, affected 23 NPPs and 14 RRs, with different stations experiencing varying levels of impact. (The EENS categorizes potential wind impacts into nine steps, ranging from "small trees sway" (maximum wind speed 34-48 KMH) to "catastrophic damage" (maximum wind speed of 184 KMH and more). For instance, several operational NPPs near the epicenter of Hinnamnor experienced maximum wind speeds of 107-129 KMH, which could potentially lead to moderate damage, but other facilities located further away were impacted by wind speeds of maximum 34-48 KMH, indicating no potential damage.

In 57% of all the instances recorded, the plants in the cyclone zone experienced winds with maximum speed of 34-48 KMH (least possible impact). Five instances of NPPs were impacted by a cyclone with maximum wind speed 107-129 KMH, which could lead to a potential moderate damage. However, the maximum wind speed alone does not directly indicate the impact on the nuclear power plants themselves. A more refined variable is required to measure the cyclones' actual impact on the nuclear site itself (see Fig.4).

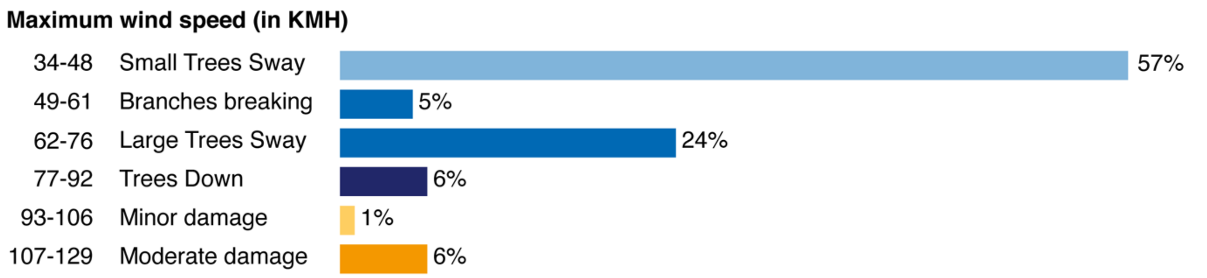

Figure 4. Cyclones by intensity

With one exception of a mild cyclone affecting a nuclear installation in USA (Palo Verde), the East Asia region was most affected, with 41% NPPs being in active cyclone zones in China, 26% in Japan and 21% in the Republic of Korea. Several NPPs in Japan (Genkai NPP) and Korea (Kori, Shin-Kori I and II, Shin-Wolsong and Wolsong NPPs) experienced cyclones with higher wind speeds of 93-129 kmh.

Earthquakes

In the timeframe between 1 May 2022 and 31 May 2023, the EENS system issued alerts for 84 nuclear facilities which may have been affected by earthquakes. The facilities potentially affected include 44 NPP in operation or under construction and 40 research reactors. The system reported on 34 potentially damaging events (see Fig.5).

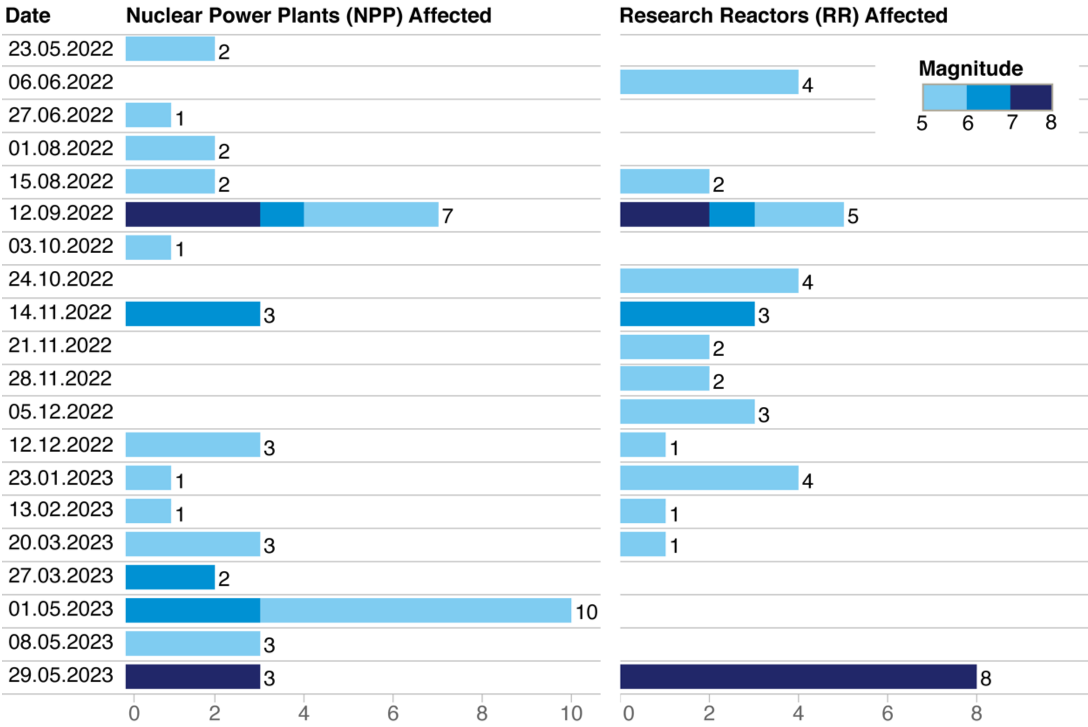

Figure 5. Earthquakes affecting Nuclear Power Plants (NPPs) and Research Reactors (RRs)

One earthquake can affect many nuclear facilities at once and have impact hundreds of kilometres away. For example, a 5.8 magnitude earthquake which happened near the west coast of Honshu (Japan) in May 2023 affected 4 nuclear facilities, such as NPP Shika (70 km from the epicentre) or Mihama and Tsuruga NPPs (224 and 232 km, respectively).

In 44 instances of NPPs being in an active seismic zone, 61% of happened in Japan and 20% in Taiwan, China. NPP Maanshan in Taiwan, China, was recorded as being affected by 9 instances of earthquakes, while Ohma, Hamaoka and Higashidori NPPs in Japan were affected 4 times.

Wildfires

In the timeframe of 1 December 2022 – 31 May 2023, 45 instances of wildfires were recorded by the EENS database in 12 countries (see Fig.6).

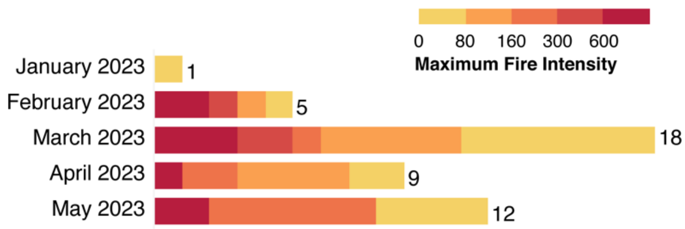

Figure 6. Wildfires by date

Of 12 countries affected, 40% of wildfires were happening in Russia, 13% in China and 11% in Laos (Fig.7).

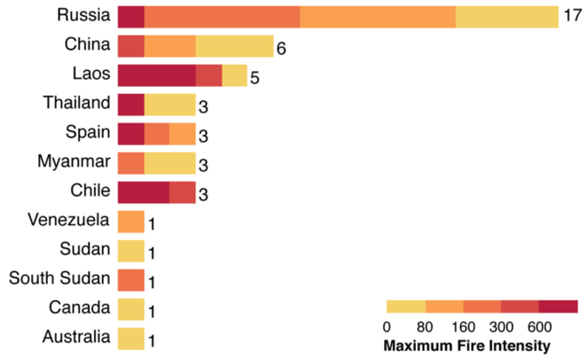

Figure 7. Wildfires by country

Wildfire monitoring continues to be crucial, as recent years saw its portion of near misses, when wildfires moved dangerously close to nuclear facilities, as in the Russian town of Snezhinsk in 2010 or forest fires around Chernobyl nuclear site in 2022.

Lessons learned

Although many nuclear facilities were impacted by natural phenomena hazard events, as summarized above, all facilities performed well and there were no radioactive releases associated with any event. Analysis of the events recorded in the EENS and review of the plant's response highlight the need for future work to increase the resilience and robustness of power plants and research reactors. Areas for improvement may include:

1. Embrace a proactive approach which would encompass near misses, comprehensive modelling for anticipating diverse scenarios, risk assessment methods, operational measures, and preparedness to manage accident consequences and business interruption in the short, medium, and long term.
2. Implement new hazard analysis techniques, including local-global time-dependent hazard models and accurate scenario anticipation modelling.
3. Develop novel risk indicators and assessment approaches, covering resilience, robustness, radiological risk, business interruption, etc., and extend performance-based risk analysis to encompass the entire production and distribution infrastructure.
4. Encourage the development of guidelines and services aimed supporting the development of contingency plans for nuclear infrastructures and their regions, supported by regional monitoring, vital area identification, risk assessment engineering, pre- and post-event operational procedures especially tailored to the risk posed by external hazard scenarios climate change related

SAFETY ASSESSMENT FOR BEYOND DESIGN BASIS EVENTS

Generic approach

Among the lessons learned from the event analysis in recent years, especially after the Fukushima Daichi accident are the importance of (1) nuclear installation design margins against external natural hazards exceeding those selected for the design basis, i.e., the calculation of design robustness able to accommodate unanticipated event scenarios, (2) adequacy of design margins to avoid cliff edge effects, and (3) independence of different levels of defence in depth. IAEA Safety Standards Series No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design, introduced specific safety requirements for a robust nuclear power plant design based on these lessons.

In the following, information is provided on the activities in place at the IAEA to support the compliance with the requirements established in the following IAEA Safety Standards Series publications: No. SSR-2/1 (Rev. 1), Safety of Nuclear Power Plants: Design; No. SSR-3, Safety of Research Reactors; and No. SSR-4, Safety of Nuclear Fuel Cycle Facilities.

In a technical document (TECDOC) under publication at the IAEA, it is made clear that design robustness against external hazards can be expressed in term of adequacy of design margins against external events exceeding the design basis. The margin assessment is performed at the nuclear installation level to determine its capability to perform the intended fundamental safety functions. The margin assessment needs to be performed within the defence in depth (DiD) framework and, therefore, the margin adequacy requirement may be different at each level of defence. Failure events that involve cliff edge effects require special consideration in assessing their seismic margin.

In practice, assessing the available margins resulting from the design is not a trivial task. The traditional design process includes a series of conservative limits and assumptions, targeted to demonstrate capacity for the design basis external events. In principle, the process is not intended to assess how much margin above the design event is achieved for each external hazard. To assess how much margin has been achieved by the design process, a safety assessment of the design will need to be conducted, considering all relevant hazards. The requirements for safety assessment of the design are established in GSR Part 4 (Rev. 1).

The adequacy assessment of ‘margins’ against external hazards needs to be done in the framework of the DiD principle: the ‘adequate margins’ may be different at each DiD level. For each DiD level, the challenges generated by the external hazards against the safety functions at that level need to be identified. The challenging mechanisms are specific for each external hazard.

The concept of ‘design margin’ is closely linked to the definition of ‘acceptable performance’ for events exceeding site specific design events. Acceptable performance can be expressed in both, qualitative and quantitative terms. For scenario based hazards, where design margin metrics cannot easily be established, acceptable performance limits for given scenarios can be directly used, instead of design margins, to define the required level of design robustness.

An integrated assessment of the design margin process would bring together design and safety assessment of the design. The latter considers the full range of hazard severity, including beyond design basis challenges. The IAEA publications recognize both, design and safety assessment, as being part of an overall design process (Fig. 8).

Following the compilation of lessons learned from events and operating practice, the fundamental assessment step is to review current design practices against external events, according to the guidelines in the IAEA safety standards. Design uses codes and standards to define SSCs able to resist design basis events, with a conservative treatment of demand and capacity.

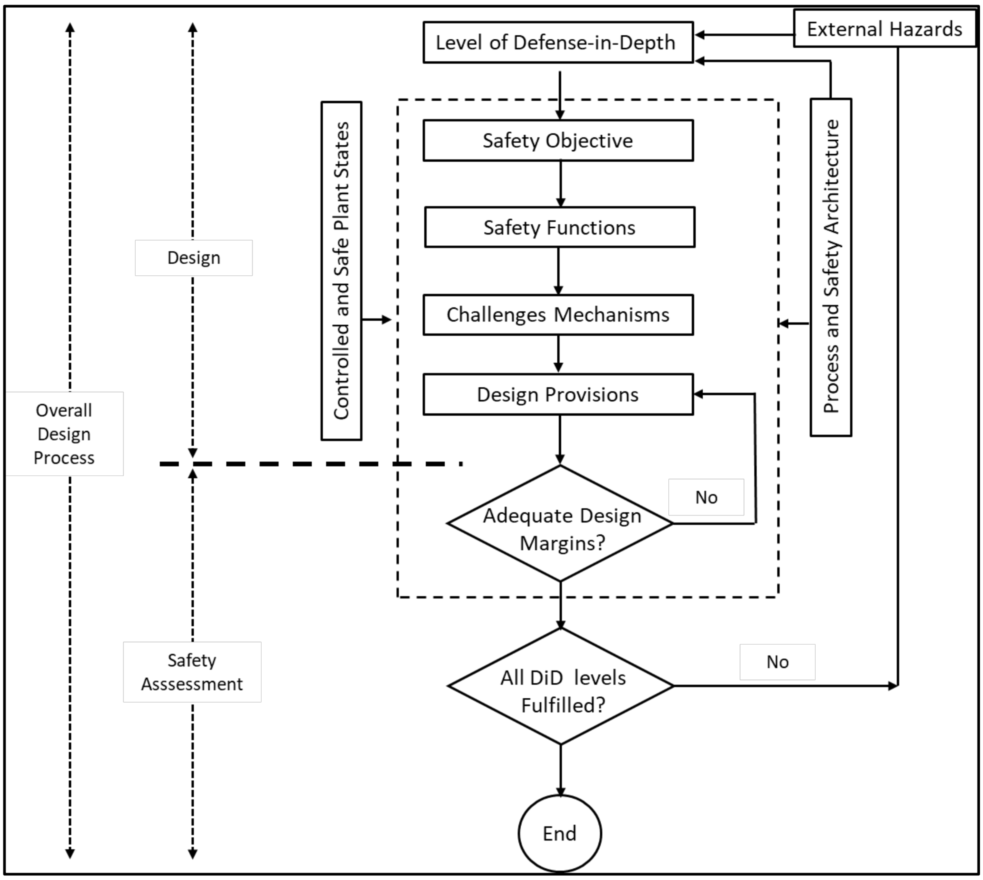

Figure 8. Schematic of the design process and interface with the safety assessment process.

Assessment method

A general framework and quantitative criteria for defining what design safety margins against external hazards are ‘adequate’ is presented in the IAEA TECDOC on “Evaluation of the adequacy of the design robustness of nuclear installations against external hazards”. The strategy of that publication is to look first to seismic hazard, for which well developed and practiced methods for hazard assessment and design margin assessment are available. For this hazard, it can be shown that the design margin can be linked to the installation-level performance against the hazard, that is, its annual frequency of seismic induced failure. The consequence is that the design margin is ‘adequate’ if it results in compliance with the frequency based installation-level performance goals set by the regulatory body. This is a quantitative definition of ‘adequacy’.

To generalize this approach to other external hazards, the publication distinguishes between three categories of hazards: Hazards in the first category, Category A, are conceptually similar to seismic hazard, in the sense that the hazard can be expressed as a single parameter (e.g. ground acceleration, wind speed, water level) and an associated annual frequency of exceendance (AFE) AFE . Therefore, for hazards in this category, the approach for assessing design margin adequacy defined for seismic hazard remains valid, even though practical methods of hazard assessment and design margin determination are less developed.

At the other end of the hazard category scheme, Category C hazards are scenario-based hazards. Realizations (events) representing these hazards are introduced in an agnostic way in the design process, that is, there is no annual frequency explicitly or implicitly associated with them. The severity of these ‘scenario based’ hazards cannot be defined using a single parameter and, therefore, it needs the definition of a set of parameters which, all together, define the severity.

For external hazards in Category C, the events considered in the design process are specified deterministically and the design needs to meet certain conditions if those events happen. Such conditions are expressed by engineering attributes, so that it can be demonstrated with adequate confidence that a severe accident and/or large release are avoided if the conditions are met. Thus, the concept of 'design margin' is less meaningful. For external hazards in Category C, acceptable behaviour (compliance with specified conditions) is used for assessing design robustness adequacy.

Category B hazards are in between categories A and C. Category B hazards are scenario-based hazards, but AFEs can be determined for each scenario. In other words, instead of having a continuous function of the parameter defining the severity of the hazard as in Category A, there is a discrete number of scenarios, each one with an associated level of severity and annual frequency of occurrence. Thus, the same concept to assess adequacy for Category A hazards can be used. However, in this case the installation-level performance (i.e. the annual frequency of failure) needs to be obtained using a summatory instead of a convolution integral.

RESILIENCE

The analysis of recent scenarios affected by climate change type of threat to nuclear installations highlighted the importance of the consideration of the concept of "resilience" in the safety assessment of a nuclear installation, particularly for its strong implication for the capability of power supply to the affected populations living in the neighbourhoods.

The resilience is measured as the capability to restore safe operation after an event, even followed by a shutdown, repair and recovery, as shown in Fig. 9.

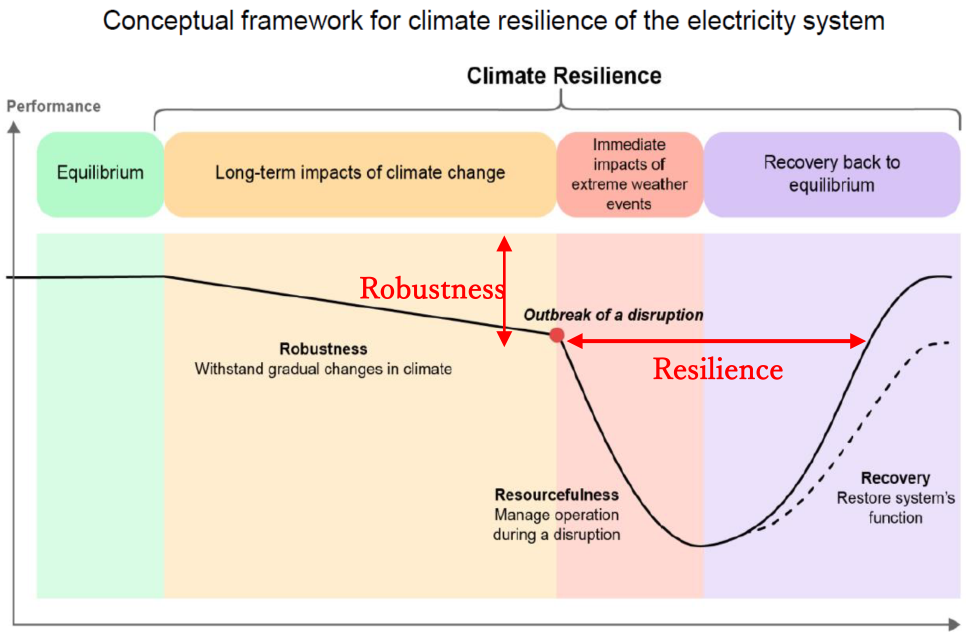

Figure 9 – Symbolic description of robustness and resilience

CONCLUSION

The assessment of plant safety in relation to external hazards should start from a proper analysis of the event scenarios, their impact on plant safety and the evaluation of the safety margin embedded in the design. Those activities are particularly important with reference to climate change affected scenarios.

In particular, the following actions have been recently identified in the nuclear safety community as essential to assess the plant safety and improve both prevention and mitigation measures:

- Analysis of the lesson learned from events including: a proactive approach on the analysis of the near misses, review of modelling for anticipating possible scenarios, methods for risk assessment, operation measures, preparedness to manage accident consequences and business interruption in the short, medium and long term.
- Improved approach to scenario screening at the design level
- Improved hazard evaluation approach, with uncertainty control, including simulation of climate change and load combination and local-global time-dependent hazard models, and accurate modelling for anticipating possible scenarios – Periodic hazard review
- Develop new risk indicators and risk assessment approaches: resilience, robustness, radiological risk, business interruption, etc. and consequently extend the risk analysis (performance based) to the whole production and distribution infrastructure
- Perform systematic risk analysis for assessment of the beyond design basis margin and cliff-edge effects
- Improve component qualification methods (by similarity?) for periodic re-assessment and post event recovery
- Review of safety assessment objectives and methodology, especially for climate-change scenarios,n, including power availability, and plant resilience
- Consideration of a “System Resilience” approach in addition to “Robustness evaluation”
- Post event fast recovery plans for short business interruption and continuous power supply to populations
- Develop increased dedicated site monitoring integrated with regional monitoring
- Encourage the development of contingency plans at nuclear infrastructures and their regions, supported by regional monitoring, vital areas identification and risk assessment engineering, pre and post event operation procedures

REFERENCES

IAEA (2015). “*The Fukushima Daiichi Accident”*, Non-serial Publications, Vienna, Austria (2015).

IAEA (2016). *“Safety of Nuclear Power Plants: Design”*, IAEA Safety Standard Series No. SSR-2/1 Rev. 1, Vienna, Austria (2016).

IAEA (2016a). Attributes of Full Scope Level 1 Probabilistic Safety Assessment (PSA) for Applications in Nuclear Power Plants, *IAEA TECDOC Series No. 1804*, IAEA, Vienna, Austria (2016).

IAEA (2019). *“Site Evaluation for Nuclear Installations”*, IAEA Safety Standards Series No. SSR-1, Vienna, Austria (2019).

IAEA (2021). *“Design of Nuclear Installations Against External Events Excluding Earthquakes”*, IAEA Safety Standard Series No. SSG-68, Vienna, Austria (2021).

IAEA (2022). “*Climate Change and Nuclear Power 2022, Securing Clean Energy for Climate Resilience*” Nuclear Power and Climate Change, Vienna, Austria (2022).

IAEA (2023). *“Development and Application of Level 1 Probabilistic Safety Assessment for Nuclear Power Plants”* IAEA Safety Standard Series No. SSG-3, Rev. 1. Vienna, Austria, in preparation (2023).