Nuclear Engineering and Design 386 (2022) 111559

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Time assessment of instrumentation survivability and severe accident guidelines application

Kevin Fernández-Cosials [a,*], César Queral [a], Miguel Sánchez-Perea [b], Fernando Robledo [b]

[a] *Universidad Politécnica de Madrid, Alenza 4 Street, Madrid 2803, Spain*
[b] *Spanish Nuclear Safety Council, Pedro Justo Dorado Street, Madrid 28040, Spain*

ARTICLE INFO

Keywords:
Instrumentation survivability
Severe Accident Guidelines
MELCOR
Station Blackout

ABSTRACT

The Instrumentation performance during a Severe Accident (SA) is currently one of the key identified gaps in Nuclear Safety. The instrumentation is licensed using the pressure and temperature reached during a design basis accident, but SA phenomena are not considered on its design limits. During a SA, it is likely that the pressure or temperature range of the instrumentation is exceeded, and therefore, their measurements may not be reliable throughout the remaining accident development. As those measurements may be used to mitigate the consequences of the SA, its correct use or interpretation can make a difference in the accident management.

For this reason, a methodology for instrumentation survival and assessment is proposed. It consists of the identification of the mitigation actions to perform together with the parameters that trigger its start and the instrumentation required for its development. The damage condition of the instruments is assessed in a continuous manner during the accident, rather than a binary state (function/not function).

In this sense, a MELCOR computational simulation of a short-term SBO sequence in a 3 loop Westinghouse PWR with a large dry containment is used as an example. It takes into account the possible degradation of the instrumentation due to pressure-temperature increases. Then, the conditions of pressure, temperature and humidity are used to estimate the instrumentation survivability during this accident. The best instrumentation option for a specific variable of interest is assessed for all SA guidelines, together with the level of hazard associated with them.

This methodology is applicable to other sequences to show the reliability of measurements and actions. Depending on the instrument availability, different alternatives are suggested that can be considered to manage the accidental sequence.

1. Introduction

The instrumentation of a Nuclear Power Plant (NPP) is a vital element to manage any accidental sequence as it can lead the plant operators to optimal or wrong actions. To study the instrumentation availability and accuracy two approaches are normally employed, one related to design basis events, (DBE), named Environmental Qualification (EQ), and other for Severe Accidents (SA) named equipment survivability.

Regarding to EQ, it is established that the equipment and instrumentation must perform its function within any environmental conditions enveloped by a DBE (H.M. Hashemian, 2006; NRC, 1983). The DBE conditions, which limit the EQ, are tested for all safety-related items proving its adequate performance.

However, the DBE conditions are not as harsh as those developed during a SA (see for example the comparison of generic DBE conditions profiles for PWRs (IEEE, 2003), and generic SA conditions (Duchac et al., 2020; IAEA, 2017)). During a SA, the environmental conditions may negatively affect the equipment and instrumentation performance. Moreover, some of those are used to mitigate the consequences of the SA, and its correct use or interpretation can make a difference in the accident development, (Lutz and Williamson, 2016).

The SA conditions and their impact are assessed under the equipment and instrumentation survivability field, on which all elements that may be used for a SA are identified and their availability and accuracy is analyzed (Yan et al., 2016). A qualification program is normally implemented in all NPPs to assess the instrumentation through their design life, with due account taken of plant conditions during

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* Corresponding author.
E-mail address: kevin.fcosials@upm.es (K. Fernández-Cosials).

https://doi.org/10.1016/j.nucengdes.2021.111559
Received 23 June 2021; Received in revised form 22 October 2021; Accepted 2 November 2021

maintenance and testing (IAEA, 2016).

The events that occurred at Fukushima Daiichi NPPs are a good example. The initial seismic events and subsequent flooding led to a Station BlackOut (SBO). The power loss impeded the proper use of the instrumentation, but even after power was reestablished, the SBO had already created a harsh environment that challenged the survivability of equipment and instrumentation. The adequate interpretation of malfunctioning or inadequate measurements of the available instrumentation was critical. Indeed, if more information about the core state would have been available and the equipment had correctly performed its function, the accident progression could have been modified (Ishikawa, 2015; Lutz and Prior, 2020). The demonstration that the equipment and instrumentation used for SA mitigation will perform its function are nowadays challenges for the nuclear power community to deal with, and a key gap in nuclear safety knowledge, (Farmer et al., 2015). This was patent in (Nystad et al., 2019), on which a degraded instrumentation scenario was used to test the operators capability.

In this sense, there are several methodologies to study instrumentation survivability and reliability of measurements during a SA. Most of them are similar to the methodologies presented in (Arcieri and Hanson, 1991; Hanson et al., 1994; Hanson et al., 1990), on which the accident is categorized in different time phases and the survivability is assessed for each instrument in terms of failure for each phase. Then, the information needed during the sequence phases are identified based on the safety objective trees. As a result, the Candidate High Level Actions (CHLAs) are fully studied and covered by the instrumentation required over the whole accident.

In order to obtain the conditions of the plant, a SA code is normally used. SA codes are capable of simulating adequately the related phenomena, providing information about the environment surrounding the different equipment or instrumentation. Currently-used codes that can obtain the plant conditions during a SA are MELCOR, ASTEC, ATHLET-CD, SCDAP/RELAP5 or MAAP, (OECD/NEA, 2015).

In the present study, a SA is simulated with the MELCOR code. Then, the conditions of pressure, temperature and humidity are used to estimate the instrumentation survivability during the accident. Additionally, its reliability is compared against the actions required by the SA Management Guidelines (SAMGs) of the accident. With those, a realistic estimation of the SA development and monitoring is presented.

This article is divided into five sections. In the first section, an introduction to the research has been presented. The second section is dedicated to the MELCOR model used for the simulations. The third section depicts the description of the methodology to evaluate the equipment survivability. The fourth section describes the application of the methodology to a SBO sequence in a PWR. Finally, some conclusions are drawn at the end of the paper.

2. MELCOR model

The MELCOR code is a fully integrated, engineering level computer code, capable of modeling accident phenomena in Light Water Reactors (LWRs). Sandia National Laboratories (SNL) developed it for the U.S. Nuclear Regulatory Commission for SA analysis, initially for Probabilistic Safety Assessment level 2. The MELCOR capabilities include the simulation of thermal-hydraulic behaviors of Reactor Coolant System (RCS) and containment, core damage process, relocation, molten core concrete interaction, behavior of fission products or hydrogen generation, among others, (Humphries et al., 2017). Currently, MELCOR and other SA codes, are subject of research programs such as MUSA or SOARCA which are focused on identifying and quantifying uncertainty sources in SA analyses, (Herranz et al., 2021; NRC, 2019). These studies are becoming more relevant, as the uncertainties associated to model the oxidation, core degradation and candling, RPV failure and other SA phenomena, are normally the largest involved in reactor simulations and will influence the results obtained. Therefore, the results obtained with SA codes have to be interpreted accordingly.

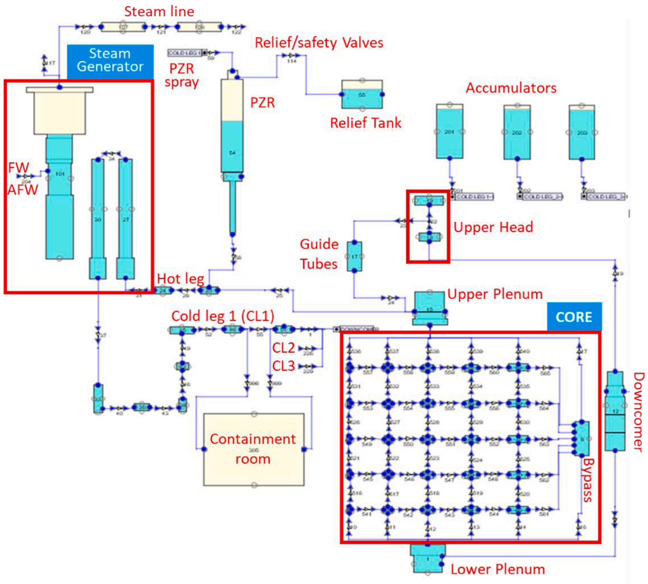

Fig. 1. Nodalization of the RCS of the PWR MELCOR model.

The MELCOR model used for the present study is a Westinghouse PWR (PWR-W) with 3 Loops already used in previous SA analyses, (Fernandez-Cosials et al., 2020). The model follows the best practice guidelines recommended in (Ross et al., 2014; SNL, 2012) in terms of core nodalization and core parameters. The RCS nodalization is shown in Fig. 1 (only 1 out of 3 loops is showed in that figure). The model includes explicit representation of the entire RCS including each of the reactor loops, the pressurizer (PZR) relief tank, the Steam Generators (SGs), steam lines until the isolation valves, and associated safety and power-operated relief valves. All the instrumentation of the plant is located in its correspondent control volume and are modelled with a thermal conductor to account for thermal inertia. The containment is divided into 51 control volumes in which the sprays are distributed, and no passive autocatalytic recombiners are included in the model. The version of the code used for the present study is MELCOR 2.2.

3. Methodology for equipment survivability assessment

As mentioned in the introduction, in order to assess the equipment survivability during a sequence several methodologies have been already established and used. There are mainly two groups; one of them uses the EQ criteria to establish the malfunction of the instrumentation and the other establishes temporal timeframes of the SA and the survivability is assessed for each instrument in terms of failure according to the time phase. An example of the first group can be found in the detailed study of (Rempe et al., 2015).

From the second group, most of the methodologies are based upon (Arcieri and Hanson, 1991; Hanson et al., 1994) and rely on the accident separation into four or five different time zones. A study on the Fukushima Daiichi accident was presented in (Clayton and Poore, 2013), on which the functional needs of the instrumentation were assessed. In Murata et al. (Murata et al., 2016), the SA is subdivided into four timeframes that follows the SA progression to analyze Fukushima Daiichi sequence. In Lee et al. (Lee et al., 2003), the methodology proposed, used for Korean NPPs, consists of dividing the accident into five time zones based on the core state and then identifying the environmental conditions for equipment survivability. An additional study for a Heavy Water Reactor, dividing the SA into four time zones from the accident initiation until core collapse, is also performed in order to analyze the equipment surrounding conditions, (Lee et al., 2012). Similar studies for the HPR1000 can be found in (Li and Lin, 2019). Moreover, the work performed by Westinghouse for the AP1000®

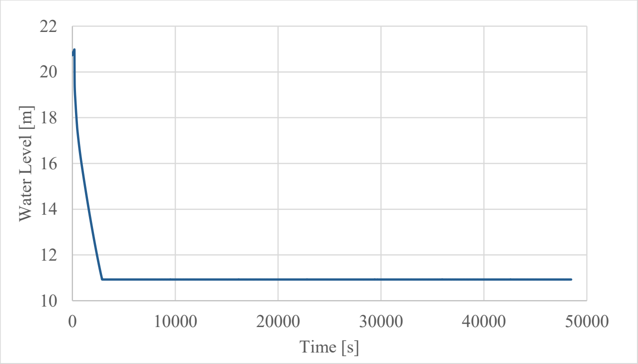

Fig. 2. Steam Generators Water Level.

involves the identification of the equipment type, equipment location, survival time required and then calculates the SA environment conditions to justify its survivability, (Scobel and Powell, 2017). This approach has also been used for the licensing process of the Korean APR1400, (KEPCO and KHNP, 2013).

In the present study, the approach taken is related to the group that uses a separation of the accident in different time frames, but modified in the sense that it treats instrumentation and time in a more continuous manner. It will focus on the Main Control Room (MCR) and Technical Support Center (TSC) staff point of view and walk through the accident comparing the requirements of the SAMGs relative to equipment and instrumentation and its degradation level. The methodology steps are summarized as follows:

1. **SMAGs entry conditions**. The accident is simulated with a computational code and an identification of entry conditions in the different SAMGs is made, together with its temporal frame during the accident.
2. Identification of the different instrumentation used for **CHLAs associated with the SAMGs**. Entering into the different Severe Accident Guidelines (SAGs) will likely initiate actions (CHLAs) to mitigate the effects of the SA. For each CHLA the parameters that are required for its development (e.g. pressure, temperatures, water levels) are identified.
3. Determination of the Instrumentation **Damage Condition evolution**. In this aspect, five different states of degradation that range from normal operation to destruction condition are defined. This degradation can be caused by severe conditions of temperature, pressure, etc. The damage condition level is related to the reliability of the measurement and will influence the use of one instrument over another. Thermal lag of the instrumentation is included.
4. Evolution of **instrumentation survivability** during the accident. Each instrument required for the implementation of the CHLA is checked against the degradation level and best measurement options are therefore provided. Finally, this also provides an indicator for the state of implementing each SAG.

4. Application of the methodology to a SA: ST-SBO

The survivability assessment method explained in the previous section is applied to an accidental sequence in the present section. The selected sequence is an SBO without recovery actions, without SLOCA (because of the presence of passive thermal seals), and without Turbine Driven Pump (TDP) availability after the SCRAM (often referred as Short-Term SBO or ST-SBO). It must be noted that the issue of ensuring proper electrical current to power the instruments (and their reading in MCR) is outside the scope of the paper even though it was a common cause of unavailability e.g. during the first tens of hours after SBO at Fukushima Daiichi unit 1.

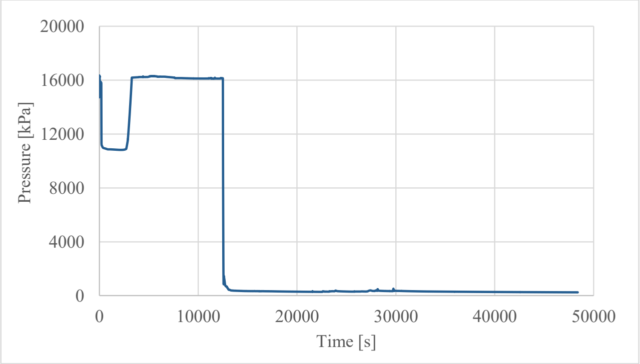

Fig. 3. RCS Pressure.

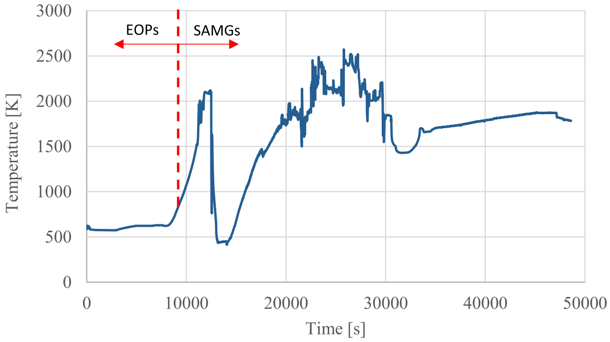

Fig. 4. Temperature in the Core Exit Thermocouples.

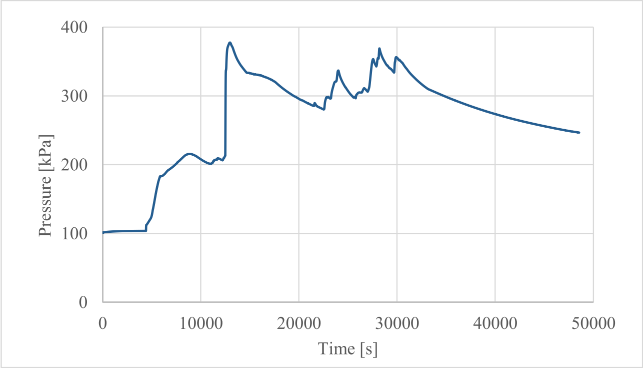

Fig. 5. Containment Dome Pressure.

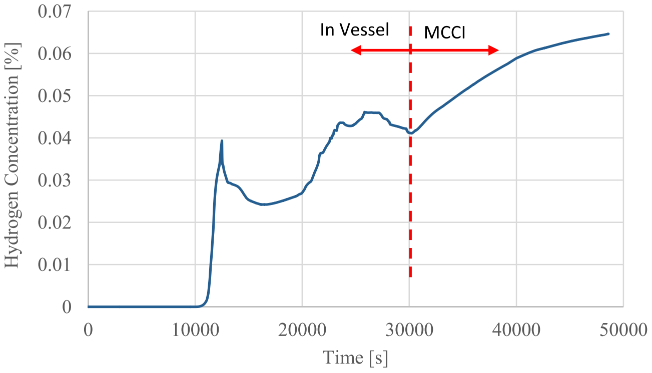

Fig. 6. Hydrogen Concentration in Containment.

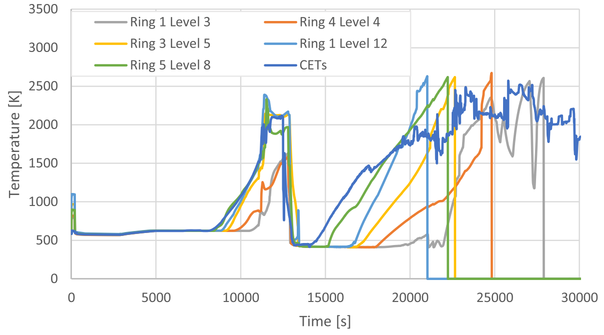

Fig. 7. Temperature of the core and RPVs at different positions.

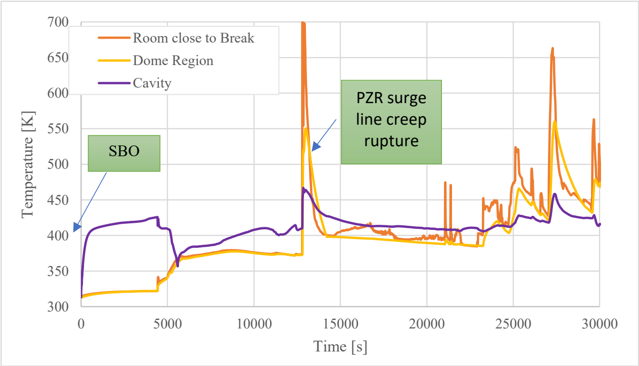

Fig. 8. Temperature at different containment locations.

Table 1
ST-SBO main events.

Time	Event	SA Phases, as per (Hanson et al., 1994)
0 s	Beginning of ST-SBO, accident managing through EOPs	Phase 1 (Up to core uncover)
3000 s	Steam Generators Dry	
3500 s	RCS pressure reaches PZR relief valves setpoint and starts losing RCS inventory	
8800 s	Beginning of core uncovery	Phase 2 (Up to fuel melting)
8800 s	Core temperature over 922 K, transition from EOPs to SAMGs	
10,200 s	Core temperature over 1173 K, Fission Products Release	
10,900 s	Core temperature over 1477 K	
12,700 s	PZR surge line creep rupture and sudden depressurization of RCS	
12,700 s	EQ temperature conditions in containment exceeded	
12,700 s	Accumulators injection begin	
13,100 s	Maximum Pressure in Containment	
21,000 s	Beginning of core Melting	Phase 3 (Up to significant core relocation)
22,500 s	Relocation of corium in the RPV Lower Plenum	Phase 4 (Up to lower head failure)
29,500 s	RPV Lower Head failure	
29,500 s	MCCI begins	Phase 5 (Up to containment failure)
50,000 s	End of Simulation	

The development of the sequence can be seen through Figs. 2-8 and Table 1. The ST-SBO leads to reactor trip, followed by a decrease in core temperatures and RCS pressure. After a short period of time, the SGs become dry, Fig. 2, and the RCS pressure starts to rise reaching the PZR relief and safety valves set points, provoking the loss of RCS inventory, Fig. 3. Because of this inventory loss, the core uncovers and the fuel temperature rises, increasing the temperature of the entire RCS, Fig. 3. Then, after 14,000 s since the beginning of the SBO, the PZR surge line fails due to creep and the pressure barrier of the RCS is lost, provoking a peak in containment pressure, Fig. 5. The pressure of the RCS lowers to the containment pressure, and in the meantime, the accumulators inject water into the RCS. This water provides some temporary cooling to the core decreasing its temperature and increasing the water level above the top of the active fuel height. However, after a short period, the water level in the core starts to decrease again, causing the fuel heat up reaching >2100 K, and provoking hydrogen generation, Fig. 6 and Fig. 7. If the fuel is over this temperature during a sufficient period of time (which decreases with higher temperatures), MELCOR will simulate the fuel melting and collapse; and in the current simulation it occurs at approximately 18,500 s. In the containment, the conditions have remained under generic EQ conditions (423 K and 482 kPa, (IEEE, 2003)) until the PZR surge line creep rupture, where they are exceeded for a short period of time, Fig. 8. The corium starts to accumulate in the Reactor Pressure Vessel (RPV) lower plenum, and finally, the RPV fails due to creep at 29,500 s. After that, Molten Corium Concrete Interaction (MCCI) starts to occur in the reactor cavity producing hydrogen and CO in the process. The simulation is stopped at 50,000 s. No hydrogen burns are supposed to occur during the simulation, as the hydrogen concentration does not surpass the deflagration limit (7%), Fig. 6.

This SBO transient serves as an example to depict and explain the current methodology, but it can be applied to other sequences such as LBLOCA or SBLOCA. Moreover, these sequences may provide more insightful information to specific NPP.

4.1. *Identification of entry conditions into the SAMGs*

During the present ST-SBO, the development of the accident would be initially managed through the Emergency Operating Procedures (EOPs), which are followed by the MCR crew. This stage is part of the design basis of the plant, and all instrumentation is supposed to work properly. Then, after the diesel generators cannot be initiated and the Core Exit Thermocouples (CET) indicate inadequate core cooling conditions (T_{CET} >922 K), the MCR crew will transit into the SAMGs and this happens 8500 s after the accident, Table 1. The SAMGs are initially followed by MCR Crew, but later the management is transferred to the TSC, who will follow the Diagnostic Process Guideline (DPG) in the new consolidated PWROG SAMG (Vayssier, 2014) to try to minimize the releases to the environment, see Fig. 9. The DPG indicates with colors and position, which SAG has priority to be initiated. Additionally, in this study the numbering of each SAG is updated to the new standard, (Gajdoš, 2017).

In this study, it is assumed that the initial response and TSC creation (SAG-1 and SAG-2) would take 30 min, so it is not possible to entry SAG-3 and below until 30 min have passed since the entry into SAMGs. Additionally, it is supposed that every time an entry condition into a SAG is satisfied and the TSC starts to follow the SAG steps, it would require at least 30 min to exit it, even if the conclusion is that no action is possible. For this example, we have used PWR-W generic entry values (T01, P01, *L*01, L02) to start each specific SAG, (CSN, 2019; Mena Rosell, 2017).

Observing at the DPG and Fig. 2, the first TSC SAG that will be entered by priority would be SAG-3 “Inject into the SG”; it will be initiated as soon as the MSC/TSC is conformed even though the SG level had dropped below the entry value 400 s after the beginning of the ST-SBO. As no actions are supposed to be performed, after 30 min, the next SAG to be entered would be SAG-4 “Depressurize the RCS” which had its

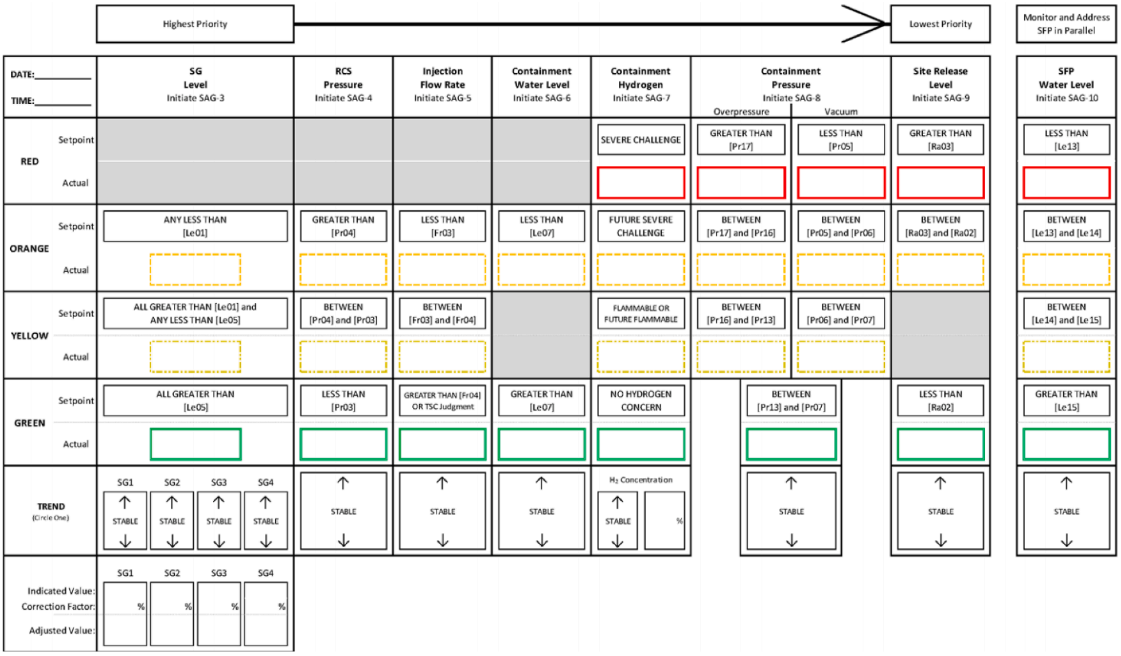

Fig. 9. Generic Diagnostic Process Guideline for PWR ((Martin Gajdoš, 2017; VAYSSIER, 2014)).

Table 2
Severe Accident Guidelines with entry conditions timings during the ST-SBO.

SAG	Entry Parameter	Entry condition satisfied
SAG-1: Initial response	Core Temperature	8500 s after SBO
SAG-3: Inject into the SG	SG level	(400 s after SBO). Could enter as soon as TSC is formed
SAG-4: Depressurize RCS	Pressure in RCS	Could enter as soon as TSC is formed.
SAG-5: Inject into RCS	RCS Temperature	8500 s after SBO
SAG-6: Inject into containment	Water level in Sump	Could enter as soon as TSC is formed
SAG-7: Reduce Containment Hydrogen	Hydrogen Concentration in containment	22700 s After SBO
SAG-8: Depressurize Containment	Pressure in Containment	(5000 s after SBO) Could enter as soon as TSC is formed
SAG-9: mitigate Fission product release	Radiation Dose	N/A
SAG-10: Inject into SFP	SFP level	N/A

entry condition satisfied since the beginning of the ST-SBO, Fig. 3, similarly to SAG-6 “Inject into containment”, but this last one has a lower priority, so it is checked afterwards. Continuing and after exiting SAG-4, the SAG-5 “Inject into the RCS” will be initiated because of the temperature in core surpasses the limit, Fig. 4. Following, the entry conditions to SAG-8 “Depressurize the containment” has been satisfied at 5000 s, see Fig. 5, but it will not be initiated because of priority after all the previous ones are done. Finally, the entry conditions to SAG-7 “Reduce Hydrogen in containment are satisfied at 22,500 s, Fig. 6. A Summary of the timing and entry conditions is presented in Table 2.

4.2. Identification of candidate high level actions and instrumentation associated.

During the present scenario, it is seen that there are many variables that provoke entries into different SAGs along the sequence. While following the correspondent SAG, a CHLA is normally initiated and developed and information about the plant status is needed before, during and after the development of the CHLA, see Table 3. All CHLA associated with each SAG are identified, and for the sake of clarity, a CHLA associated with SAG-5 and its required instrumentation is shown below:

CHLA “Inject into the RCS”: This CHLA will be initiated during SAG-5. Its goal is to prevent the core to heat up and provoke fuel melting, otherwise, fuel melting can occur. Several safety systems can be used for this purpose. The entrance to this action occurs when the core temperature exceeds a limit.

The instrumentation and measurements needed for this CHLA are the following:

Before the injection, it is necessary to estimate the core temperature with the Core Exit Thermocouples (CET), and/or the cold leg and hot leg Resistance Temperature Detectors (RTDs).

During the injection, a precaution must be made to not over pressurize the RCS. For this reason, the RCS pressure, the SGs pressure and SGs level must be monitored through the wide range RCS pressure, PZR pressure (with pressure transmitters), SG wide and narrow range levels and SG pressure.

After the injection, it is necessary to monitor the RCS Pressure (with wide range force-balance transmitters), RCS Temperature (with RTDs and CETs) and the water level (RVLIS and the Source Range Monitors) to confirm the adequacy of the CHLA.

The variables required for each SAG is summarized in Table 3, the instrumentation associated with the variables is associated in Table 4, (Basic, 2018; Basic, 2015). The Computational Aids (CAs) or other inferences are not taken into account as indicators of the value of the variable. Only instrumentation type A, B, C and D as per the Regulatory Guide 1.97 is used, (NRC, 1983).

4.3. Identification of the instrumentation degradation level

Given the CHLA actions with their corresponding need for data, the necessary instrumentation has been already identified. The indicator reliability is normally challenged during the course of the accident; however, it will not be evaluated in a binary form of functioning/not-functioning, but in a more continuous manner, using five stages of degradation or Damage Conditions (DCs). This range covers from normal operation to complete destruction of the instrument (see Table 5).

Table 3
Severe Accident Guidelines Instrumentation Requirements and related CHLAs.

SAG	CHLAs Associated	Variables used for entry, during and after CHLAs of SAG
SAG-1 Initial Response	Depressurize RCS Inject into RCS Inject into SGs	RCS/Core Temperature Containment Pressure Containment Temperature RCS Pressure H_2 Concentration in Containment SG water level SG pressure RPV water level
SAG-2 TSC Recommending Strategies	Creation of the TSC (not a CHLA)	–
SAG-3 Inject into the SG	Inject into the steam generators Depressurize SGs	RCS Pressure RCS/Core Temperature SG water level SG pressure
SAG-4 Depressurize RCS	Depressurize the RCS	RCS pressure Containment Pressure Hydrogen Concentration RCS/Core Temperature
SAG-5 Inject into RCS	Inject into the RCS Restart RCPs Depressurize SGs	RCS/Core Temperature RCS Pressure SG water level SG pressure RPV water level Containment Pressure Containment Temperature
SAG-6 Inject into containment	Spray into containment Inject into containment	Water level in sumps
SAG-7 Reduce Containment Hydrogen	Operate Hydrogen Recombiners Operate Hydrogen Igniters	H_2 Concentration in Containment
SAG-8 Depressurize Containment	Operate Fan Coolers Spray into containment Vent the Containment	Containment Pressure Containment Temperature H_2 Concentration in Containment
SAG-9 Site Release	Spray Buildings to Scrub Releases	N/A in the model
SAG-10 Inject into SFP	Inject into SFP Spray into SFP	N/A in the model

Table 4
Instrumentation used to obtain required SAG variables.

Variables	Instrumentation
RCS/Core Temperature	Core Exit Thermocouples Hot leg RTDs Cold Leg RTDs CVCS letdown (if operating) RHRS inlet (if operating)
RCS pressure	Wide Range RCS pressure PZR Pressure transmitter Accumulators Pressure transmitter Safety Injection header pressure or flowrate
SG level	Narrow Range SG Wide Range SG
SG Pressure	SG pressure FW Line Pressure
RPV level	RVLIS Source Range Monitor Power Range monitor
Containment Pressure	Containment Pressure wide range Containment Pressure narrow range Containment Spray, sump suction or H2 sampling lines.
Hydrogen Concentration	Containment Hydrogen monitors
Containment Temperature	Containment RTD
Containment Water Level	Sump level

Table 5
Damage Condition Ranges.

Damage Condition 1	**Normal Operating Conditions.** These are adequate conditions for the measurement. They usually lie within their EQ range.
Damage Condition 2	**Anomalous Operating Conditions I.** The operating conditions are challenging or above the EQ design, but useful measurements in tendency and values are still obtained.
Damage Condition 3	**Anomalous Operating Conditions II**. The limit is greatly surpassed, and measurements or values are no longer valid. The information on tendency and order of magnitude is still useful.
Damage Condition 4	**Damaged Operating Conditions**. The instrument measurements are only reliable in terms of tendencies, not values or orders of magnitude. It is not possible to recalibrate the instrument in this stage, so it's DC cannot decrease after reaching DC-4.
Damage Condition 5	**Destruction Conditions**. The measurements lack any value and they should not be used at all. The instrument became unreliable for future measurements whatsoever.

These five stages discretization can be useful as some measurements can be substituted or complemented by others in case the first ones are not fully reliable. Each instrument is identified with a location inside the computational MELCOR model explained in Section 2. The instrumentation locations are similar to the ones used in (Rempe et al., 2015), but they can vary for other NPPs.

To define the limits on which the instrumentation is supposed to work, several studies assumed that instrument performance is degraded if pressure, radiation dose and temperature exceed instrumentation EQ values (Chen and Huang, 2021; Hanson et al., 1994; Rempe et al., 2015). However, these studies recognized that the assumption of degraded instrument performance for any conditions exceeding the EQ might be conservative, particularly if the environmental conditions exceed the values by only a small amount or short periods of time. This is also confirmed by the experiments on hydrogen deflagration of (King et al., 1988; WEC, 1985) and TMI-2 accident (Rempe and Knudson, 2013). Additionally, even though some instruments have a wide EQ range (i.e. RCS RTDs), the accuracy of the measurements is strongly reduced at high temperatures and this will be noted in the DC. Finally, some instrumentation has components inside the RCS and inside the containment; the components that lie in containment such as wires, are treated in the same way as the containment instrumentation.

Then, to set the damage condition of each instrument, several references have been used and merged on the generic PWR-W instrumentation simulated, (Arcieri and Hanson, 1992; Bachellerie et al., 2003; Chien and Hanson, 1991; EPRI, 1993; Giot et al., 2017; Hanson et al., 1990; Horn et al., 1993; Rempe et al., 2015; Rempe and Knudson, 2013), (see Table 6 and Table 7). In particular, the limits behind each choice are explained below:

1. The **Wide Range RCS Pressure** Transmitter EQ ranges from 0 to 20 MPa, however, given that the system works using differential pressure between the containment and the RCS if the Containment pressure is high and the RCS pressure is low, the inaccuracy of the measurement is increased. Additionally, this measurement can be also influenced by the evaporation of the reference water column and provide inaccurate measurements as it was the case for Fukushima accident, (Ishikawa, 2015; Nozaki et al., 2014; TEPCO, 2017), This evaporation is supposed to begin 30 min after the containment temperature has exceeded 422 K, (Clayton and Poore, 2013). Finally, if the fluid temperature exceeds 1530 K in the pressure measurement point (e.g. RHR injection point) or in the containment atmosphere, the sensor is supposed to fail.
2. The **Pressurizer Pressure** Transmitter has a generic range from 11 MPa to 20 MPa, so it does not provide information below 11 MPa. Additionally, as the RCS pressure transmitter, if the temperature exceeds 1530 K, it is assumed to fail.

Table 6
Degradation Level for NPP Instrumentation during a SA.

	Wide Range RCS Pressure	Pressurizer Pressure	Accumulators Pressure	Core Exit Thermocouples	Hot Leg RTDs	Cold Leg RTDs
DC-1	Range (0–20 MPa)	Range (11–17.2 MPa)	Range (0–5.5 MPa)	Range (273–645 K)	Range (273–645 K)	Range (273–645 K)
DC-2	P_{RCS} <0.25 MPa & P_{Cont} >0.2 MPa CEC > EQ	CEC > EQ	CEC > EQ	645 K < T_{core} <923 K	645 K < T_{RCS} <873 K	645 K < T_{RCS} <873 K
DC-3	30 min after T_{cont} >422 K	–	–	923 K < T_{core} <1173 K	–	–
DC-4	–	–	After RCS full depressurization	1173 K < T_{core} <1530 K	873 K < T_{RCS} <1530 K	873 K < T_{RCS} <1530 K
DC-5	T_{cont} >1530 K	T_{cont} >1530 K	T_{cont} >1530 K	T_{core} >1530 K	T_{RCS} >1530 K	T_{RCS} >1530 K

Table 7
Degradation Level for NPP Instrumentation during a SA.

	RVLIS	Source/Power Range Monitors	Containment Recirc Sump Level	Hydrogen Measurement	Containment RTD Temperature	SG Water Level
DC-1	Range (0–100%)	Range 0 – 10^6 Range 0 120%	Range (0–2.74 m)	Range (0–10% H_2)	Range (273–422 K)	Range (0–100%)
DC-2	CEC > EQ	CEC > EQ	CEC > EQ	CEC > EQ	CEC > EQ	CEC > EQ
DC-3	30 min after T_{cont} >422 K	After Core Melt	–	–	T_{cont} >673 K	30 min after T_{cont} >422 K
DC-4	After Core Melt	After Core Relocation in LP	–	–	–	–
DC-5	After LP core relocation	After RPV Failure	After RPV Failure	After RCS/RPV Failure with core damage	T_{cont} >1530 K	T_{cont} >1530 K

3. The **Accumulators Pressure** transmitters can also be used to assess RCS pressure. They generally have a range from 0 to 5.5 MPa. Its DC behavior is similar to the PZR Pressure transmitters. Additionally, this measurement will not be able to observe RCS re-pressurizations, because of the non-return valves in the Accumulator lines.
4. The **CET,** normally they are Type K Thermocouples and have an EQ range from 373 to 1530 K, however, their accuracy is reduced as the temperature increase because the potential for electrical shunting between the thermocouple elements can introduce significant errors. The CETs are supposed to fail because the metallic parts will melt above 1530 K. This is noted in four stages of CET degradation.
5. The **Hot Leg RTDs and Cold Leg RTDs** have a similar approach as the CETs. As the temperature increases, the accuracy diminishes, until its possible melting at 1530 K.
6. **RVLIS** provides the water level in the RPV, but it is based on differential pressure between the upper and lower plenum. Therefore, its DC is alike to the RCS Pressure Transmitter with the addition that if the core melts and it is relocated in LP, core debris can enter the measurement tap and can interfere with the measurement. This measurement can be also influenced by evaporation of the reference water column, like the Wide Range RCS Pressure Transmitter, and provide inaccurate measurements (Nozaki et al., 2014).
7. **Source and power Monitors** for RPV level. The source is an ex-core ionization chamber that may provide useful information on RPV water level. When the core starts to degrade and melt the accuracy becomes very limited. This is also true for the power monitor. Additionally, if the temperature in containment exceeds the EQ limit, the instrument may have a reduced accuracy.
8. **The Containment Hydrogen Monitor** measurements are normally made through a sample line that connects the containment atmosphere with the auxiliary building. These measurements can be affected by the containment humidity, as the condensation in the tube may lead to an erroneous value, and additionally, after core melting and RPV failure or RCS breach, these lines are a path for FP to bypass the containment so they should not be used.
9. **Containment Temperature RTDs** are assumed to work under containment EQ conditions, but their accuracy can be extended into SA conditions. Therefore, its DC evolution is similar to RTDs platinum or nickel type.
10. **Wide Range Containment Pressure**. These sensors and transducers are located outside containment, in the auxiliary building. Therefore, the conditions where they measure should not be so severe as to result in the failure of the sensors or the transducers. Thus, the containment pressure indication is expected to be reliable for all phases of a SA.
11. **Sump Water Level.** This measurement is subject to the containment conditions, but after RPV Failure, this measurement can provide unrealistic values because of the possible interaction with corium or debris and the pressure taps.
12. **Steam Generators Wide and Narrow Range level.** The SG level is normally supposed to function during all stages of a SA; however, similar to the RVLIS, the reference water column is located in the containment, and it could be subject of evaporation after certain amount of time.
13. **Steam Generators Pressure.** The SG pressure is measured outside containment, and therefore it is supposed to be functional during the full SBO.

Additionally, the aforementioned instrumentation with containment components, could be subject to DC-2 if the Containment Environmental Conditions (CEC) exceed the EQ. The CEC used for this generic PWR are 422 K for temperature limit and 480 kPa for pressure in 100 % relative humidity conditions, (IEEE, 2003). Furthermore, these instruments can reach DC-5 if the containment conditions are so harsh that the instrumentation wires that connect with the control room are damaged; this is supposed to occur at a containment temperature of 1560 K, based on (WEC, 1985).

Finally, some instrumentation would have reduced accuracy because of additional phenomena that occurs during a SA sequence, such as cracking of the thermowell or opening of the platinum element in RTDs from a strong shock/vibration (Hashemian and Jiang, 2009), or the spraying with cold water of an overheated component. As these phenomena are not easily traced with a SA code and they are not normally taken into account (Rempe et al., 2015), they are not included in the present methodology. Finally, damage induced by radiation is not included in the present study but it is expected to be included in the future.

4.4. *Evolution of the instrumentation survivability during the accident*

Once the DC of each instrument used for applying each SAG is set, its condition can be assessed in a continuous manner during the accident.

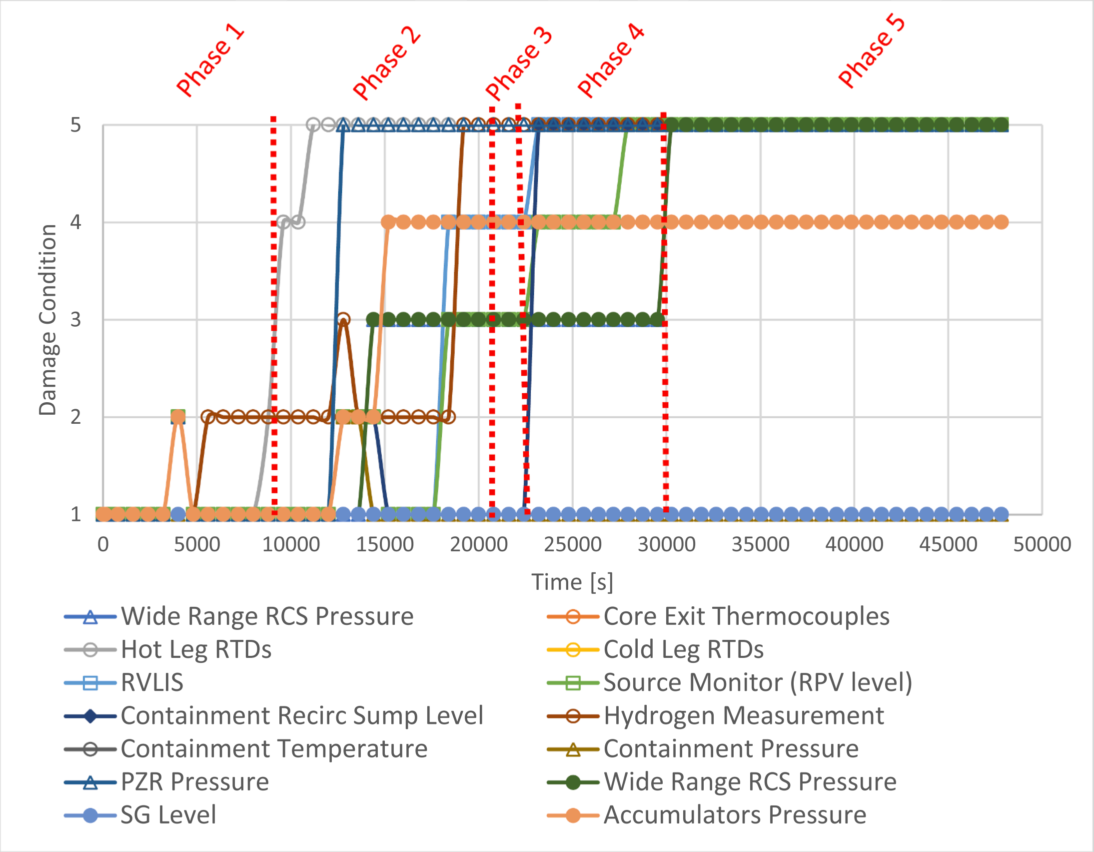

Fig. 10. Damage Conditions for all Indicators and accident phases as per (Hanson et al., 1994).

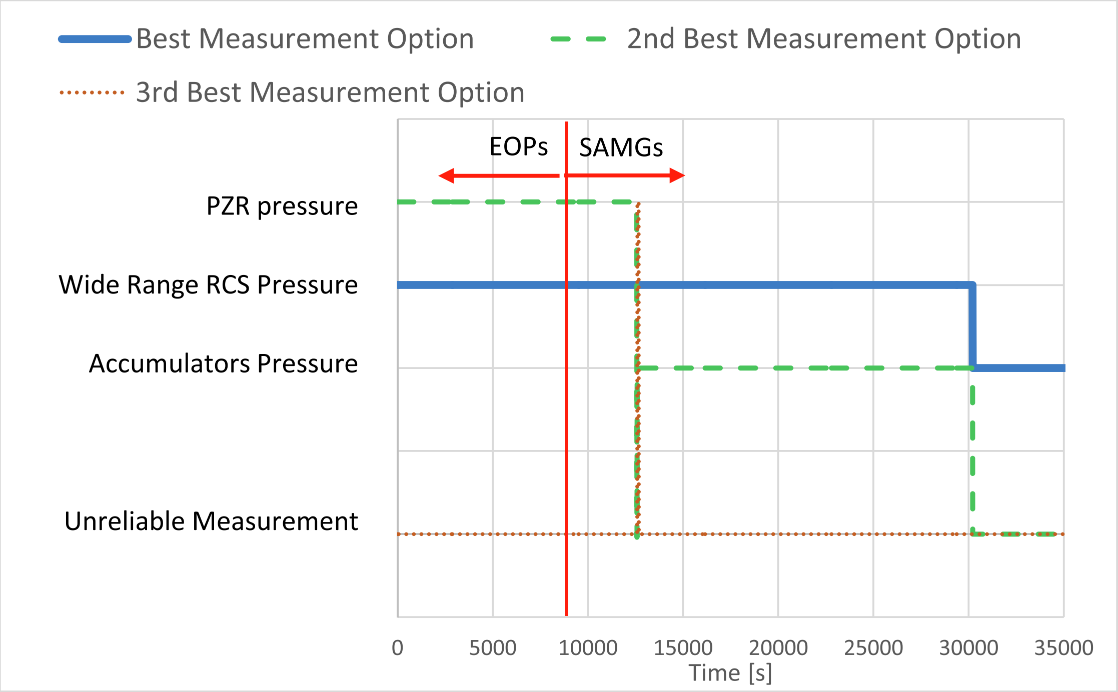

Fig. 11. Best Measurement for RCS Pressure.

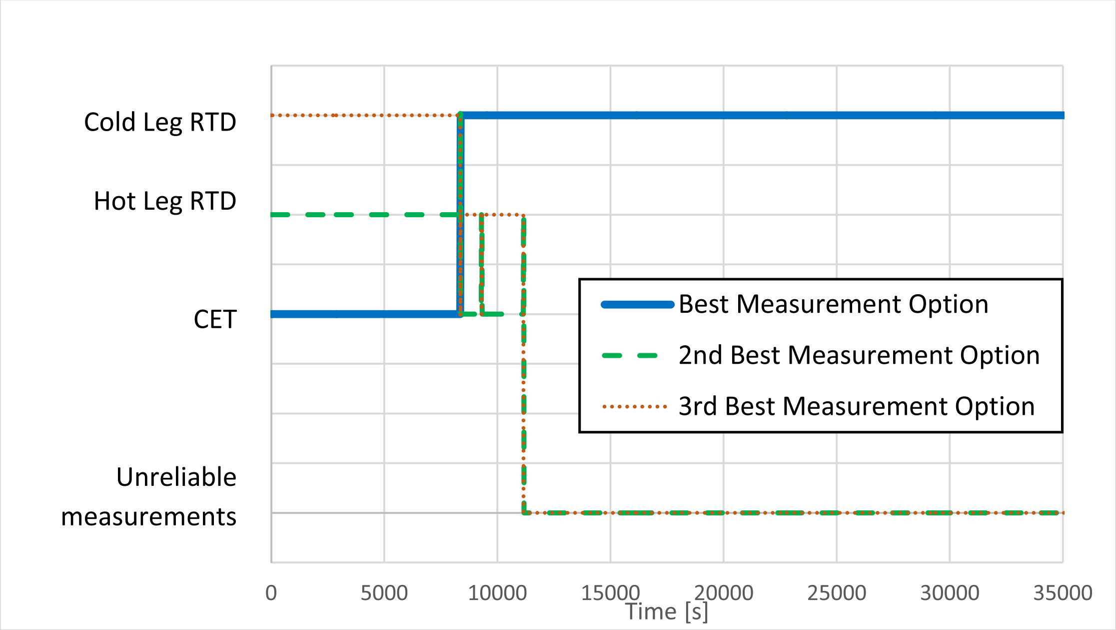

Fig. 12. Best Measurement for Core Temperature.

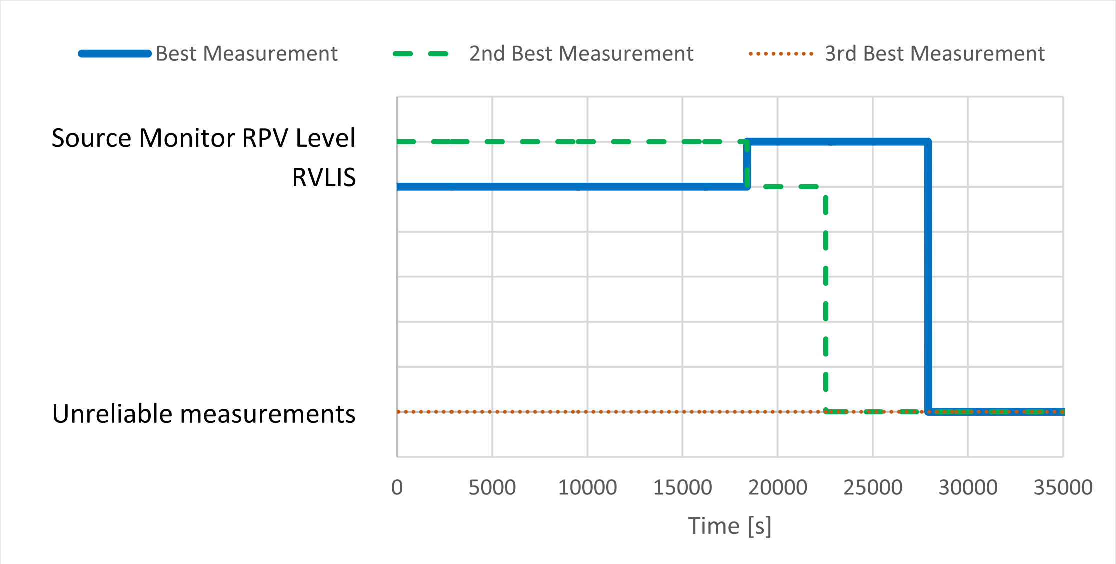

Fig. 13. Best Measurement for RPV Level.

The evolution of the DCs of the different indicators is shown in Fig. 10. The measurements are generally reliable until the core starts to heat up after 7500 s. As the RCS heats up, some of the indicators reach the destruction condition (DC-5), because the temperature is too high; and after the creep RCS rupture, those indicators should not be used.

After the core temperature rises over the SAMGs entry, the SAG-3 and SAG-4 would be initiated to try to maintain the core cooled. From the MCR/TSC staff point of view, after the core damage occurs (8500 s), the less damaged indicators are the cold leg RTD, and wide range RCS pressure measurement. So, to obtain RCS information, these indicators should be first observed, see Figs. 11-15. After relocation of the core into the lower plenum, some indicators are completely destructed; and the best options to obtain information about the core may be to recall previous information. Then, after the RPV failure (29500 s), just a couple of instruments are still valid to evaluate the plant conditions.

In Fig. 11 it is seen that the Wide Range RCS pressure is the best measurement until the PZR creep rupture, and after its water reference column has been partially evaporated, the accumulators pressure is the best option until the RCS full depressurization. Fig. 12 shows that the RCS and core temperature best measurement option is the cold leg RTDs when the core heats up previously to the PZR surge line creep rupture. The best measurement to obtain the RPV level, shown in Fig. 13, changes from the RVLIS to the source monitors when the corium relocates to the lower plenum. The choice for best measurement for SG level, Pressure and containment do not change during the whole simulation. It is remarkable that the hydrogen concentration entry condition should only be assess through the Computational Aids, as the only instrument to obtain the entry value cannot be used, see Fig. 16.

When observing the timing of entry into the different SAGs, it is seen that one of the most problematic entry condition assessment will be for the SAG-5 “Inject into the RCS”. When the core temperature surpasses the SAG entry condition, the CET and Hot Leg RTDs almost fall in the

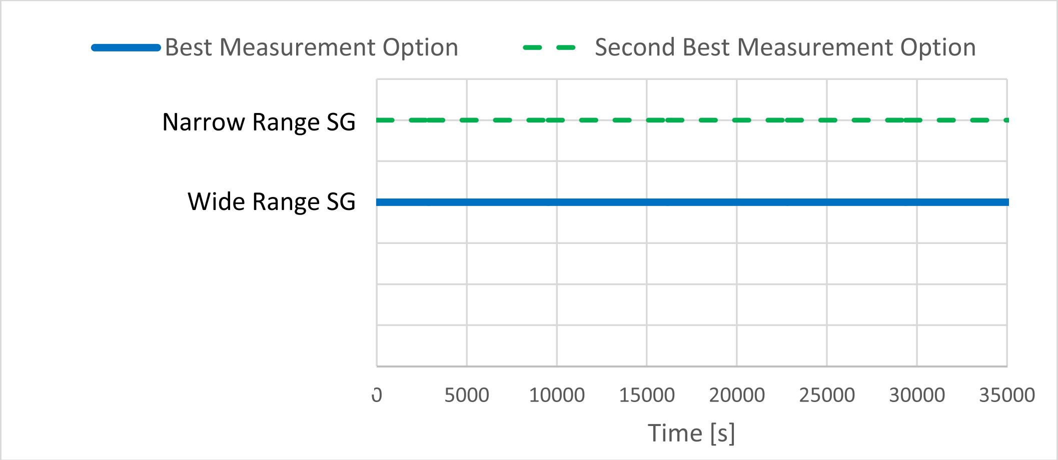

Fig. 14. Best Measurement for SG Level.

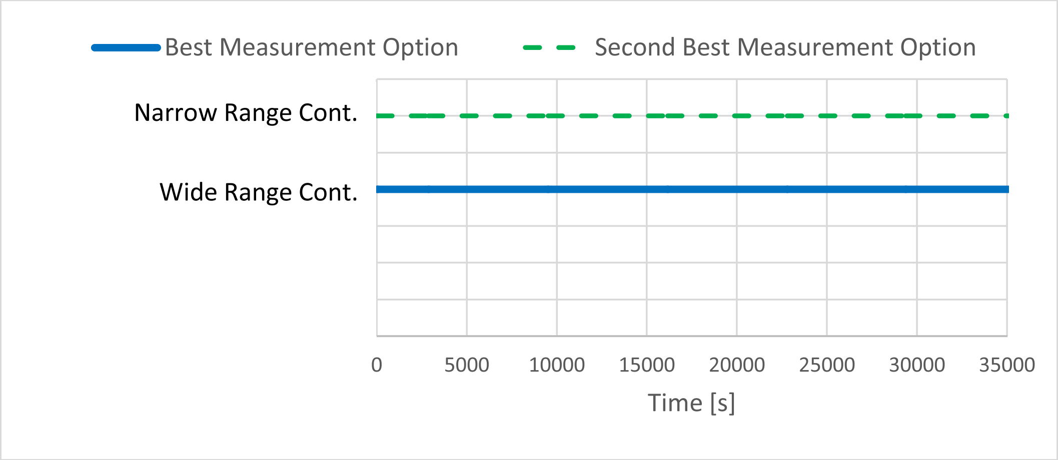

Fig. 15. Best measurement for Containment pressure.

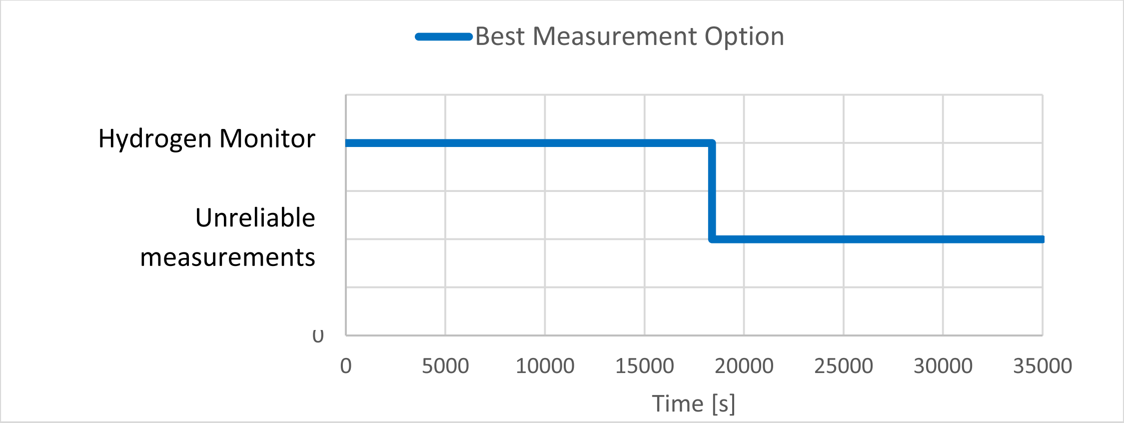

Fig. 16. Best Measurement for Hydrogen Concentration in containment.

DC-4 and reach destruction conditions soon after. For this reason, it would be key to use the cold leg RTD to assess the core state in this stage of the accident.

Comparing these results to previous literature, (Hanson et al., 1994; Hanson et al., 1990), it is seen that the instrumentation available for the different phases is merely similar, with some differences on the state of the cold leg RTD and the neutron source monitors. Accordingly, the previous literature considers the instrumentation impaired without having reached DC-5 in the present analysis.

Taking into account that no human actions are included in this analysis, the summary of entries into the different SAGs is shown in Table 8, accounting for 30 min to exit a SAG on which no action can be made. If this information is available to the TSC crew, they will be in a favorable position when determining which instrument provides the

Table 8
Summary of Actions and measurements needed during the accident.

Timing of Events	Action	Instruments used for Action
0 s	Start of the ST-SBO	N/A
8500 s	Entry into SAMGs, Entry into SAG-1 and SAG-2, beginning of formation of TSC	Core Exit Thermocouples (Best)
10300 s	Entry into SAG-3	Wide Range SG (Best) Narrow Range SG (Second Best)
12100 s	Exit SAG-3 and entry SAG-4	RCS pressure wide range (Best) PZR Pressure (Second Best) Accumulators Pressure (Not reliable)
13900 s	Exit SAG-4 and entry SAG-5	Cold Leg RTDs (Best) Core Exit Thermocouples (Not reliable) Hot leg RTDs (Not reliable)
15700 s	Exit SAG-5 and entry SAG-6	Water level in sumps (Best)
17,500	Exit SAG-6 and entry SAG-8	Containment Pressure wide range (Best) Containment Pressure narrow range (Second Best)
19,300	Exit SAG-8 and entry SAG-3	Wide Range SG (Best) Narrow Range SG (Second Best)
21,100	Exit SAG-3 and entry SAG-4	RCS pressure wide range (Best) Accumulators Pressure (Second Best) PZR Pressure (Not reliable)
26,500	Entry SAG-7	Hydrogen Monitor System (Unreliable). Use of computational aids as only option.
26500-end	Entry into different SAGs	No change in Best option for measurement until the end of simulation.

most reliable information to develop the correspondent CHLA.

The final outcome of this work can be summarized in Fig. 17 on which the applicability of the SAG is assessed. On this picture the “Good” status means that all instrumentation that could be used to develop the SAG (As seen in Table 3 and Table 4), is in DC-1. The “Careful” status implies that at least one instrument has reached DC-2 or higher. The “Warning” status indicates that at least one variable to develop the SAG has all its related instrumentation with DC-2 or more, and finally the “Blind” status means that all instrumentation related to the application of the SAG is under destruction conditions, (DC-5). This manner of showing the SAG information could be useful for the TSC when dealing with an accident.

5. Conclusions

The right interpretation of instrumentation measurements during a SA is a key point for implementing the CHLAs of each SAG in a successful manner. CHLAs development requires measurements before, during, and after an accident to control different effects CHLAs provokes on the plant state.

The present paper has presented a methodology for assessing instrumentations survivability in a continuous manner. To assess the measurement reliability, five different DCs are set, ranging from a slight loss in accuracy, to the complete destruction of the instrument. The DC have been determined using the existing bibliography on causes of damage for all the indicators. These different DCs could help TSC staff to make decisions about the reliability of certain measurements.

As an example, a ST-SBO has been simulated in a PWR-W with the MELCOR 2.2 code. In this accident, several SAG entry conditions of the DPG will be satisfied leading to CHLAs requiring several measurements about the state of the plant. In this sequence, the different instrumentation DC vary during the accident, the best measurement varies as the sequence progresses, and the entry conditions should be assessed with different instrumentation because some measurements are unreliable. For example, after core damage, the cold leg is the best temperature measurement option during most of the sequence. Additionally, if the instrumentation associated with each SAG is cross checked with its DC, it is possible to know the potential misinformation the TSC would face while dealing with the accident, through the SAGs

In this work, only the instrumentation DC has been assessed.

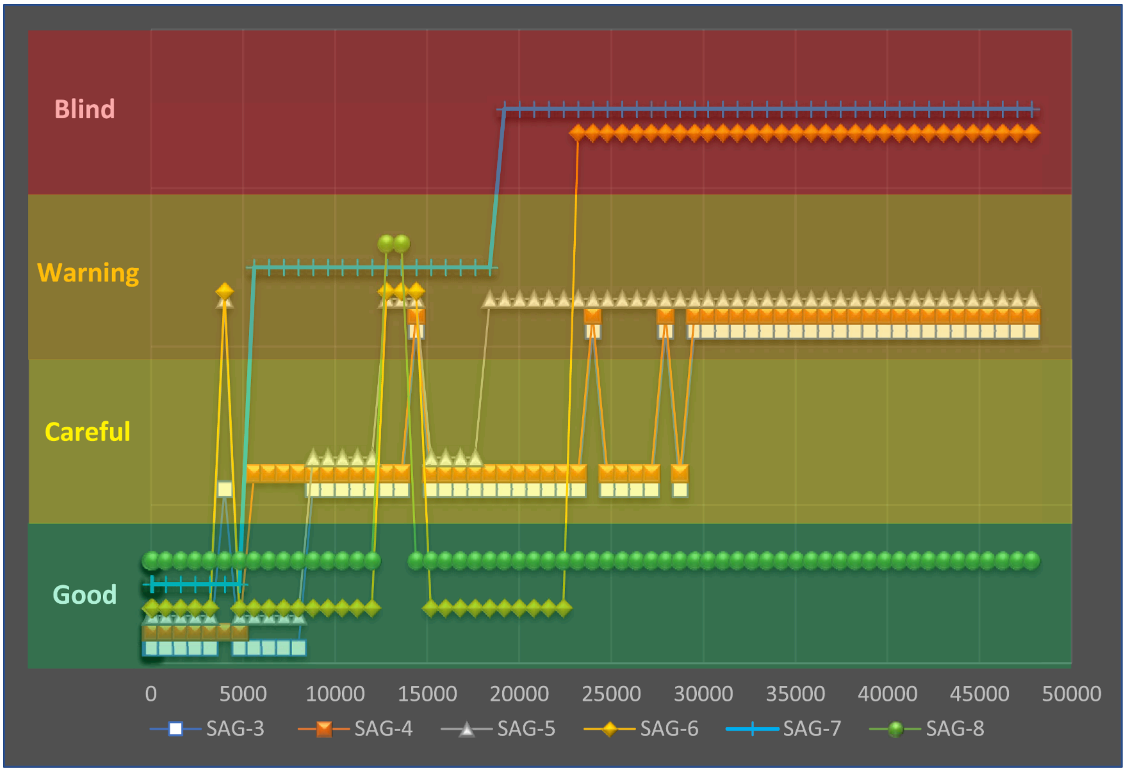

Fig. 17. SAG Application status along the ST-SBO.

However, as indicated by (Farmer et al., 2015), the key elements to study during a SA include also the equipment and penetrations survivability. Future applications of this method of continuous screening will be used to evaluate the survivability of equipment such as valves, safety injection systems, and the containment penetrations, and also include radiation damage; but more important, it can be applied to a wide range of sequences to provide the TSC/MCR, as much information as possible if they are able to identify the sequence they are experiencing for training purposes.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been performed in the framework of CSARP agreement between CSN and UPM. The authors acknowledge the previous works of the UPM MELCOR models performed by Francisco Martin-Fuertes, Juan Manuel Martín-Valdepeñas, Rafael Bocanegrea and Gonzalo Jimenez.

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