Equipment Testing for Severe Accident Conditions

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Abstract: The operational states of a nuclear power plant can be generally categorized as normal operation and accident conditions. The latter one can be further divided into so-called design basis accidents and design extension conditions. Design extension conditions include in the worst case conditions with core melting, called severe accidents. Instrumentation and equipment important for mitigating severe accident need to be tested to ensure the functionality during the severe accident environmental parameters and the mission time, which may be in the order of weeks or even years. The traditional environmental qualification method is not suitable in all cases for testing the severe accident instrumentation and dedicated mitigation equipment. Moreover, design extensions conditions and especially severe accidents are mostly not addressed in equipment qualification standards. This paper summarizes some aspects of the severe accident conditions testing.

Keyword: Severe accident, NPP, DBE, I&C, EQ

1 Introduction

Environmental Qualification typically denotes qualification of systems important to safety and their equipment/components exposed to harsh environment, which is performed by qualification methodology and processes governed by regulations and standards. Environmental Qualification takes into account ageing effects arising due to normal service conditions (ambient and process) over a lifetime of the plant. This drives the purpose and scope of an Environmental Qualification Program, which is to provide auditable assurance that essential equipment, required to mitigate the consequences of a DBA, will perform their intended safety functions when exposed to the harsh conditions resulting from that accident, and that this capability will be maintained over the life of the station. EQ is defined according the IAEA terminology as the generation and maintenance of evidence to ensure that equipment will operate on demand to meet system performance requirement during normal and abnormal conditions and postulated design basis events[1].

This description/definition does not mention upon design extension conditions, which are 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[2]. Design extension conditions include e.g. extended station black out, extreme natural hazards and also severe accident. Accident conditions more severe than a design basis accident and involving significant core degradation are termed severe accidents[5].

While design basis events are well defined in NPP design, the design extensions conditions are relative new issue within EQ. The Fukushima – Daiichi accident demonstrated, that some I&C equipment have to perform their functions also during accidents beyond the design, i.e. severe accidents. Common EQ need not be in all cases suitable for design extension conditions and especially for severe accidents. This fact required a methodology, guide for testing for SA conditions. First step was done by the IAEA, that established a working group summarizing all the knowledge on testing and proposed first guide, that was issued in 2017 as IAEA TECDOC 1818[3].

This paper does not describe the actions concerning severe accident management and/or selecting of equipment of the scope. Nevertheless, some basic information on SA is described below.

2 Severe accident

Severe accidents[3] are characterized by the fuel damage resulting from the loss of the ability to sufficiency cool in either the reactor core or fuel stored in the spent fuel pool. During the progression of a severe accident, the remaining barriers between the highly radioactive fuel inside the reactor core and the environment are challenged. The loss of sufficient capability cool the core will eventually lead to coolant release into the containment causing an increase in pressure, humidity and temperature in the containment. Core degradation is associated with producing high quantities of steam, hydrogen and other combustible gases which can exceed the containment design pressure. Flooding can also occur due to the initiating event itself or as a consequence of mitigation strategies which lead to coolant release or cooling water injection into the containment. Hydrogen release (and other combustible gases) is one of the crucial phenomena associated with severe accidents. The common goal of every mitigation strategy is to prevent hydrogen burn to the greatest extent possible, or at least to only allow deliberate and controlled burns. Maintaining the containment hydrogen concentration below dangerous limit is therefore an essential requirement for achieving of a controlled stable state. The potential acceleration of propagating flame can challenge containment integrity. The occurrence of severe accident is usually linked with significant changes to the chemical composition the containment atmosphere and sump inside of the containment. This chemical change (if any) is a consequence of release of aerosols and degraded materials and may results in an adverse aggressive corrosive environment which has to be appropriately accounted for in survivability assessment.

The main goal during execution of the mitigation strategy (and which drives the need to assess survivability of dedicated equipment) is to prevent failure of the last barrier and subsequent radiological release into the environment. This includes (in order of relative importance) containment integrity preservation, stabilization of the degraded core, limitation of release (leakage of the containment), long term stabilization of the affected unit and securing of unaffected unit, if any. The equipment dedicated to severe accident mitigation support these goals.

2.1 Equipment for monitoring and mitigating SA

Information about equipment for monitoring and mitigating severe accident can be found e.g. in IAEA documents[3][4][5]. Depending on the plant design and SA mitigation strategies, the following systems may require testing for severe accident conditions:

- Containment systems including penetration, isolations, valves, hatches, airlocks seals etc.;
- Reactor coolant system (RCS) depressurization;
- Hydrogen mitigation (monitoring and recombination);
- Melt stabilization;
- Containment heat removal system (CHRS);
- Designated accident mitigation equipment;
- Accident monitoring system.

The main function of the accident monitoring system is to provide reliable and unambiguous information during the extreme conditions of a severe accident. The main parameter for determining the status of the reactor core is typically core exit temperature. The main parameter for determining the containment integrity are temperature, pressure, water level, hydrogen concentration, steam content and radiation level[3]. Important parameters to monitor during emergency response are contained in IAEA GSG-2.1[6].

The qualification process requires the knowledge about the mission time. How long the equipment is expected to be in operation. It must be defined the safety function. It can be only passive, like prevent radioactive material release outside containment (cable penetrations) or active like sensors that need to be functional all the time. There is also equipment that is active only during a short period of time (e.g. valve opening).

3 Testing

The use of traditional environmental qualification methods for design basis accident conditions (e.g. LOCA, HELB) is acceptable; however they may need to be tailored specifically to address conditions unique to severe accidents. The direct application of traditional environmental qualification methods may not be practical. Hence, the testing procedure for equipment used in severe accident conditions is not called qualification, but rather "Assessment of Equipment Capability to Perform Reliably under Severe Accident Conditions"[3].

Nevertheless, the testing to severe accident conditions is basically similar in procedure and methodology to DBA qualification. A typical process with the responsibilities may be following:

- Select equipment to be tested; responsible is designer and/or NPP vendor
- Define EQ parameters and mission time; responsible is designer and/or NPP vendor
- Develop a qualification procedure; responsible is testing laboratory with NPP
- Conduct the testing; responsible is testing laboratory
- Evaluate results, issue report; responsible is testing laboratory

3.1 Environmental parameters

Severe accident environmental parameters can either be calculated or derived from the analysis of severe accidents or from data obtained from actual severe accidents which have occurred at NPP. A number of severe accident modeling methods or codes are available e.g. ASTEC (accident source term evaluation code; IRSN France and GRS Germany), MAAP (Modular accident analysis program; EPRI), MELCOR (Methods for estimation of leakages and consequences of release; Sandia, US). These codes are available to determine different severe accident phenomena. From the testing point of view, the following parameters characterizing the harsh environmental conditions during severe accidents are most important:

- Radiation; beta, gamma, neutrons, change of energy with accident progress, dose rates, doses of individual contributors, total integrated dose
- Temperature; profile for the whole accident, fire if any
- Pressure; whole long term pressure profile, impulse pressure
- Atmosphere; steam, overheated steam
- Flooding; how long equipment is flooded, at which temperature pressure, water level
- Hydrogen combustion and other explosive gases; how the temperature and pressure increase during such a phenomena
- Chemical processes; chemical spray solution, composition during flooding, smoke
- Vibration; internal and/or external origin

These parameters have to be defined to simulate the SA conditions and test the functionality of the equipment.

For some NPPs a plant specific severe accident profiles and scenarios for the simulation already exist. They may differ very much and always depend on the applied code, type of reactor and on the decision what shall be included into the SA and on the mitigation strategy.

3.1.1 Some examples

PWR 1; during LOCA profile the temperature increases to 127 °C for 1 hour, while during subsequent SA the temperature increases due to hydrogen combustion shortly to 270 °C and it is hold for few days at 150 °C and up to 1 year at 120 °C. Total integrated dose increases during SA approx. 10 times. With the running SA, less and less equipment need to be functional.

PWR 2: Quite different scenario exists for older units of the same design and in the same location.

Severe accident is, in this case, localized only in the reactor shaft. Severe accident scenarios prescribes only small temperature increase comparing to LOCA (127 °C versus 135 °C); but high pressure increase due to the shaft flooding is expected.

BWR 1: Profile used for simulating hydrogen burning requires holding the temperature almost 500 °C for 1 day with subsequent decrease to 100 °C for 6 days. Pressure is up to 700 kPa.

BWR 2: Generic test profiles for temperature, pressure (gas pressure and the hydrostatic pressure) and water level for the first 30 days of SA show relative small increase comparing the LOCA profile.

The required mission time for the instrumentation and equipment during severe accident is the important input parameter into the testing procedure; the mission time may be in the order of hours or even years since not all instrumentation or equipment can be replaced during a severe accident. Therefore, following the SA reproduction, a long period in submerged conditions has to be simulated. This may really take one year and even more in some cases. Such a long period needs to be accelerated to meet industrial requirements. This is commonly achieved using the Arrhenius approach at elevated temperature. During this test, the equipment is loaded with appropriate voltage and current and the functionality must be proved. Several questions about appropriate time for simulation, Arrhenius model, influence of voltage on equipment in spray solution at elevated temperature and similar topics have to be studied to execute the testing as reliable as possible.

During SA, the equipment is also exposed to gamma, beta and neutrons radiation. Moreover, related energies and the dose rates change as the accident goes on. Together with these changes, the accident temperature and pressure decrease. Therefore, the effect of irradiation on the material may be strongly dependent on the accident phase. Studies should be done on this open issue.

Another uncertainty is the role of beta radiation with different energies on the equipment degradation under SA conditions. Similar situation can be found for neutron irradiation where more studies on the influence of accident irradiation with neutrons of different energies are needed.

3.2 Testing procedure

Although this paper describes the test procedure for design extension condition e.g. severe accident testing, it is based on same qualification process used for DBA qualification as described in international standards, rules or IAEA documents e.g.[2][7]. The main differences are following:

- They do not exist specific standards and rules for SA testing.
- The SA environmental conditions are often quite different comparing to DBE, e.g. hydrogen combustion, as mentioned above. This may bring some complication with simulating
- Large uncertainties affecting severe accident phenomena modeling.

3.3 Standards

While the EQ for design basis events is well described in existing standards, like IEEE, IEC, KTA, RCC-E, EUR etc., the design extensions conditions and especially severe accidents are mostly not addressed in these standards. However some of them refer to postulated accidents, which may include also SA. The new IEC/IEEE 60780-323 standard[2] states: “For equipment expected to undertake and manage relied upon for design extension conditions, including severe accident conditions, this international standard shall be used by defining new DBE profile covering these scenarios. Conservatism taken into account to define this severe accident profile should nevertheless be adapted.” However, no specific information on how to develop a tailored qualification program is given. An analysis of exciting nuclear standards and rules (international and national) concerning electrical and I&C equipment is given in IAEA document[3]. The following has been concluded from the analysis of applicable standards:

- Almost all standards require that qualification to severe accidents be considered for the electrical and I&C equipment.
- Requirements are given in a descriptive form; in other words only provide what is expected from the qualification.
- Testing to severe accident conditions is similar in procedure and methodology to DBA qualification, which can be described generally by the test sequences due to operational limits, aging (radiological and thermal), seismic test and accident simulation test.

3.4 The second part

Qualification margin is the difference between the specified accident conditions at installed equipment locations and the more severe conditions assumed when qualification is established. Some amount of margin has to be available to provide confidence that generic qualification conclusions can be applied to the installed equipment. Qualification margin is used to account for normal variations in equipment production, reasonable errors in defining accident conditions and satisfactory performance, measurement inaccuracies and other uncertainties.

The standards and international guides recommend margins to apply during DBE service conditions. But severe accident conditions do not necessarily apply these margins, do not require the same rigorous demonstration and the same conservatism a standard qualification process. The SA condition are often very “hard” and increasing the severity due to margin application (typically + 8 °C and +10 % pressure) may be demanding. At present, individual NPPs have different approach to the application of the margins. Some requires adding margins according to IEC/IEEE 60780-323[2]. Some NPPs that strictly follow the standards and that are very interested in successful qualification (equipment has been already installed) do not require margins as the existing EQ standards are not directly related to SA. This is an issue that shall be solved.

3.5 Acceptance criteria

Instrumentation and equipment for severe accidents should fulfill certain performance criteria in order to achieve the desired reliability. These criteria should be derived from the functions to be performed. For example, instrument accuracy during severe accident is of less importance than trend indication. More important is instrument functionality and availability in long term. In most cases the instrumentation might not be replaced during and after a severe accident. The reliability on functionality of the equipment is essential for the strategy to mitigate the effects of a severe accident by for instance opening or closing valves, starting pumps, electrical conductivity, containment penetration integrity, etc.[3]. Selecting of the tested functional properties and their acceptance criteria relay on the specific strategies and measures that should be executed in order to limit the severe environmental conditions. Acceptance criteria need to be stated before the qualification programme and it is based on the equipment survivability assessment that provides reasonable assurance that all I&E credited for severe accident conditions (i.e. temperature, pressure, humidity, radiation, and flooding) can perform its intended function.

3.6 Test sequence

To perform reliable testing for severe accident it is important to define the sequence of accident events to be simulated. Accident events mean in this case seismic, DBA and SA. Typically, SA will not occur as a consequence of a seismic event. Therefore, it is not necessary to perform the seismic test to demonstrate the survivability for severe accident conditions. Moreover, SA will not develop after design basis accident, but rather during this event; always depends on the scenario. Hence, it is not necessary to simulate whole design basis event profile before starting the SA. On the other hand the standard IEC/IEEE 60780-323[2] and relevant standards for qualification require simulating all the accident conditions.

This is very important issue that must be clearly explained before starting testing for SA conditions. Simulating all the accidents on one sample may be for the equipment demanding.

4 Summary

Equipment qualification ensures that designated equipment is qualified for their intended function during their service life and possible accidents. While the anticipated environmental conditions during design basis accidents are well defined in the plant safety analysis, environmental loading conditions, profiles and test procedures experienced in severe accidents are not addressed yet.

The qualification methods for qualifying plant equipment important to safety are established in the important standard IEC/IEEE 60780-323. This equipment qualification standard is limited to the accident profiles, environmental parameters and accident duration anticipated during design basis accidents. Almost all standards for EQ require that qualification to severe accidents be considered for the electrical and I&C equipment, but requirements are given in an unambiguous form.

Severe accidents are characterized by the fuel damage. During the progression of a severe accident, the remaining barriers between the highly radioactive fuel inside the reactor core and the environment are challenged. The main goal during execution of the mitigation strategy (and which drives the need to assess survivability of dedicated equipment) is to prevent failure of the last barrier and subsequent radiological release into the environment. The equipment dedicated to severe accident mitigation need to be qualified.

Some issues concerning the SA testing procedure are following:

- Quite clear rules and regulations. There is not wide spreading agreement how to test the equipment for SA conditions. The only one document is the new IAEA TECDOC 1818 document [3].
- Knowledge of the environmental parameters during SA that shall be simulated. In some cases, the procedure may be quite complicated and new test procedures have to be developed. This is, for example, the case of hydrogen combustion.
- The required mission time may be quite long, more than 1 year. Simulation needs to be accelerated to achieve reasonable testing time. Nevertheless, models and procedures need to be developed.
- Simulation of irradiation conditions with the definition the role of gamma, beta and neutron irradiation. Moreover, the energies of the irradiation and the dose rates dramatically change during the SA. Therefore, the influence of the irradiation on the equipment change.
- Acceptance criteria could differ from the criteria for DBA.
- Qualification margin need to be defined. Standards recommend some margins for DBA. However margins for SA should be developed.
- Define before testing, if SA can occur after seismic event or DBA and if these events need to be simulated prior SA simulation.

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