Highlights of Safety Enhancements of Research reactors Based on Safety Reassessments following the Fukushima-Daiichi Accident

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Abstract. This paper presents, on the basis of available information at the international level, an overview on the safety reassessments (called also complementary safety assessments or stress tests) performed on research reactors in light of the March 2011 accident at Fukushima-Daiichi NPP. The main focus is on safety enhancements resulting from these reassessments, including modifications of facilities to enhance their robustness against extreme natural hazards, strengthening reactor Defence-in-Depth, enhancing emergency preparedness and response, and improving regulatory supervision. Considerations are also presented on use of a graded approach for the stress tests and on follow-up of implementation of the resulting safety enhancements.

Key Words: Fukushima Daiichi NPP accident, lessons learned, research reactors safety reassessments, safety enhancements.

1. Introduction

Following the Fukushima-Daiichi NPP accident which occurred on 11 March 2011, specific safety reassessments (called also complementary safety assessments or stress tests)[1] were performed for nuclear installations in many countries on requests of the regulatory bodies or decisions of the operating organizations. Their main objective was to take into account the feedback and preliminary lessons learned from this accident, which cover technical and organizational aspects, including in particular the design of the facilities against extreme natural hazards associated with the site, the emergency preparedness and the regulatory oversight. The emphasis of the safety reassessments carried out was mainly to evaluate the robustness of nuclear installations and their ability to withstand effects of extreme but credible hazards which are more severe than those considered in the design basis, and to address the Defence-in-Depth, the performance of fundamental safety functions as well as the continuity of facility monitoring function in such conditions. Although the primary focus of these safety reassessments has been on NPPs, many countries have extended their scope to include research reactors and fuel cycle facilities due to the fact that lessons learned from the above mentioned accident are also applicable to different types of nuclear installations.

In order to promote harmonization and consistency of the approaches concerning safety reassessments of research reactors in light of the feedback from the accident at Fukushima-Daiichi NPP, a "guideline document" was developed by the Agency and published as IAEA Safety Report No. 80 [1]. The methodology established in this publication is based on a deterministic approach with a focus on analysis of extreme natural events and beyond design events for research reactors, as well as consideration of combination of events and possible interactions with other facilities at the site.

This paper presents, on the basis of available information at the international level, an overview on the stress tests performed for research reactors, with a main and general focus on the resulting safety enhancements without designating specific research reactors. These

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[1] The terms safety reassessment, complementary safety assessment and stress test as used in this paper have the same meaning.

include modifications of facilities to enhance their robustness against extreme natural hazards, consideration of Design Extension Conditions[2] in safety analyses and improvement of consistency and completeness of analyses related to site specific extreme hazards, and enhancement of emergency plans as well as associated equipment and procedures for mitigation of severe accidents. Considerations on use of a graded approach in performing stress tests, and follow-up of implementation of the resulting safety enhancements are also presented in this paper.

2. Specific Aspects Related to Research Reactors and Use of a Graded Approach

According to the IAEA Research Reactors Data Base there are currently around 248 operational research reactors in 58 countries. About 68% of these reactors have power less than 1MW and about 65% of them are more than 40 years old. Aging of the Structures, Systems and Components (SSCs), Safety management including regulatory oversight, and emergency preparedness and response are among important generic safety issues for research reactors worldwide.

Periodic safety reviews are still not performed for many research reactors despite significant changes in their site characteristics and utilization programme. Despite the fact that the radioactive material inventory of these facilities is much lower than for NPPs, some research reactors present significant potential hazards, mainly due to their old design, the type and amount of their radioactive inventory, the quality of their confinement/containment and their location near populated areas.

Taking into account the above elements and the diversity of design and operation of research reactors as well as associated risks, a graded approach need to be applied to safety reassessments in light of the accident at the Fukushima-Daiichi NPP, and has to be commensurate with the risks posed by the research reactor and its site [2]. Grading was applied in several countries to the determination of research reactor priorities and selection criteria for performing the safety reassessments. Grading was also applied to the scope and level of details of review of design basis events and assessment of beyond design basis events as well as to the emergency arrangements to be established.

As for NPPs, the fundamental safety functions for research reactors are: control of reactivity, removal of heat from the reactor and from the fuel storage systems, and confinement of radioactive material, shielding against radiation and control of planned radioactive releases, as well as limitation of accidental radioactive releases. The stress tests need to:

- Refer to the current status of each research reactor as built and as operated and use the most unfavourable conditions including core configurations, existing and planned experimental facilities, and experimental devices.
- Focus on robustness of existing reactor protection (design features and procedures) against impact of extreme events and fulfilment of the fundamental safety functions.
- Cover any consequential loss of fundamental safety functions and relevance of mitigation actions.

Possible impact of items which are non-safety classified on items important to safety should also be evaluated. This implies the necessity of detailed walkthroughs of the facility, to

[2] Accident conditions that are not considered for design basis accidents, but that are considered in the design process of the facility in accordance with best estimate methodology, and for which releases of radioactive material are kept within acceptable limits. Design extension conditions could include severe accident conditions.

examine in situ the facility systems and their anchoring for protection against seismic events, their design basis robustness as related to seismic hazard, flooding hazard, back-up electrical power supply, and fire protection.

For many research reactors there was no review of the site wide characteristics and associated hazards to verify compliance with the approved design bases, considering changes in population distributions, implementation of new facilities onsite or offsite, or modifications of existing facilities. Such review should consider the whole site in a graded approach and should address the impact of extreme natural events on the site as a whole, taking into account onsite multiple hazards, effect on communication and site access routes, and possible loss of offsite support as a consequence of such events.

3. Brief Overview of the Performed Stress Tests

The actions launched at the international level immediately after the Fukushima-Daiichi NPP accident, including those initiated by the IAEA [3], were focussed exclusively on the safety of NPPs. In March 2011, the European Union (EU) launched a process for a comprehensive risk and safety assessments (stress tests) of all NPPs in its Member States. The assessment methodology was established by experts from the European Nuclear Safety Regulators Group (ENSREG) and the West European Nuclear Regulators' Association (WENRA). The focus of these stress tests was on the robustness of safety margins of NPPs in three areas: extreme natural events such as earthquakes, floods and extreme weather conditions; loss of electrical power or loss of ultimate heat sink for heat removal (and combination of both), and management capabilities for severe accidents.

Many countries expanded the scope of stress tests to include research reactors and applied the same methodology as for NPPs. In this process, priorities were given to research reactors according to their risks and following a graded approach (in some cases the reassessments were performed only for research reactors having power levels above a certain threshold value). The general focus of the performed safety reassessments was on the response of research reactors in case of extreme natural events and on the verification of preventive and mitigation measures covering the initiating events, the loss of fundamental safety functions and the management of severe accidents. Some post Fukushima reassessments also included multi-facility events, spent fuel storage pools, and security breaches, sabotage and Cyber-attacks. In some countries the stress tests considered accident scenarios beyond the design basis of the facilities to determine design margins for key SSCs and cliff-edge effects beyond which fundamental safety functions will be lost.

One adequate approach applied by many licensees was to first assess the current status of the facilities and verify their conformity with the adopted design basis and license conditions, and then expand the scope of the assessment to Design Extension Conditions. This included in some cases conduct of specific walkthroughs of the facility to check that the items important to safety and the engineered safety features are in good operating conditions, assessment of the consequences of external events (earthquake, flooding,..) combined with a total loss of electrical power supply, and verification of existing margins to severe accidents (reactor core damage, containment damage and off-site releases).

The results of research reactor stress tests were reviewed by the national regulatory bodies and action plans were established for implementing safety improvements in the short term, medium term and long term timeframe.

The IAEA promoted the use by its Member States of the IAEA safety report No. 80 for performing safety reassessments for research reactors in light of the Fukushima Daiichi NPP accident. The IAEA also facilitated peer reviews of results of safety reassessments through the organization, at regional and international levels, of several dedicated technical meetings and workshops.

A survey was carried out by the IAEA in 2011-2012 concerning the performance of stress tests for research reactors. Preliminary analysis of the results of this survey was presented during the International Conference on Research Reactors held in November 2011 in Rabat, Morocco [4]. This survey provided useful indications on the number of countries which launched post Fukushima actions for research reactors, but it did not allow having a clear vision concerning the technical validity and completion of the stress tests, the status of their review and approval by the regulatory body as well as the status of implementation of resulting corrective measures.

4. Main Issues Identified from the Safety Reassessments

4.1. Regulatory Supervision

The feedback from Fukushima-Daiichi NPP accident highlighted the importance of the independence and effectiveness of the regulatory supervision, and showed that the role and intervention of the regulatory body are essential not only during normal operation of the facilities but also in accident situations. It showed also that the regulatory body shall have the necessary resources and abilities to perform safety assessments in all operating and accident conditions, including in case of extreme events.

In many countries, independence and effectiveness of the regulatory supervision for research reactors need strongly to be improved in accordance with the provisions of the Code of Conduct on the Safety of Research Reactors [5]. This includes in particular strengthening regulatory infrastructure and regulatory body safety assessment capabilities, and improving regulatory requirements and standards. For example for the majority of research reactors there is no regulatory requirement to perform periodic safety reviews, which are an efficient means for enhancing safety.

4.2. Design Requirements and Safety Analyses

One of the important lessons learned from the accident at Fukushima Daiichi NPP, is that the design envelope and the safety analysis of nuclear installations should be expanded to include credible natural events considered as Beyond Design Basis Accidents (BDBAs) and which constitute what is referred to as “Design Extension Conditions”. Considerations should also be given to the magnitude and combination of natural hazards (seismic, flooding, extreme weather, etc.), to extreme or beyond design internal events and to events related to human activities such as airplane crashes.

Analyses presented in the Safety Analysis Reports (SARs) for several research reactors are not always consistent. For example, in the case of high power research reactors and a large loss of coolant accident (LOCA) caused by a severe earthquake, analyses presented in the SAR are performed with a credit given to existing safety engineered features for keeping the reactor core partially covered (e.g. Emergency Core Cooling Systems - ECCS - from different coolant supply including reservoirs feeding the coolant by gravity, core spray systems, etc.). However, the mechanical resistance of the ECCS and its good functioning in the conditions of the severe earthquake that caused the LOCA are not always clearly demonstrated.

In the case of a LOCA causing core uncovering in low power research reactors, the SARs of some facilities include only elements demonstrating the conservation of fuel integrity without an evaluation of the high radiological doses in the facility due to the loss of biological shielding (pool water) during the accident.

In the same manner, deterministic analyses of the consequences of airplane crashes shall not be limited only to the direct mechanical impact on the reactor building, but shall also take into account the effects of kerosene burning on SSCs important to safety. This is not the current case for the majority of operating research reactors.

In general, combination of events was not considered for research reactors (e.g. extreme earthquake that leads to an internal event such internal flooding and/or fire, earthquake and release of hazardous material including radiations from another installation on the site). Seismic analyses, including evaluation of seismic behaviour of reactor building and SSCs important to safety, need to be reviewed and updated, for example to take into account new data acquired concerning the seismicity of the site and/or to confirm the ability of control rods to shut down correctly in case of earthquakes. This issue is very important; particularly for research reactors using fuel plate assemblies where the available space for control rod insertion is narrow. Only in few cases, the seismic behaviour of control rods was tested using shaking tables.

4.3. Total Loss of Electric Power Supply

For the majority of research reactors, the safety analyses need to be further expanded to take into account a prolonged and total loss of electrical power supply (off-site, diesel generators and batteries). In many cases, only the loss of off-site electrical power supply was analyzed in the SARs taking into account the operation of backup power supply systems. A total loss of electrical power supply will lead to the loss of forced cooling of the fuel and to an automatic shutdown of the reactor, as well as to the loss of control and monitoring of the safety parameters of the facility.

In the case of pool type reactors, the evacuation of residual power could be ensured by natural circulation of the pool water after an automatic opening of flappers installed on the primary coolant pipes (one flapper is usually sufficient for ensuring core cooling). The opening of the flappers, which are passive components, occurs within a short delay after the stopping of the primary coolant pumps and it is triggered by the mechanical action of counterweights. In general, cooling water in many research reactors has enough volume to keep the reactor core immersed over a long period of time.

Some high power research reactors (several tens of MWs) need electrical power for a limited time to maintain a forced cooling of the fuel after the reactor shutdown. The availability of emergency electrical power supply and emergency core cooling system (ECCS) for such reactors need to be reviewed and ensured, for example by means of increasing redundancy level and improving reliability of onsite and offsite electrical power supply systems, as well as of emergency power supply system and uninterruptible power supply (UPS).

A total loss of electrical power supply will generally result in a loss of negative pressure in the reactor building, which occurs after a certain delay depending on the quality of the reactor building leaktightness. It could also result in uncontrolled releases to the environment and in a loss of the instrumentation monitoring safety parameters of the facility. This includes, in particular, the loss of activity monitoring and filtration of the air released by the stack to the environment. Provisions need to be implemented to ensure timely electrical power supply for the emergency ventilation system and security light, and for monitoring important safety parameters of the facility.

4.4. Emergency Preparedness and Response

Technical and organizational provisions for emergency preparedness and response for research reactors need to be commensurate with the potential risks associated with the facilities. Envelope credible accidents in low power research reactors could lead to significant radiological consequences mainly within the facility itself and its site (high doses to operating staff, contamination of different locations of the facility and the site).

High power research reactors, where the inventory of radioactive materials is normally much more important, require the establishment of onsite and offsite emergency plans as well as developed emergency organizations. For the different research reactors there is a need to review the regulatory requirements and the adequacy of the onsite and offsite emergency provisions, including the response to radiological emergencies and the readiness of the response teams. The review should also cover site accessibility and existing communication routes, emergency equipment, and performance of periodic emergency drills. There is also a need to review organizational aspects including the role of the regulatory body in case of an emergency, the role and responsibility for taking decisions, and the communication with offsite authorities.

4.5. Other Safety Aspects of the Fukushima Daiichi NPP Accident

4.5.1. Risk of Hydrogen Explosion

In general there is no significant hydrogen generation in fuels of research reactors, but the cold neutron sources (CNS) installed in some research reactors contain hydrogen/deuterium. The CNS design features (double containment, seismic qualification), the low quantity of hydrogen /deuterium and the large volume available in the reactor building would ensure dispersion of possible hydrogen/deuterium leakage below the explosive limit.

4.5.2. Cooling of spent fuel storage

For the majority of research reactors, spent fuel storage pools are located inside the reactor building. Natural convection cooling can remove decay heat of spent fuel without boiling risk and no forced cooling system is needed. In some research reactors, there are water make up systems for spent fuel storage pools, which do not require electrical power supply.

5. Highlight of Safety Enhancements

The safety reassessments performed for many research reactors identified solutions to prevent or mitigate unacceptable consequences from fundamental safety function failures, and corrective measures for improving Defence-in-Depth, operational safety and accident management.

The safety improvements resulting from performed safety reassessments covered mainly organizational aspects, technical aspects and safety demonstrations.

5.1. Organizational Aspects

The Fukushima-Daiichi NPP accident increased awareness of governmental authorities of several countries on the necessity to ensure a high level of nuclear safety and the need to define clearly the role and responsibilities of the government, the regulatory body and the operating organization in the management of extreme emergency situations. Some Improvements of regulatory framework and regulatory effectiveness were achieved in countries operating nuclear power plants. Efforts need to be continued for enhancing effectiveness of regulatory oversight in countries operating only research reactors.

Few countries reformed their regulatory systems and issued nuclear laws for ensuring transparency, further independency and effectiveness of the regulatory body.

5.1.2. Emergency Preparedness and Response

The Fukushima-Daiichi accident highlighted the need for establishing robust emergency arrangements for many research reactors. Emergency plans and associated procedures were reviewed and improved to ensure their adequacy for mitigating consequences of severe accidents initiated by extreme natural events impacting several facilities on the site.

Availability of emergency equipment adapted to envelope accident conditions were also examined and ensured in many cases. For example portable emergency power supply generators were procured for many facilities to provide electricity to items important to safety, in case of a total loss of onsite and offsite electrical sources. Redundant water supplies for emergency core cooling were also ensured.

For some facilities, the operating organizations installed a reinforced emergency control room designed with significant safety margins to resist to extreme natural events, from which it is possible to shut down the reactor and maintain it in safe shutdown status, if this could not be achieved from the main control room. It is also possible to monitor certain key safety parameters reported to the emergency control room, and to control the operation of some safety systems, such as the emergency ventilation system, that should be restarted to mitigate radiological consequences of accidents. Conditions that could prevent the operating staff from working in the main control room could include high radiation level if the control room is not shielded from the reactor operation area, entry of contaminated air, fire in the control room or any event that damage the main control room. Post-accident monitoring systems were also installed in some facilities to monitor variation of key safety parameters during and after an accident.

5.1.3. Training

Training programmes were established in some countries by operating organizations and regulatory bodies, and were reviewed and updated to cover Design Extension Conditions for research reactors, including for example extreme natural events and total loss of electrical power supply.

Dedicated training sessions were implemented for operating organizations and regulatory bodies staff to improve their response in BDBA conditions. Training activities were also organized at regional and international levels to facilitate sharing of good practices in performing stress tests.

5.2. Technical Aspects

Several modifications and upgrading works based on feedback from Fukushima Daiichi accident were performed in many research reactors mainly to enhance their robustness against extreme natural events, and to strengthen Defence-in-Depth and operational safety. They included seismic reinforcements of SSCs, increasing robustness of reactor buildings against earthquakes and severe meteorological events, and implementation of additional monitoring instrumentation, such as seismic detectors with associated automatic actions to scram the reactor and close pool isolation valves at low ground acceleration. This would ensure early automatic shutdown of the reactor before occurrence of possible significant damage of the reactor building. Additional instrumentation was also implemented in some facilities to monitor important safety parameters during emergency situations, such as core monitoring instrumentation, radiation monitors, and radioactive release monitoring.

Modifications and upgrading works also included provision of emergency portable electrical power supply (diesel generators) to operate items important to safety in case of a total blackout, and implementation or improvements of ECCS (such as installation of water supply storage) to prevent potential fuel damage in case of a large LOCA. Emergency ventilation systems were also installed or refurbished in some facilities to ensure control and filtration of radioactive releases to the environment. It should be noted that the above mentioned additional measures implemented in the facilities to mitigate the consequences of severe accidents should not in any case reduce the attention for the prevention of accidents.

Other improvements were related to protection against internal fires and fires from external origin (installation of fire detection and alarm system and fire extinguishing means, clearing of woods to prevent forest fires).

5.3. Safety Demonstration

For some research reactors, improvements to safety demonstrations included consideration of Design Extension Conditions in the safety analyses, and implementation of additional engineered safety features for ensuring performance of fundamental safety functions. They also included updating of safety documents to take into account site specific hazards, combination of events, and re-evaluation of safety of spent fuel storages.

Conclusions

Safety reassessments performed for research reactors in light of the Fukushima-Daiichi NPP accident resulted for many of them in an effective strengthening of the Defence-in-Depth and improvements of facility capabilities to withstand beyond design events. They also resulted in a strengthening of the effectiveness of the regulatory bodies and in improvements of the safety analysis consistency for several research reactors.

Mechanisms should be established for ensuring regular updates at the international level on implementation status of stress tests and resulting safety enhancements for research reactors. In this regard, the specific surveys launched by the IAEA and its safety review missions conducted in many countries could be an adequate means for collecting and reviewing information on this subject.

Peer review process should be continued and facilitated by the IAEA, via technical meetings and workshops, to promote sharing good practices on performing stress tests and on different research reactor safety matters.

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