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AMHYCO

Enhancing H_2 & CO Combustion Risk Management

Research and Innovation Action

NFRP-2019-2020

D1.1 Critical assessment of key elements of combustible gases management in containment

WP1 – final report

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Executive Summary

During the course of a severe accident (SA) in a light water nuclear reactor, large amounts of hydrogen could be generated and released into the containment during reactor core degradation. Additional burnable gases (CO) may be released into the containment in case of molten corium/concrete interaction (MCCI). This could subsequently raise a combustion hazard. As observed during the Fukushima accidents, hydrogen and carbon monoxide combustion could cause high pressure peaks that could challenge the reactor containments and lead to the failure of surrounding buildings and to the loss of the safety equipment. To minimize this risk, most of the mitigation strategies adopted in European countries are based on the implementation of Passive Autocatalytic Recombiners (PARs). Nevertheless, studies of representative accident sequences indicate that, despite the installation of PARs, it is difficult to prevent, at all times and for each location, the formation of a combustible mixture potentially leading to local flame acceleration. To better understand the phenomena associated with the combustion hazard and to address the issues highlighted after the Fukushima Dai-ichi events, such as the explosion hazard inside the venting systems, or the potential flammable mixture migration into spaces beyond the primary containment, the AMHYCO project aims to propose innovative enhancements in the way combustible gases are managed in case of a severe accident in currently operating reactors.

For this purpose, the AMHYCO project pursues three specific activities, including experimental investigations of relevant phenomena related to hydrogen / carbon monoxide combustion and mitigation with PARs (Passive Autocatalytic Recombiners), improvement of the predictive capabilities of analysis tools used for explosion hazard evaluation inside the reactor containment, as well as enhancement of the Severe Accident Management Guidelines (SAMGs) with respect to combustible gases risk management based on theoretical and experimental results.

As first step, a critical review of the available literature had been performed with the objective to form the basis for the project regarding (1) PAR efficiency under ex-vessel conditions, (2) existing PWR SAMGs regarding containment risk management (3) H_2/CO combustion and the available engineering correlations for combustion risk estimation, (4) equipment and instrumentation surveillance under severe accident conditions.

This report provides a survey on the available literature related to the four topics mentioned above. This report is made up of four separate chapters, each dealing with one of the aforementioned topics:

Chapter 1 provides an overview on the available experimental data and on existing model related to PARs behaviour under ex-vessel conditions (CO, lack of O_2, high pressure, high temperature). The performed survey shows that separate and integral tests were conducted at intermediate and large-scale facilities providing details that help improving the PAR models. Even if most of the

performed experiments are relevant to in-vessel conditions, recent investigations were performed to provide data concerning PARs behavior in conditions with presence of CO and lack of oxygen that are relevant for severe accident late phases. Actually, several experimental programs have been conducted to study the effect of carbon monoxide on PAR operation. The observations range from CO conversion to CO_2 without any interference with the hydrogen recombination to full catalyst deactivation due to catalyst poisoning. Until now, the conditions for the transition between both regimes are unclear as well as the PAR deactivation mechanisms.

Regarding PARs modelling, several approaches were developed ranging from engineering correlations to more details CFD models taking into account all relevant phenomena as thermal radiation, detailed chemical reactions on the surface and in the gas. The engineering correlations are usually implemented in the safety simulation codes (both LP and CFD) and help performing scenarios analysis to assess the PAR design. On the other hand, the PAR detailed models help understanding the phenomena that affect the PAR operation and provide then ways to improve the engineering correlations (PAR ignition limit definition for example). Both engineering and detailed models were validated on experiments dealing with hydrogen. Their validation on conditions with carbon monoxide is still unsatisfactory due to the lack of adequate experiments. This issue will be addressed in the framework of the WP3 of the AMHYCO project. Consequently, the experimental program in WP3 will provide data to improve the engineering PAR models to be implemented in the safety tools and used in the framework of WP4 to simulate severe accident scenarios including late phases.

Chapter 2 provides a survey on the hydrogen management requirements, on the related mitigation measures in use in the operating PWRs in Europe, Asia and America and on the considerations adopted in severe accident management strategies to prevent adverse effects that engineering systems (i.e., sprays, containment venting, local air cooler, suppression pool, latch systems) actuation may have regarding the hydrogen risk. This survey emphasized the following:

- The adopted requirements address only in-vessel phase and aim to preserve the containment integrity. The availability of the safety systems, as sprays or venting line, which could be needed to manage the severe accident late phases, is not considered.
- Only few countries adopt quantitative criteria for the requirement.
- The mitigation means are designed accordingly to the adopted requirements for in-vessel conditions.
- Only few existing SAMG recommendations concern the use of safety systems (CHRS, sprays and coolers) in case of severe accident late phases.
- The existing monitoring systems do not measure carbon monoxide concentration.

This chapter be used as a reference for WP4 and WP5 where the possibility of SAMG extension will be addressed.

Chapter 3 aims to provide a critical assessment of the H_2/CO combustion engineering correlations and models and their validation status. For this purpose, a survey of flammability limits and flame acceleration criteria relevant to severe accident late phases conditions is provided. Thus, the effect of oxygen starvation, of the initial temperature, of the initial pressure, of diluent (steam, carbon dioxide) and of the carbon monoxide is discussed. Similarly, a survey of the existing engineering combustion models and their validation status is provided. This review shows that the H_2/ CO combustion in representative conditions of severe accident late phases is poorly investigated. Only few data are available in the open literature. Thus, additional experimental and theoretical investigations are needed to fill the observed knowledge gaps. This issue will be addressed in the framework of the WP3 of the AMHYCO project. Consequently, the experimental program in WP3 has to provide corresponding both fundamental data, as laminar flame speed or turbulent flame speed, and correlations, as flammability limits or flame acceleration criteria. The obtained experimental results will help improving the existing engineering combustion models to cover the conditions expected in the late phases of severe accident.

Chapter 4 reviews the main criteria and principles of Environmental Qualification and Survivability Assessment and aims to serve as a technical data repository of interesting values of the main stressors assessed in PWR NPP qualification programmes in European and non-European countries. Both Design Basis Accident (DBA) and Design Extension Conditions with core melting (DEC-B) are considered. The DBA qualification is explained in more detail in this review, as licensing procedures and information are more standardized than in the case of SA instrument surveillance. Also, SA survivability assessments generally rely on DBA criteria, so technical data and procedures should be compared to their more developed EQ counterparts.

This chapter should be used as a reference technical document for further AMHYCO WPs, namely WP4 where equipment and instrumentation surveillance under SA scenarios will be compared with the data gathered in this report, and WP5 where proposals for SAMG long-term-operation improvements and guidelines for equipment and instrumentation survivability assessment will be given, considering typical containment qualification requirements as the ones described herein.

Abbreviations and Acronyms

Acronym	Description
BDBA	Beyond Design Basis Accident
BWR	Boiling Water Reactor
BWROG	Boiling Water Reactor Owners Group
CA	Computational Aid
CHLA	Candidate High-Level Action
CHRS	Containment Heat Removal System
CFD	Computational Fluid Dynamics code
DBA	Design Basis Accidents
DBE	Design Basis Event
DEC	Design Extension Conditions
DOE	Department of Energy (USA)
EMC	Electromagnetic Compatibility
EOP	Emergency Operating Procedures
EPRI	Electric Power Research Institute
ERT	Emergency Response Team
EQ	Environmental/Equipment Qualification
EQML	Environmental Qualification Master List
FCVS	Filtered Containment Venting System
GDC	General Design Criteria
GOTHIC	General-purpose containment code with 3D capability, developed by NAI

HELB	High Energy Line Break
I&C	Instrumentation and Control
IAEA	International Atomic Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
KWU	Kraftwerk Union AG
LDB	Licensing Design Basis
LFL	Lower flammability limit
LOCA	Loss-Of-Coolant Accident
LP	Lumped Parameter code
LTO	Long Term Operation
LWR	Light Water Reactor
MCCI	Molten Core/Concrete Interaction
MSLB	Main Steam Line Break
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
OBE	Operating Basis Earthquake
OSSA	Operating Strategies for Severe Accidents
PASS	Post-Accident Sampling System
PAR	Passive Auto-catalytic Recombiner
PWR	Pressurized Water Reactor
RPV	Reactor Pressure Vessel
SA	Severe Accident
SAM	Severe Accident Management

SAMG	Severe Accident Management Guidelines
SBO	Station Blackout
SOAR	State-Of-the-Art Report
SRP	Standard Regulatory Plan (NRC)
SSCs	Systems, Structures and Components
SSE	Safe Shutdown Earthquake
SFP	Spent Fuel Pool
RG	Regulatory Guide
RHR	Residual Heat Removal
PIE	Postulated Initiating Event
PWR	Pressurized Water Reactor
PWROG	Pressurized Water Reactor Owners Group
PAICC	Pressure peak obtained by considering adiabatic, complete and isochoric combustion
Y^+	Non dimension thickness of the shear layer
UFL	Upper flammability limit
WP	Work Package

Foreword

This report is a collective work prepared by the AMHYCO project members. Members from the Advisory Board and the End Users Group took part in carefully proofreading various chapters. We would like to express our thanks to all those who contributed in one way or another to this report.

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Chapter 1:

Overview on PAR behavior in SA late phases conditions

1. Introduction

During the course of a severe accident (SA) in a light water nuclear reactor (LWR), large amounts of hydrogen (H_2) could be generated and released into the containment during reactor core degradation and vessel components oxidation. Additional burnable gases (H_2 and CO) may be released into the containment in case of molten core/concrete interaction (MCCI). This could subsequently cause combustion in the containment building, if ignited. As observed during the Three Mile Island Unit I and the Fukushima Dai-ichi accidents, hydrogen combustion could cause high pressure peaks that could damage the containment building (and/or the reactor building for BWRs) and eventually lead to the failure of surrounding buildings. An explosion may also be a safety concern in spent fuel storage areas, where flammable conditions may be reached if, under accident conditions, the fuel is not correctly cooled and an adequate ventilation is not provided. In any of these cases, the explosion may lead to radioactive products release into the environment. To prevent explosions, most of the adopted mitigation strategies are based on the implementation of Passive Autocatalytic Recombiners (PARs).

To characterize PARs performance and their behavior within severe accident representative conditions, experimental and theoretical investigations have been performed by industries, research centers and universities in last decades. These investigations were made considering only the in-vessel conditions where the reactor containment atmosphere is mainly composed of H_2, steam and air.

The knowledge gained in the early research helped establishing the design of PARs and their implementation in the reactor containment to satisfy the adopted safety requirements (Lopez-Alonso, E. Papini, & Juménez, 2017). Nevertheless and despite the installation of PARs, studies of representative accident sequences indicate that it is difficult to prevent, for all times and locations, the formation of a combustible mixture potentially leading to local flame acceleration.

Regarding the PARs performance in ex-vessel representative conditions, only a few investigations were performed recently (see details in Section 2). For this purpose, dedicated experimental and theoretical investigations are planned in the framework of the WP3. To give a bibliographic support of this work, this report aims to provide an overview of available data relevant to late phases conditions of severe accidents.

2. Overview on PARs experimental programs

As a catalytic recombiner is self-starting and self-feeding and does not requires external power to work, that is why it is called “passive”. A passive autocatalytic recombination starts up when the hydrogen concentration exceeds 1-2 %vol. The chemical reaction between hydrogen and oxygen to form water vapor is exothermic and starts only after overcoming the required activation energy and reaching specific concentration conditions, like H2 concentration being around 1-2%. The heat of catalytic reaction drives flow through the recombiner by natural convection, which continuously brings gas containing hydrogen from the surroundings into the PAR, thereby developing a self-sustained process (Figure 1).

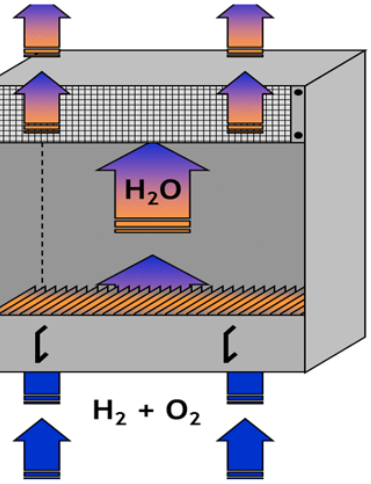

Figure 1: PAR operation scheme

Different PAR models were developed by several manufacturers around the world. Depending on the PAR design, the catalytic module may have different shape (sheets for Framatome/Areva/Siemens and AECL/CNL PARs, cartridges filled with pellets for NIS PARs and honey comb for Korean and Russian PARs).

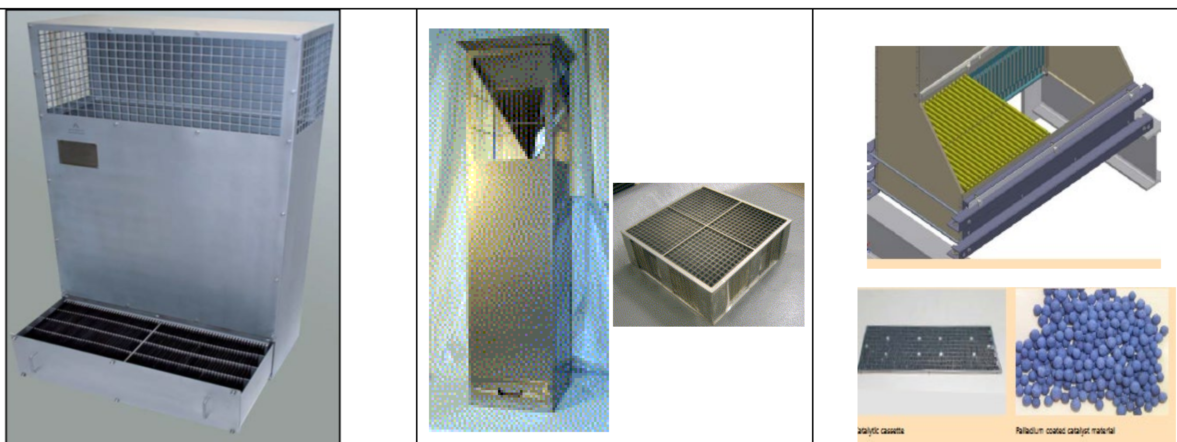

Figure 2: Examples of PAR design (a) with catalytic sheets, (b) honeycomb (c) pellet cartridges

Before implementing PARs inside the reactor containment, extensive qualification tests campaigns were performed by the manufacturers with the objectives to comply with the following major design features (Bachellerie, 2003):

1) Have a low self-starting threshold hydrogen concentration (2-3 % vol.),

2) Be active in low oxygen concentrations (< 5%vol) (pre-inerting BWR, post-inerting submarine reactors),
3) Be active at low temperatures (from 15-50 °C depending on the applications),
4) Withstand high catalyst temperature (700-800 °C),
5) Be active in pressurised atmosphere (several bar),
6) Be active in saturated steam or with high wetness level (line break, spray system),
7) Be insensitive to the carbon monoxide (due to corium-concrete interaction after vessel rupture),
8) Accept up to 400-500 kGy absorbed radiation dose,
9) Have a long lifetime (equal to those of nuclear power plants),
10) Be insensitive to poisoning during accident conditions:
    a. Iodine and aerosols produced by core melting (both radioactive and non-radioactive isotopes),
    b. Organic iodine produced by chemical reactions between molecular iodine and paints,
    c. Fire products, such as carbon, sulphur, hydrochloric and sulphuric acids,
    d. Boric acid present in primary water and released with steam.

Besides these development tests performed by manufacturers, qualification test programs were conducted (Leteinturier, et al., 1998) in several research centres to measure PARs depletion rates under a range of hydrogen concentrations, steam/pressure conditions and various potential adverse poisoning conditions. More recently, detailed investigations (Poss, 2010) (Liang, Gardner, & Clouthier, 2020) (Klauck, et al., 2016) with highly instrumented facilities have been performed to address phenomena not yet fully understood, to provide details needed for code validation and to study conditions not addressed before.

The aim of this section is to provide a brief overview on the outcomes of the past and recent experimental programs related to PAR operation with a focus on conditions relevant to late phases of severe accidents, such as low oxygen concentrations, carbon monoxide, high gas temperature and high pressure.

2.1. Insights from experimental programs (up to 2000)

This section provides, based on publicly available data, an overview of the main outcomes of experiments performed before the year 2000. The objective is to highlight, when possible, the main outcomes related to conditions to be addressed in the framework of the AMHYCO project. The most recent experimental programs will be described in the next section.

Following the outcomes of the European PARSOAR project (Bachellerie, 2003), which summarized the state of the art on PARs and released a handbook for PAR implementation in nuclear power plants, four main experimental programs were initiated in Canada, USA and Europe with facilities of different scales.

2.1.1. Experimental programs

Battelle Model Containment Facility

The Battelle Model Containment (BMC) was designed according to the geometry of a down-scaled German nuclear power plant (see Figure 3). The cylindrical multi-compartment containment model with a diameter of 12 m had a height of 9 m. The experimental program investigated the performance and effect of Siemens (today Framatome) and NIS PARs in a multi-compartment geometry under conditions of stratified and homogeneous steam-air-hydrogen mixtures.

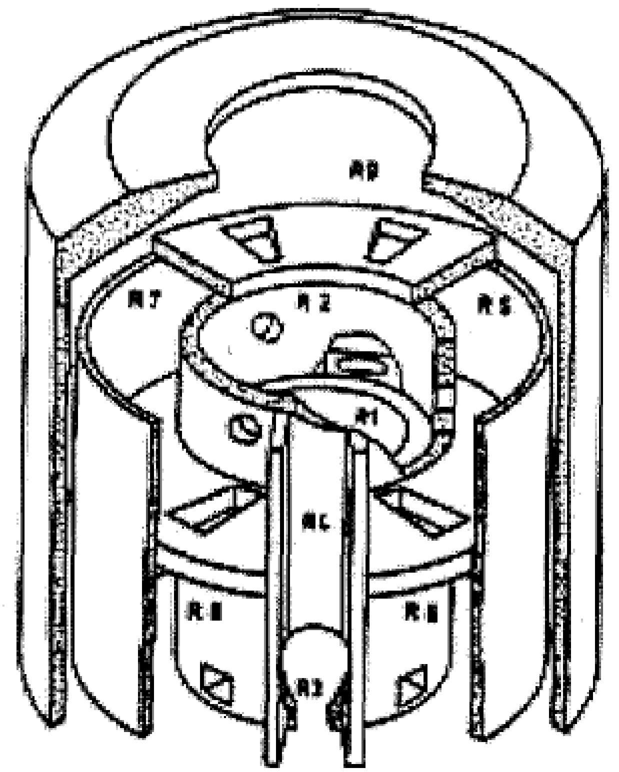

Figure 3: BMC facility (Braillard, 1997)

Sandia Facility

The Surtsey vessel in Sandia National Laboratory (USA) (see Figure 4) was a stainless steel pressure vessel with an internal working volume of 99 m³. The tests addressed the optimisation of NIS PARs with respect to gas-phase ignition and also the effect of steam and scale (number of cartridges) on the PAR performance.

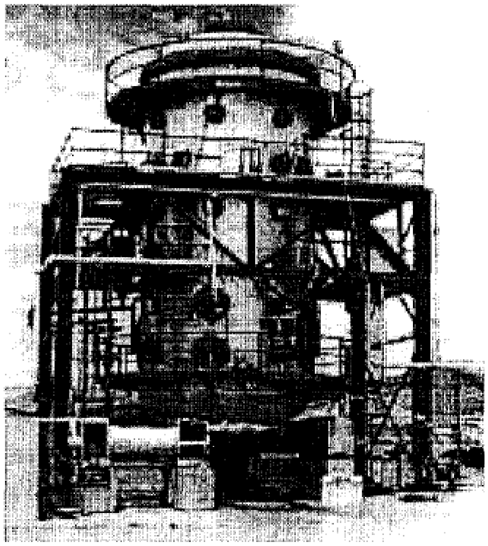

Figure 4: Sandia facility (Braillard, 1997)

H2PAR Facility

H2PAR was a facility (see Figure 5) operated by the French Institute for Nuclear Protection and Safety (IPSN, former IRSN), and was located at CEA Cadarache research centre (France). The facility was made of a double terphane (polyester film) vessel. The internal volume was about 8 m^3 with a diameter of 2 m. The objectives of the H2PAR program were to characterize the Siemens (today Framatome) and AECL (today CNL) PARs behavior under representative severe accident conditions in a PWR. Thus, the test program was performed within four test series (Rongier P., 1998):

(1) preliminary tests for the aerosol source preparation, (2) reference tests with recombiner without aerosols, (3) operational tests of the recombiner in the presence of aerosols, and (4) tests for studying the risk of ignition induced by the recombiner.

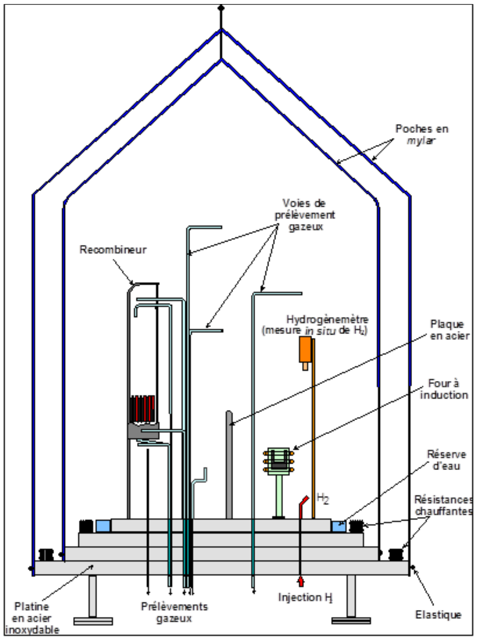

Figure 5: H2PAR Facility (Leteinturier, et al., 1998)

KALI H2 Facility

The KALI H2 facility (see Figure 6) was located at CEA Cadarache research centre (France) (Bachellerie, 2003). The KALI vessel was a 15.6 m^3 steel cylindrical vessel (4.6 m high, 2.1 m diameter), and had a maximum allowable working pressure of 12 bar at 473 K (Figure 6). The experimental tests were restricted to 10 % vol. hydrogen concentration in dry air.

The KALI facility allowed to simulate the thermohydraulic conditions of severe accident or design-basis accident atmospheres and to reproduce mixtures with air, steam and hydrogen. The facility was also equipped with a carbon monoxide injection system, a cold water spray system, and a mixing fan inside the vessel to have homogeneous mixture. The following topics were investigated: (1) the effect of water spray, (2) the analytical study of Siemens (today Framatome) and NIS recombiners both in design-basis accident and in severe accident conditions, (3) the self-ignition induced by recombiner (in dry/wet atmospheres), (4) the effect of long time (one week) thermal degradation of electric cable fire, (5) the recombination rate and the possibility of self-ignition, (6) the simulation of catalytic recombiner thermal power, and (7) the measurement of the gas velocity.

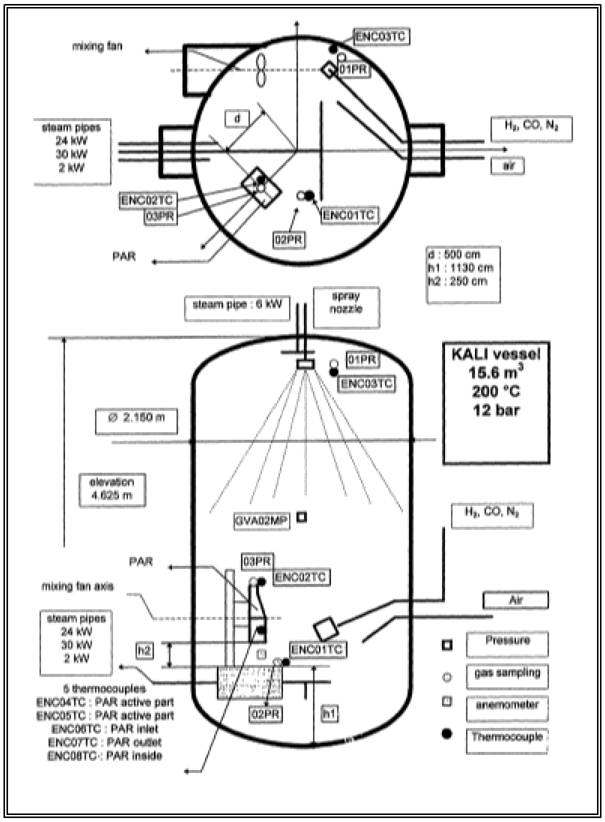

Figure 6: KALI H2 facility (Bachellerie, 2003)

2.1.2. Main outcomes

The experimental programs, described above, addressed several topics related mainly to in-vessel conditions, but some of the findings are relevant for the topics to be addressed in AMHYCO. The following conclusions were extracted from (Bachellerie, 2003):

- **Effect of Oxygen Concentration**: some BWR containment designs are pre-inerted with an oxygen concentration below 5 % vol. The PARs tested in the KALI-H2 facility at low oxygen concentration started up after a 1-5 minutes delay and reduced the oxygen concentration below 2 %.
- **Effect of Containment Temperature**: The effect of the containment temperature was tested in a range of 15 to 100 °C. The recombination rate decreased with an increase in the temperature because the molar densities of oxygen and hydrogen in contact with the catalyst sites were smaller at higher temperatures. The reduction in the PAR capacity could be as much as 10 to 20 %. The tests carried out at higher temperatures in wet conditions (severe accident) showed that all recombiners started up immediately or with short delay (few minutes) while their capacity was reduced by the effect of containment temperature.
- **Effect of Pressure**: The hydrogen recombination rate increases with an increase in the pressure.

- **Effect of Carbon Monoxide**: As for hydrogen, carbon monoxide oxidises on platinum or palladium catalysts in the presence of oxygen. The oxidation of carbon monoxide on the catalyst may result in partial inhibition of the catalyst with respect to oxidation of hydrogen, since carbon monoxide molecules occupy active sites of the catalyst. At low temperatures, CO is easily adsorbed on active sites of the catalyst and inhibits the capacity of the catalyst to oxidise hydrogen. The carbon monoxide on catalyst surfaces is consumed as soon as the temperature increases. Under oxygen-rich pressurised water reactor conditions, the PARs recombination rate of H_2-CO mixtures is greater than H_2 mixtures due to the exothermic reaction of carbon monoxide and oxygen to form carbon dioxide. Under low-oxygen boiling water reactor conditions, CO delays recombination significantly, but only when oxygen concentrations fall below about 2 vol. % (Braillard, 1997).
- **PAR ignition limit determination**: Several experiments were conducted on French facilities H2PAR and KALI-H2 on the possibility of ignition induced by PARs. The conclusions of these experiments lead to define the following "PAR ignition limits" depending on gas mixture (Leteinturier, et al., 2002):
    - in the tests with dry air, ignition was observed between 5.5 and 6.8 vol% hydrogen;
    - with 9.2 vol% steam, ignition was detected at approximately 8.5 vol% hydrogen;
    - with 31 vol% steam, ignition appeared at approximately 8.6 vol% hydrogen;
    - with 45 vol% steam, ignition was observed at about 10 vol% hydrogen;

  The results relating to the ignition limits of the tested recombiner model obtained in the KALI-H2 and H2PAR tests are summarized in Figure 7.

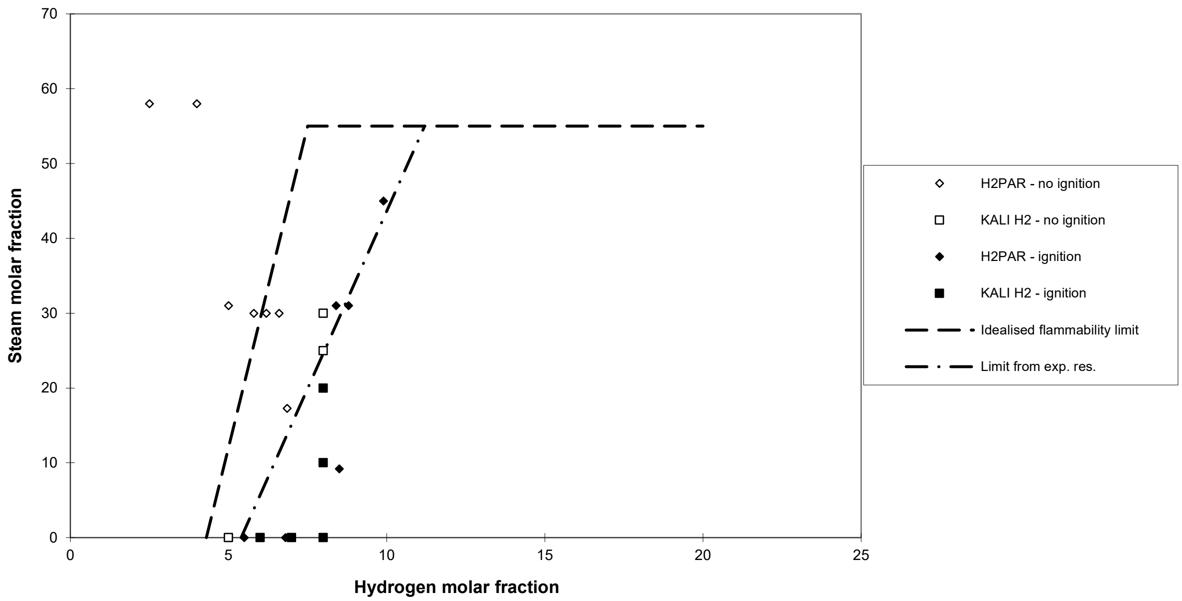

Figure 7: Ignition limit from KALI-H2 and H2PAR tests (Leteinturier, et al., 2002)

2.2. Main outcomes from recent experimental programs

The aim of this section is to provide an overview of the main results obtained recently in the framework of the experimental programs performed by FZJ (H2REKO) and by CNL (LSVCTF, CTF,..), as well as in the framework of the OECD/NEA projects THAI, THAI2 and THAI3. The progress made in modelling is also provided.

2.2.1. REKO-3 experiments at FZJ

The REKO-3 facility is operated since 2000. Experimental campaigns have been performed in the framework of the nuclear safety research program of the Helmholtz community as well as within three national projects funded by the Federal Ministry for Economic Affairs and Energy. The results are providing insights into operational characteristics of PARs using catalyst sheets, e.g. Areva and AECL.

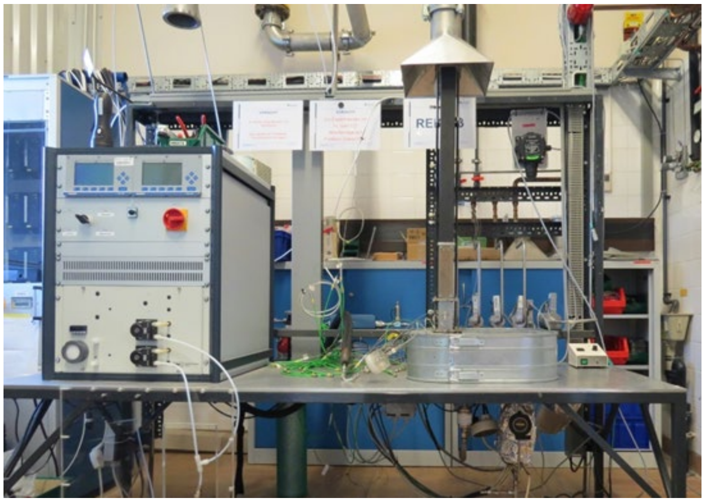

Figure 8: REKO-3 facility

The facility allows studying the operational behavior of a cutout from the catalyst section of a PAR under well-defined boundary conditions. For this purpose, the catalyst sheets are mounted inside a vertical rectangular flow tube with a cross section of 14.6 x 4.6 cm² and exposed to a mixture of different gases (hydrogen, air, nitrogen, steam, carbon monoxide, etc.). Inlet conditions are controlled by means of mass flow controllers and pre-heater. Key measurements are gas and catalyst temperatures (contact and optical measurements) and the downstream composition of the gas mixture (determination of recombination rate).

The tube is fed with a constant flow which is characterized by

- Volumetric flow rate / flow velocity
- Gas temperature

- Gas composition (mixture of air/nitrogen/steam/hydrogen/carbon monoxide)

The instrumentation allows the measurement of

- Gas temperature down and upstream of the catalysts
- Catalyst temperature at several positions along the catalyst sheets
- Gas composition behind the catalyst sheets (and in some test series along the catalyst sheets)

As the facility generates steady-state data, the tests are especially designed for the development of detailed PAR models.

General results

The results show that the reaction of hydrogen and oxygen on the catalytic surface is controlled by the diffusive mass transfer of hydrogen and oxygen through the boundary layer. As a consequence, the catalyst temperature only has a weak impact on the overall recombination rate. In addition to the stoichiometry of the chemical reaction, the diffusion coefficients of hydrogen and oxygen as well as the bulk concentration of both species are relevant for the reaction kinetics. This finding is highly relevant with regard to the understanding of the general operation under oxygen-lean conditions (Reinecke, Böhm, Drinovac, Strut, & Tragsdorf, 2006) and in the presence of carbon monoxide (Klauck M. , et al., 2014).

As a consequence of the interaction between the diffusion-controlled reaction and the different heat transfer modes (convective heat transfer between catalyst surface and gas, heat conduction inside the catalyst sheets, heat radiation between catalyst sheets and exchange with the environment), the catalyst temperature develops a significant profile from the bottom edge (max. temperature at the inlet of the catalyst section) to the top edge (min. temperature at the outlet of the catalyst section) with typical gradients between 100-200 K (Reinecke, et al., 2013).

Oxygen starvation

Fundamentally, the conditions of oxygen starvation are reached when the recombination rate of hydrogen decreases below the optimum value. In REKO-3 experiments the critical oxygen concentrations, i.e. the minimum oxygen concentration for optimum hydrogen recombination, have been determined for different hydrogen concentrations. According to the laws for diffusive mass transfer, the critical oxygen concentration $y_{O2,crit}$ can be calculated according to

$$y_{O2,crit} = \frac{1}{2}\left(\frac{D_{H2,m}}{D_{O2,m}}\right)^{\frac{2}{3}} y_{H2}$$

with the hydrogen concentration y_{H2} and the diffusion coefficients $D_{i,m}$ of both species in the gas mixture (Reinecke E. A., Böhm, Drinovac, Struth, & Tragsdorf, 2006.).

Presence of steam

Steam was found to have no significant impact on the steady-state recombination (Reinecke E. A., Böhm, Drinovac, Struth, & Tragsdorf, 2006.).

Presence of carbon monoxide

As a general conclusion, the experimental results indicate that PAR operation in the presence of carbon monoxide can be divided into three different regimes (Klauck, Reinecke, & Allelein, 2021):

- Regime I: Undisturbed parallel reaction of hydrogen and carbon monoxide with oxygen (oxygen-rich atmosphere)

  If sufficient oxygen is available for both hydrogen and carbon monoxide both species react simultaneously to produce steam and carbon dioxide. Further reaction products were not observed. Due to the fact that the diffusion coefficient of CO is lower than the one of hydrogen the reaction rate of CO is lower than for hydrogen. The additional exothermal reaction of CO leads to increased catalyst temperatures.

- Regime II: Constrained parallel reaction of hydrogen and carbon monoxide with oxygen (oxygen-lean atmosphere)

  When CO is competing with hydrogen for oxygen, the effect of oxygen starvation (see above) can be observed for higher oxygen concentration as for hydrogen only. In agreement with the experimental findings, the critical oxygen concentrations can be calculated based on diffusive mass transfer formulas (Klauck M. , 2019) :

$$y_{O2,crit} = \frac{1}{2}\left[\left(\frac{D_{H2,m}}{D_{O2,m}}\right)^{\frac{2}{3}} y_{H2} + \left(\frac{D_{CO,m}}{D_{O2,m}}\right)^{\frac{2}{3}} y_{CO}\right]$$

- Regime III: Reaction termination due to catalyst poisoning

  Oxygen starvation leads to decreasing recombination rates. As a consequence, the temperature level of the catalyst surface may decrease below a critical value, leading ultimately to the entire termination of the reaction on the catalyst surface due to catalyst poisoning. Catalyst poisoning is a reversible occupation of the active sites by CO adsorption at "low temperatures". Although the effect of catalyst poisoning could be clearly demonstrated (Klauck, Reinecke, & Allelein, 2021) (Freitag, 2020), the present database does not allow for a systematic identification of the poisoning limits. As a working hypothesis, the “critical temperature” could be a function of hydrogen and carbon monoxide concentration.

Ignition on hot catalyst sheets

Independent from the gas mixture, a catalyst temperature of approx. 980 °C (+10 °C / -20 °C) is required to ignite the gas mixture on the hot catalyst surface (Chakraborty, et al., 2017). In the presence of CO, less hydrogen is needed to reach the ignition temperature due to the additional exothermal heat production. In the presence of large amounts of steam, oxygen-lean conditions are easily reached which inhibit an ignition.

2.2.2. THAI experiments in the frame of OECD/NEA projects

The test facility THAI (thermal-hydraulics, hydrogen, aerosol, and iodine) aims at addressing open questions concerning gas distribution, behaviour of hydrogen, iodine and aerosols in the containment of LWRs during severe accidents. Main component of the facility is a 60 m^3 stainless steel vessel, 9.2 m high and 3.2 m in diameter, with exchangeable internals for multi-compartment investigations. The maximum design pressure of the vessel is 14 bar which allows hydrogen combustion experiments at SA-relevant hydrogen concentration level.

Among other topics, the THAI experimental research covers investigations related to mitigation systems employed in LWR containments by performing experiments on the performance behaviour of passive autocatalytic recombiners (Gupta, 2017).

In order to fill existing knowledge gaps with regard to PAR performance under a range of accident-typical conditions, three different commercial PAR designs based on plate-type (provided by AREVA GmbH, Germany, and AECL (now CNL), Canada) and pellet-type catalysts (provided by NIS Ingenieurgesellschaft mbH, Germany) have been investigated in a comparable manner in the THAI test facility. The large vessel volume allows the operation of medium-sized commercial PAR with unrestricted natural convection, which includes the interaction of PAR performance with the vessel atmosphere, miming then the real conditions in reactor containment. The investigated PAR units differ in their geometry, size and use of catalyst material. For the PAR performance tests, the plate-type PAR units were scaled down to the size of the THAI test facility by reducing the number of catalyst sheets. A limited number of tests have also been conducted with the smallest available 1/8th module of the pellet-type NIS PAR without modification. The total catalytic surface of the investigated PAR units was in the range of 1.44–1.89 m^2 (Gupta, 2017).

The variation in test parameters to investigate PAR performance and ignition behaviour included:

- initial vessel pressure between 1.0 bar and 3.0 bar,

- initial gas temperature between ambient and 117°C,
- atmosphere steam content of 0–60 vol%.

Moreover, variation in oxygen concentration and PAR overload by high hydrogen concentration had been considered to address oxygen starvation and PAR ignition conditions.

Tests started with an initially air-filled atmosphere. The vessel instrumentation allowed the measurement of pressure, temperatures, gas injection rates and distribution of gas concentrations in the vessel atmosphere; the PAR instrumentation provided the inlet flow velocity, the inlet and outlet gas temperatures, gas concentrations (hydrogen, oxygen) and the local catalytic surface temperatures.

Majority of the PAR performance tests consisted of two test phases with two consecutive hydrogen injections. In the first test phase, hydrogen is released at a low rate (~0.15 g/s) into the test vessel. Immediately after onset of PAR operation, hydrogen is switched to higher injection rate (~0.30 g/s) resulting in further increase of hydrogen concentration and hydrogen recombination rate. Hydrogen injection is interrupted as soon as a level of approximately 5.5 vol% hydrogen at the PAR inlet (i.e. below the expected PAR ignition level) has been reached. Measurements of decreasing hydrogen concentrations and other relevant parameters are used to determine the PAR performance. Prior to starting the second test phase, oxygen in vessel atmosphere is replenished if necessary for a test with "ignition" or further reduced by injecting nitrogen for a test with "oxygen starvation". In the second test phase, hydrogen injection is again resumed at mass flow rate of about 0.30 g/s. For the investigation of PAR ignition, hydrogen concentration is increased until the operating PAR becomes so heavily loaded that ignition occurs. Immediately following an ignition, hydrogen release has been terminated.

General results

In principle, the performance behaviour of the three investigated PARs varied within a well specified range. Some differences occurred due to specific design features, such as gas velocity and gas residence time between the catalyst elements inside the PAR which in turn depend on the chimney height of the respective PAR design.

Recombination onset

Minimum hydrogen concentration required for the onset of hydrogen recombination is an important feature of a PAR. In the THAI PAR tests, onset of recombination has been studied in the first test phase by slowly increasing hydrogen concentration (typically 0.16 vol%/min). The first indication of hydrogen recombination onset is a moderate increase in catalyst temperature. As soon as catalyst temperature further increases, buoyancy-induced convection flow inside the PAR housing starts and the hydrogen concentration at the PAR outlet drops forming a second criterion for recombination onset. For the complete PAR performance test series, test results indicate that hydrogen concentration required for the onset of hydrogen recombination by PARs varies from 0.2 vol% to 4.4 vol% depending on temperature, pressure, and steam content. Dry atmosphere, elevated pressure and temperature promoted early recombination onset. Steam-saturated conditions resulted in delayed onset. Once being heated up, the PARs remain operating until a lower concentration threshold of approximately 0.3 vol% has been reached.

Oxygen starvation

Additional tests using AREVA and NIS PARs have been conducted in the framework of OECD/NEA-THAI2 to investigate the PAR onset and performance behaviour under oxygen-lean (almost inert) atmosphere. The tests started with purging the vessel with nitrogen to reduce the oxygen content in the vessel atmosphere near to an inert level. Once the pre-defined thermal-hydraulic test conditions were established with an initial hydrogen content of 4 vol% in nitrogen or nitrogen/steam atmospheres, oxygen was injected. Test results indicated prompt onset of hydrogen recombination with measured value of oxygen concentration at the PAR inlet below 0.5 vol%. The demonstration of adequate hydrogen recombination rate (amount of hydrogen recombined per unit time) and hydrogen depletion efficiency are the important criteria to confirm the PAR performance. In THAI tests, the hydrogen recombination rate is calculated by use of data measured at PAR: inlet temperature, inlet flow velocity, inlet/outlet gas concentrations, and the vessel pressure. After PAR onset, the recombination rate increases with the hydrogen concentration and with pressure. The effect of increasing steam content combined with an increasing temperature in THAI tests was determined to be very small on the measured hydrogen recombination rate. At a given hydrogen concentration of 4 vol% at the PAR inlet, increasing the steam concentration from 0 vol% to 60 vol% results in about 30% reduction in the recombination rate. The observed effect might be due to temperature rather than steam as increase in temperature from ambient to 97°C (associated with 60 vol% steam) will decrease the buoyancy by about the same order of magnitude for a fixed hydrogen depletion efficiency. The buoyancy force calculated from the difference in gas density at the PAR inlet and outlet, is the driving force for convective flow and, in turn, affects the hydrogen recombination rate.

Hydrogen depletion efficiency at a given hydrogen concentration is also PAR design specific as it mainly depends on the gas residence time in the PAR catalyst zone and on the diffusion length from the vertically flowing gas to the catalyst surface (and probably also on catalyst material). For the three investigated PAR designs, the hydrogen depletion efficiency was determined to be varying between 40 and 60% in an atmosphere containing sufficient oxygen surplus. THAI test results indicate that hydrogen depletion efficiency significantly decreases with increasing pressure. This behaviour may be explained by the increase of gas diffusion resistance with pressure.

The aforesaid range of 40–60% hydrogen depletion efficiency remains unaffected as long as sufficient oxygen is available for hydrogen recombination at the PAR inlet. The test results provide evidence that an oxygen-to-hydrogen ratio higher than stoichiometric is required for PAR to operate at design capacity. A minimum oxygen surplus ratio defined as $\Phi = 2 \times C_{O2}/C_{H2}$ between 2 and 3 (depending on the PAR design) is necessary to ensure unimpaired PAR performance independently from steam content. The minimum value of the oxygen surplus ratio is significantly higher than the stoichiometric ratio ($\Phi = 1$). The need for a significantly high surplus of oxygen can be explained by the large differences in molecular diffusivity of hydrogen and the other gases involved.

PAR ignition

The PAR tests conducted in the THAI test facility markedly improved the level of knowledge on ignition potential by PAR. The test data also provided inlet conditions at which PAR induces an ignition. THAI test data indicated that ignition is directly correlated with the PAR catalyst surface temperature which in turn depends on the hydrogen concentration present at the PAR inlet. The pre-requisite for the PAR induced ignition varies with the specific PAR design. Nevertheless, from the THAI experiments, a narrow range of parameters at the time of ignition could be identified. In dry conditions, ignition was observed at maximum catalyst temperatures of 890-920 °C and minimum hydrogen concentration of 5.5-7.5 vol% at the PAR inlet. In the presence of condensing steam, the catalyst temperature range was 960-1005 °C at 8-9 vol% hydrogen (in 45 vol% steam).

Due to limited number of experiments conducted with the pellet-type PAR, no clear picture of PAR induced ignition behavior could be drawn. However, during the tests it was observed that in case of high load (>5.2 vol% hydrogen), the PAR releases glowing particles into the surrounding atmosphere. This visible effect coincides with a marked additional hydrogen/oxygen recombination in the bulk which under the investigated test conditions significantly supports hydrogen recombination by PAR without relevant pressure effects. The THAI PAR ignition test data did not indicate any flame acceleration under investigated test conditions.

Presence of carbon monoxide

In the framework of the national THAI program, a test series was performed to investigate the PAR performance in the presence of carbon monoxide. Ratios of injection mass flow rates of hydrogen and carbon monoxide were investigated between 4:1 and 7:1 based on hypothetical release of CO by the molten core concrete interaction. The volumetric CO recombination rate is noticeably lower as compared to the hydrogen recombination rate and also the depletion efficiency with respect to CO is reduced as compared to hydrogen under normal operating conditions. Comparing to pure hydrogen conversion, the addition of CO increases the heat released from the recombination which in turn increases the flow velocity through the PAR slightly. The slightly faster flow reduces the residence time of CO and H2 at the catalytic surfaces and therefore the H2 conversion efficiency is slightly smaller as compared to tests performed without

CO. Overall, the simultaneous CO oxidation at a typical H2/CO ratio above 4 does not have a noticeable negative effect on the H2 recombination.

PAR induced ignition was monitored in test HR-51 at a concentration of 5.7 vol% H2 and 1.2 vol% CO, corresponding catalytic plate temperature was at 855 °C. A comparable test without carbon monoxide injection required a hydrogen concentration of 6.6 vol% to obtain similar plate temperatures triggering ignition of the mixture. The resulting peak pressures of both tests are almost identical.

Under lack of oxygen, hence in the oxygen starvation regime, the PAR depletes hydrogen and carbon monoxide at a similar level of conversion efficiency. This can be well explained by the fact that CO and O2 exhibit very similar diffusion coefficients. The autocatalytic reaction is generally diffusion controlled and under surplus of hydrogen compared to available oxygen, the hydrogen conversion is controlled by the diffusion of oxygen towards the catalytic surface instead of hydrogen (Freitag, 2020).

2.2.3. CNL experiments

Experimental study on PARs were conducted at Canadian Nuclear Laboratories (CNL) in facilities of various scales : (1) Large-Scale Vented Combustion Test Facility (LSVCTF) that has a total volume of 60 or 120 m^3 depending on the configuration, (2) Containment Test Facility (CTF) that has a total volume of 6 m^3, and (3) Hydrogen Safety Test Facility that has a total volume of 0.25 m^3. Standard full-size PARs, designed by AECL were tested in the LSVCTF (Gardner, Liang, Clouthier, & MacCoy, 2020) (Liang, Gardner, & Clouthier, 2020) (Gardner & Marcinkowska, 2011). PARs with a reduced number of catalyst plates (typically 3) in a half-sized PAR housing were tested in the CTF. PARs with a reduced number and size of catalyst plates (approximately 260 times smaller than a full sized PAR based on catalyst surface area) were tested in the HSTF (Gardner, et al., 221). Small pieces of PAR catalyst (i.e., coupons) were tested in a Catalyst Activity Bench Scale (CABS) apparatus and a Spinning Basket Reactor apparatus. The experiments were focused on examining a number of PAR parameters: self-start threshold (also known as start-up), recombination rate and ignition limit.

General operation (recombination rates)

Hydrogen removal rate (or capacity) is defined as the amount of hydrogen recombined per unit of time (such as kg/h). The PAR capacity is generally expressed as a function of hydrogen concentration at the inlet, pressure and temperature. For the AECL designed 31-plate PAR unit, the following empirical equation has been presented by Bachellerie et al. (Bachellerie, 2003):

$$R_{H2} = (0.15196\, C + 0.0126\, C^2)\left(\frac{298}{T}\right)^{1.10974}\left(\frac{P}{10^5}\right)^{0.57769}$$

where R_{H2} is the PAR capacity in kg/h, C is the concentration of hydrogen at the PAR inlet in vol%, T is the ambient temperature in Kelvin, P is the ambient pressure in Pascal. The capacity is approximately 0.8 kg/h at 4 vol% hydrogen, 100 kPa and 25 °C.

Impact of increasing pressure

The effect of elevated ambient pressure on hydrogen recombination rate was examined by comparing the tests performed at atmospheric pressure in the LSVCTF with the tests under pressure in the CTF and HSTF. The experiments were performed at pressures of up to 3 bar(g). The above recombination rate equation, originally developed from the CTF tests, matched the HSTF results reasonably well (Gardner, et al., 221).

Impact of high relative humidity

The effect of relative humidity was studied with a full-size AECL PAR in the LSVCTF by varying the temperature and steam concentration independently while investigating the self-start, recombination rate and ignition limit (Gardner, et al., 221) of the PAR. All tests were conducted at roughly atmospheric pressure.

In general, when humidity and temperature were studied independently, it was found that AECL's PAR recombination rate is not affected by humidity. A small impact of humidity was found for self-start and ignition. For self-start, it was found that at a higher humidity, a slightly higher hydrogen concentration was required. However, the maximum increase in hydrogen concentration was 0.5 vol%. Finally, a trend was found between humidity and the PAR-induced ignition threshold. Increasing humidity up to approximately 30 vol% steam resulted in an increase in the PAR-induced ignition hydrogen concentration (Gardner, Liang, Clouthier, & MacCoy, 2020).

Conditions for gas-phase ignition due to high PAR temperatures

Gas phase ignition induced by PARs was studied by Gardner et al. (Gardner, et al., 221). The experiments were performed on a full-size AECL PAR in the LSVCTF with well-mixed gas mixtures under quiescent conditions at atmospheric pressure. The experiments focused on understanding the gas-phase ignition threshold caused by hot catalyst plates, and the effect of humidity/steam and temperature (independently).

The general conclusions from the study suggest that there is an effect of humidity on the hydrogen concentration threshold for PAR-induced hydrogen ignition. Whereby, an increase in humidity (i.e., steam concentration) requires a higher hydrogen concentration to induce an ignition. Ambient temperature was found not to significantly impact the required hydrogen concentration for the PAR-induced ignition. It should be noted that the range of ambient temperatures covered in this study were between 25 and 65 °C.

Oxygen starvation

The effect of oxygen starvation on PAR performance (self-start and recombination rate) was investigated in both the CTF and HSTF. Tests were performed with a range of oxygen surplus ratios, temperatures and pressures, to evaluate the PAR performance under a full range of conditions.

The general conclusions from the study include:

- When the oxygen surplus ratio ($\phi = 2 \cdot C_{O2}/C_{H2}$) > 2, no effect was found to the hydrogen recombination rate in all conditions tested. When $\phi \leq 1.5$, the recombination rate was significantly reduced. In other words, when the oxygen concentration was equal to or greater than the hydrogen concentration, PAR recombination rate was found to be unimpaired. Conversely, when the oxygen concentration is less than the hydrogen concentration, the hydrogen recombination rate is reduced.
- The results from the HSTF compared well with the experiments performed in the OECD THAI program.
- With oxygen-limited conditions, the PAR self-started with significantly less hydrogen than in oxygen rich conditions. When the hydrogen concentration was held constant, and oxygen was added to the test vessel, the PAR showed activity with each 0.1 vol% addition of oxygen.

Presence of steam

To achieve the desired humidity in PAR experiments, steam is typically added to the facility, so its impact on PAR performance is the same as relative humidity.

Presence of carbon monoxide

The parallel H_2 and CO recombination efficiencies and rates were examined in the CTF, LSVCTF, and HSTF facilities. Complementary small-scale tests were also conducted in the CABS apparatus using prototype coupons (to mimic PAR plates) to determine the temperature and CO concentration thresholds for the CO poisoning effect on the platinum catalyst PARs (Liang, Gardner, & Clouthier, 2020).

The CABS tests demonstrated that a minimum temperature of 70°C is required to prevent catalyst poisoning in the presence of less than 0.2% CO in 3% H2–air mixtures. At a given temperature and H_2 concentration, the minimum CO concentration can be lower if the catalyst is pre-poisoned, or higher if the catalyst activity has been initiated. The CO poisoning effect is temporary and the PAR can restore its activity when it is re-exposed to a CO-free H_2–air mixture. When a self-started

PAR is exposed to H_2–CO–air mixtures, recombination reactions with H_2/O_2 and CO/O_2 take place in parallel. The conversion efficiency is close to 60–65% for H_2/O_2 recombination and 25–34% for CO/O_2 recombination. The recombination efficiency decreases rapidly when H_2 concentration drops to less than 2% for both recombination reactions.

Further experiments are planned in the HSTF to investigate PAR-induced ignition with the presence of carbon monoxide, beginning in 2021.

Effect of Ambient Conditions

Experiments were conducted in the LSVCTF to examine the PAR performance under various ambient flow conditions (Liang, 2016). Under quiescent conditions, PAR self-sustained buoyancy force draws in fresh hydrogen-rich mixture to the PAR inlet and the hot recombination product exhausts from the PAR outlet. However, experiments with a strong background turbulent flow resulted in fast dissipation of recombination heat and gas mixing, leading to a slight increase in the self-start threshold, modest reduction in the capacity, and slight increase in the ignition limit. A strong convective flow directed to the PAR outlet created a downward flow through the PAR catalyst plates. The PAR functioned with a small increase in self-start threshold, a modest decrease in the overall hydrogen removal rate, and a slight decrease in the ignition limit due to higher catalyst temperature. With a weaker downward flow, the overall hydrogen removal rate could be significantly reduced due to competition with the upward buoyancy force.

Deuterium

A variety of experiments were performed at multiple scales (in the spinning basket reactor, CABS and CTF) to investigate PAR self-start and recombination rate with deuterium in place of light hydrogen (protium). In general, no noticeable effect on PAR recombination rate was found with deuterium. A small difference was found with start-up behavior; however, the difference was considered not to be significant since the PAR can easily start below the hydrogen lower flammability limit.

In addition, many tests have been performed in the LSVCTF, CTF, CABS and HSTF to investigate the PAR behaviour with catalyst that has been in-service in CANDU reactors. Approaches to accommodate the degradation behaviour have been investigated and implemented.

2.3. Conclusions

Both past and recent experimental programs were conducted to improve the knowledge on PAR behavior in representative severe accident conditions. The past experimental programs addressed the PARs global behavior and were focused mostly on determining the PARs efficiency. Whereas, the recent programs were focused on deeper investigation on phenomena affecting PARs behavior. Thus, separate and integral tests were conducted at "meso" and large-scale facilities providing details that help improving the PAR models. Even if most of the performed experiments are relevant to in vessel conditions, recent investigations were performed to provide data concerning PARs behavior in conditions with presence of CO and lack of oxygen that are relevant for severe accident late phases.

The following table summarizes the conditions relevant to severe accidents late phases already addressed in the experimental programs presented above.

Table 1: Summary of the addressed conditions in the recent experimental programs

(+ partially addressed, ++ completed)

Topics	Programs		
	REKO	THAI	CNL
Oxygen starvation	++	++	+
Effect of CO	+	+	+
Effect of containment temperature	++	++	++
Effect of containment pressure		++	++
Effect of steam	+	+	++
PAR ignition	++	++	++
PAR deactivation	+	+	+

3. Overview on PAR modelling

This paragraph provides a survey on the engineering PAR correlation issues from the experimental programs and also on the advanced developed models

3.1. Engineering correlation

The experiments, presented in Section 2, were conducted with the objective to investigate aspects of PARs, such as hydrogen removal rate and efficiency, start-up conditions, and effects of poisoning, oxygen starvation and steam.

These experiments investigated the global behaviour of a PAR in a large environment in order to demonstrate the effectiveness and to facilitate the derivation of simplified ('black-box') models for long-term severe accident analyses. These empirical correlations describe the hydrogen consumption rate for a reference PAR type as a function of the gas composition, temperature and pressure. The hydrogen consumption rates proposed by the different manufacturers are given by the following empirical correlations (Braillard, 1997):

AECL $$\dot{r}_{H_2} = (0.15196 \cdot C_{H_2} + 0.0126 \cdot C_{H_2}^2) \cdot (\tfrac{298}{T})^{1.10974} \cdot p^{0.57769} \quad [\tfrac{kg}{h}]$$

Framatome $$\dot{r}_{H_2} = \eta \cdot min(X_{H_2}, 2 \cdot X_{O_2}, 0.08) \cdot (A \cdot p + B) \cdot tanh(X_{H_2} / 0.5) \quad [\tfrac{g}{s}]$$

NIS $$\dot{r}_{H_2} = 1.134 \cdot C_{H_2}^{1.307} \cdot \frac{p}{R \cdot T} \quad [\tfrac{g}{s}]$$

where X_i is the volume fraction and C_i the volumetric concentration (vol%) of the hydrogen and oxygen respectively, p is the pressure (bar), T the absolute temperature (K) and A and B and the other constants respectively are model parameters which include all residual influences and conditions at the validation experiments and depend on the PAR model. The Framatome correlation can be used to describe the PAR efficiency under different conditions (e.g. oxygen depletion or spray). Moreover, this correlation had been extended recently to address severe accident late phase as follow:

The H2 and CO mass recombination rate (sink) are given (LOEFFER, 2019) :

$$\dot{r}_{H_2} = \min\left(X_{H_2}, \frac{2 \cdot X_{O_2} X_{H_2}}{\left(X_{H_2} + X_{CO}\right)}, 8.0 \frac{X_{H_2}\left(X_{H_2} + 1.75 X_{CO}\right)}{\left(X_{H_2} + X_{CO}\right)^2}\right) \cdot (A \cdot p + B) \cdot \tanh\left(X_{H_2} + X_{CO} - X_{\min}\right) C_1 \quad [\tfrac{g}{s}]$$

$$\dot{r}_{H_2} = \min\left(X_{CO}, \frac{2 \cdot X_{O_2} X_{CO}}{\left(X_{H_2} + X_{CO}\right)}, 8.0 \frac{X_{CO}\left(X_{CO} + 1.75 X_{H_2}\right)}{\left(X_{H_2} + X_{CO}\right)^2}\right) \cdot (A \cdot p + B) \cdot \tanh\left(X_{H_2} + X_{CO} - X_{\min}\right) C_1 C_2 \quad [\tfrac{g}{s}]$$

As a first approach these correlations are implemented in both LP and CFD tools by means of volumetric sinks and sources of energy, mass and momentum or as a 'black-box' model directly in LP and CFD codes as described for example in (Meynet, Bentaib, Bleyer, & Caroli, 2008) (Bentaib, Caroli, Chaumont, & Chevalier-Jabet, 2010).

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3.2. Advanced models

This section aims to emphasize the contribution of the recent experimental programs to the PAR modelling improvement

3.2.1. REKO-DIREKT

The goal of REKO-DIREKT development at FZJ was to develop a PAR model describing all relevant aspects of PAR operation with a good balance between physical correctness and computational efforts. On the one hand, the model includes the most relevant physical phenomena to be applicable for different PAR types and geometries. At the same time, the model can be coupled with system or thermal fluid dynamics codes to serve as an external PAR model. Consequently, the code calculates not only the conditions at the PAR outlet (i.e. gas temperature and concentrations, mass flow) but also local catalyst temperatures and gas concentrations along the catalyst sheets inside the PAR.

The FORTRAN 90-based code is a further development of the High Temperature Reactor (HTR) thermal hydraulics code DIREKT. The name refers to the solution algorithm, which solves the central equation matrix of the temperature field directly and not iteratively. The model is based around the interaction of the catalyst section and the chimney. For this purpose, the 2D code models all relevant heat and mass transfer processes inside the catalyst section (Böhm, 2006) . A chimney model describes the mass flow through the PAR box due to density differences (Simon, et al., 2014).

PAR operation simulated by the code includes the following processes:

- catalytic reaction of hydrogen with oxygen to form steam,
- catalytic reaction of carbon monoxide with oxygen to form carbon dioxide,
- temperature that arises on the catalyst plates as a result of the exothermic reactions,
- heating of the gas mixture flowing through the recombiner, and
- vertical flow induced by the change in density inside the chimney.

The input required by the model includes the PAR geometry (including PAR box and catalyst sheets) as well as

- inlet gas composition (oxygen/nitrogen/steam/carbon monoxide/carbon dioxide)
- inlet gas temperature
- pressure

to provide the following output data:

- chimney flow velocity
- outlet gas composition
- outlet gas temperature, and
- catalyst temperature profiles.

Model development supported by REKO-3 data

The model of the catalytic reaction is based on mass transfer correlations and has been developed alongside the REKO-3 experiments (see section 2.2.1). In this model, the conversion rate of hydrogen corresponds with the diffusion rate of the gaseous hydrogen through the boundary layer to the surface, which can be described by means of Sherwood laws ($Sh \sim Re^n\ Sc^m$), where Sh is the Sherwood number, Re is the Reynolds number and Sc is the Schmidt number. The coefficients n and m are semi-empirical values which depend on the specific local flow conditions.

This approach has been validated against experimental data (Reinecke, Böhm, Drinovac, Strut, & Tragsdorf, 2006) and has also been successfully applied to predict the behaviour of PARs under oxygen starvation conditions (Reinecke, Kelm, Struth, Schwarz, & Tragsdorf, 2007) as well as in the presence of carbon monoxide (Klauck M. , et al., 2014).

Validation: Full interpretation of OECD/NEA THAI data

The experimental program performed in the frame of the OECD/NEA THAI and THAI2 projects offers a comprehensive data base which is especially suited for the validation of numerical PAR codes. In the framework of the validation of the PAR code REKO-DIREKT, a total of 32 experiments of both projects including two different PAR types (AREVA and AECL) have been simulated (Reinecke, Kelm, Steffen, Klauck, & Allelein, 2016).

Taking into account the broad parameter field including pressures between 1 and 3 bar, steam concentrations up to 60 vol% and low-oxygen conditions as well as the significant differences of both PAR types' geometries, "the results achieved are highly convincing and confirm the suitability of the code for the simulation of the operational behavior of full-scale PARs" (Klauck M. , et al., 2014)

Implementation: COCOSYS, CFX, containmentFOAM

A prerequisite for the application of REKO-DIREKT within the framework of accident analyses is the implementation in system/accident or thermal hydraulics codes. At present, the model has been coupled with the LP code COCOSYS and the CFD codes ANSYS-CFX and containmentFOAM.

The implementation of REKO-DIREKT in COCOSYS (developed by GRS/Germany) was carried out by GRS within the framework of the national project RS1508 (Spengler, et al., 2014). "RDR" was implemented as an independent module and thus does not belong to the inner part of the code system, consisting of the COCOSYS main driver as well as the main modules, such as THY (thermal hydraulics), AFP (fission products) and CCI (core-concrete interaction). After successful test of the interface by GRS, the coupled program version (COCOSYS v3.0beta) has been validated using the database of the code-to-code benchmark "Generic Containment" (Simon, et al., 2014). Furthermore, the coupled version has been used to simulate a generic accident scenario in order to demonstrate the potential adverse effects of carbon monoxide on PAR operation in the late phase of a severe accident (Klauck, Reinecke, & Allelein, 2021).

In order to simulate PAR operation as well as its interaction with the hydrogen transport inside containment compartments, REKO-DIREKT has been coupled explicitly to the commercial CFD code ANSYS CFX 15 (ANSYS Inc., 2013). Data handling between REKO-DIREKT and CFX is performed by means of the CFX Memory Management System (MMS), which can be accessed by both codes. The coupling is performed on a master-slave base, i.e. the REKO-DIREKT execution is fully controlled by CFX. For this purpose, the program flow of REKO-DIREKT has been modified to run only a single time step for each call. All variable fields are stored in the MMS and read out as an initialization for the next REKO-DIREKT call. Validated against large scale experiments in the THAI facility, the implementation of REKO-DIREKT in ANSYS CFX 15 allows consistent simulation of experimental transients regarding all available measurements as well as derived quantities like the recombination rate (Reinecke, Kelm, Steffen, Klauck, & Allelein, 2016).

In a similar way, REKO-DIREKT is also coupled with containmentFOAM (Kelm, et al., 2021).

3.2.2. COCOSYS

COCOSYS, developed by GRS (Germany), provides a LP code system on the basis of mechanistic models for the comprehensive simulation of all relevant processes and plant states during design basis and severe accidents in the containments of LWRs. For the identification of possible deficits in plant safety, quantification of the safety reserves of the entire system, assessment of mitigation measures of SAM concepts and the safety evaluation of new plant concepts, the code provides two PAR models (Liang, Sonnenkalb, Bentaïb, & Sangiorgi, 2014). The fast running PAR model based on parametric correlations for AREVA PARs (see section 3.1) calculates the depletion rate of hydrogen and carbon monoxide. The detailed 1D-junction model for all AREVA type PARs and one for AECL PARs was used in the OECD/NEA-THAI project. There is no detailed modelling and validation for AECL PARs (missing geometrical data). A model for NIS PARs is under development.

Based on the experimental findings from the REKO-3 facility (see section 2.2.1), the reaction kinetics modelling of the detailed 1D-junction model has recently been changed from Arrhenius-type reaction kinetics to a diffusion approach comparable with REKO-DIREKT. Post-calculations of the OECD/NEA-THAI HR experiments as well as the old Gx4 experiments show very good results using the revised PAR model (Nowack, 2010). The updated PAR model has been used by GRS for a re- evaluation of the PAR concept in German PWRs (Sonnenkalb, Band, Nowack, & Schwarz, 2015).

3.2.3. ASTEC

The severe accident integral code ASTEC, developed by IRSN (previously developed jointly with GRS), simulates the behaviour of a whole nuclear power plant under severe accident conditions, including severe accident management by engineering systems and procedures. Since 2004, the ASTEC code is progressively becoming the reference European severe accident integral code through in particular the intensification of research activities carried out in the frame of the SARNET European network of excellence and, more recently, through projects like EC/CESAM and NUGENIA/TA2/ASCOM. The code provides two level of PAR models: the fast running PAR model based on parametric correlations for AREVA and AECL PARs (see section 3.1) calculates the depletion rate of hydrogen and carbon monoxide and the detailed 1D-junction model for both AREVA and AECL PARs. Both models were validated on basis of experiments from H2PAR, KALIH2 and THAI. (Plumecocq, 2005)

3.2.4. GOTHIC

GOTHIC is an integrated, general-purpose thermal-hydraulics software package for design, licensing, safety and operating analysis of nuclear power plant (NPP) containments, confinement buildings and system components. It solves the conservation equations for mass, momentum and energy for multi-component, multi-phase compressible flow in three fields: vapor, continuous liquid and droplets. GOTHIC uses empirical correlations to calculate heat transfer between the fluid domain and 1D or 2D structures by convection, condensation and evaporation. It also uses 1D correlation for the fluid friction with solid structures.

The thermal-hydraulic calculations of GOTHIC are based on a single control volume (CV) or a network of them connected by flow paths or 3D connectors. A control volume can be subdivided into 2D or 3D Cartesian grids. Thus, GOTHIC can perform both LP and 3D containment analyses offering a balance between accuracy -due to its 3D capabilities- and computational cost, using empirical correlations, based on bulk properties, to define friction and heat transfer between the fluid and the solid structures, instead of attempting to model the boundary layers.

GOTHIC creates 3D geometries thanks to a porosity factor applied on each cell volume and face area in a pre-established Cartesian mesh. By blocking certain cells or cell faces, complex geometries can be modelled by modifying the porosity factor.

The 3D capabilities of GOTHIC in simulating basic flows for containment analysis have been extensively investigated, simulating Specific Effect Tests (SETs) in facilities like PANDA, CSTF, BFMC or CVTR (EPRI, 2018). A large validation effort against light gas experiments has been performed with 2D and 3D models, as can be seen in (Andreani, Kapulla, & Zboray, 2012) (Hultgren, Gallego-Marcos, Villanueva, & Kudinov, 2014) (Paladino, Zboray, Andreani, & Dreier, 2010).

The complete GOTHIC software package provides an integrated analysis environment with a graphical and menu driven user interface (GUI) to create GOTHIC models. This software package (EPRI, 2018) also includes a numerical solver to execute transient simulations and a post-processor to plot and extract results.

3.2.4.1. PAR model description

GOTHIC contains a simple built-in PAR component model which makes this tool useful to analyse the response and capability of PARs inside the containment. PARs are included in GOTHIC through the component "H2 recombiner", which is used to model forced and natural convection recombiners of either the ignition or catalytic type. This component must be placed on a flow path. When hydrogen-air mixture passes through the flow path, a specified fraction of the hydrogen will turn into steam. As oxygen concentrations affects the recombination rate, PARs cannot operate in an oxygen deprived ambient, so the amount of hydrogen that can be recombined relies on a stoichiometric ratio 2:1 meaning that every two H_2 molecules will require a O_2 molecule to continue the recombination process (Papini, et al., 2018).

The PAR performance strongly relies on user defined parameters, so a good understanding of the PAR behaviour is mandatory to reduce the user effect when modelling PAR performance. For example, in operation mode, a passive autocatalytic recombiner generates a local heat source which produces steam leading to buoyancy induced mixing, condensation on walls and equipment, and the possibility of stratification in the hydrogen accumulation. To analysis these phenomena, it is necessary to use modelling tools that have predictive capability for: complex 3D flow, diffusion (molecular and turbulent), and possible stratification. That is, a CFD code or a CFD-like code such as GOTHIC (Liang, 2016).

3.2.4.2. Validation

Several efforts have been done to validate the PAR model using GOTHIC (NEA, 2015). In the public literature, it can be found a research work done by AECL in which two GOTHIC simulations were performed against an integral test conducted in the THAI vessel using a scale-down AECL PAR unit. The PARs were modelled using a "black-box" type built-in component model in GOTHIC following two different approaches:

- Approach I: A PAR component was used, as illustrated in Figure 9a.
- Approach II: A PAR component was used together with a volumetric fan (Figure 9 b); the volumetric flow for the fan was defined based on the PAR recombination rate.

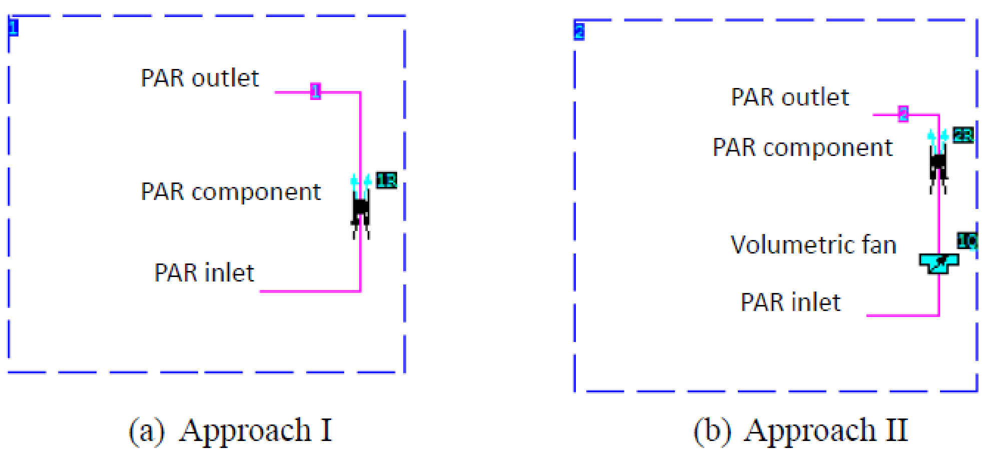


Figure 9. PAR component and modeling approaches in GOTHIC (Liang, 2016)

The PAR efficiency or recombination rate was user-defined. GOTHIC properly captured most of the testing events and trends involving PAR operation and gas mixing processes (hydrogen distribution, PAR induced buoyancy flow, natural convection, and steam condensation on walls) as well as PAR induced combustion. To a reasonable degree, GOTHIC predictions matched well with the measurements.

3.2.5. ANSYS codes (CFX, FLUENT)

The CFD model implemented by FZJ in ANSYS CFX 14 (ANSYS Inc., 2013) is based on the rate determining step of the catalytic recombination of hydrogen/carbon monoxide with oxygen (Kelm, et al., 2021). For the simulation of the catalytic process only the transport of the species is considered. The outer surface of the catalytic coating is modeled as a wall. The chemical reactions are implemented as single-step reactions:

$$H_2 + 1/2\,O_2 \rightarrow H_2O\,,$$
$$CO + 1/2\,O_2 \rightarrow CO_2\,,$$

by means of sinks and sources of mass and enthalpy in the cells adjacent to the wall. The reaction rate is predicted by fully resolving the species boundary layer ($y^+ < 1$) which allows the reactant flux to be solved by Fick diffusion only. Consequently, the molar reaction rate can be described as:

$$\widehat{\omega}_k = \bar{c}\, D_k \left(\frac{\partial X_k}{\partial z}\right)_{wall} \quad \text{for} \quad k = H_2, CO, O_2\,,$$

where $\bar{c}$ is the molar concentration of the mixture, D_k the effective diffusion coefficient of the species k in the mixture and X_k the molar fraction of the species k. To enable the model to predict the reaction rates under oxygen starvation conditions, the transport of oxygen is also considered. The system of compressible Reynolds-averaged Navier-Stokes equations is closed by the k-ε based shear stress transport (SST) turbulence model. This low Reynolds approach avoids using wall functions by integrating up to the wall. The k-species are described by the ideal gas equation of state and temperature dependent properties. As buoyancy is the major driving force, the full buoyancy model with the production and dissipation of turbulence is included. The radiative heat transfer between the plates and also with the environment is considered by means of a Monte Carlo model (ANSYS Inc., 2013). The gas mixture is considered to be optically thin. Only the heat transport by absorption or reflection between the walls and the in/outlet boundaries is modeled. A gray spectral model with an average emissivity of 0.7 for the catalytic surface and 0.5 for the metallic structures is applied. In case of REKO-3 validation, the external blackbody temperatures for the radiative heat exchange with the in/outlet boundaries are estimated from the thermocouples at inlet and at outlet. This CFX model has its main advantage in predicting the detailed thermal hydraulic and transport phenomena within a real PAR channel and is used for the assessment of new catalyst designs. It has been extensively validated against the entire REKO-3 database and against experiments with cylindrical catalysts (Kelm, et al., 2021).

3.2.6. PARUPM code

3.2.6.1. Model description

PARUPM is a non-proprietary model that has been implemented into the MELCOR code and which simulates the performance of a PAR device. The model accounts for the different phenomena intervening in the recombiner, assumed to be a series of vertical flow channels delimited by vertical parallel plates (Jimenez, 2007).

- Heat and mass transfer between the gaseous mixtures and the catalytic surface in a channel-flow driven by natural convection,
- Adsorption/desorption of species at the surface of the plate,
- Surface chemical reactions and subsequent heat release,
- Radiation heat exchange with the surroundings.

These phenomena occur simultaneously, and they must be able to be solved in a coupled way. The coupling will be carried out by means of expressions of the mass and energy balance at the interface between the catalytic plate and the gaseous stream that runs constantly next to it (Jimenez, 2007) .

Particularly, the model is adapted and developed for surface chemistry, and heat and mass transfer between H_2, CO, air, steam, and CO_2 mixtures and vertical parallel Platinum-coated surfaces. The model is based on a simplified Deutschmann (Deutschmann, Schmidt, Behrendt, & Warnat, 1996) reaction scheme for methane surface combustion and the analysis by Elenbaas (Elenbaas, 1942) for buoyancy-induced heat transfer between parallel plates. Mass transfer is treated by the heat and mass transfer analogy. To further study the detailed model see (Jimenez, 2007)

This model focuses on the heterogeneous mechanisms, considering the homogeneous reactions in the gaseous flow negligible. Thus, the recombination on the catalytic plates happens due to heterogeneous processes for the CO and H_2 combustion catalyzed with Pt. These processes are described by the Deutschmann model for CH_4 combustion over Pt plates through a series of 20 reactions which, after considering the applicability to PARs, narrow to 10. The reduced chemistry model is shown on next table.

Elementary reaction	S_{ia}	A_i	E^{act}_i (J/mol)
1a $H_2 + 2\,Pt(s) \rightarrow 2H(s)$	0.046	-	-
1d $2H(s) \rightarrow H_2 + 2Pt(s)$	-	3.7×10^{17}	$R(8110\text{-}722\theta_H)$
2a $O_2 + 2\,Pt(s) \rightarrow 2O(s)$	$0.07\times(300/T)$	-	-
2d $2O(s) \rightarrow O_2 + 2Pt(s)$	-	3.7×10^{17}	$R(25631\text{-}7220\theta_O)$
3a $H_2O + Pt(s) \rightarrow H_2O(s)$	0.75	-	-
3d $H_2O(s) \rightarrow H_2O + Pt(s)$	-	10^{13}	40300
IV $OH + Pt(s) \rightarrow OH(s)$	1.00	-	-
4 $H(s) + O(s) \rightarrow OH(s) + Pt(s)$	-	3.7×10^{17}	11500
5 $H(s) + OH(s) \rightarrow H_2O + Pt(s)$	-	3.7×10^{17}	17400
6 $OH(s) + OH(s) \rightarrow H_2O + O(s)$	-	3.7×10^{17}	48200
7a $CO + Pt(s) \rightarrow CO(s)$	0.84	-	-
7d $CO(s) \rightarrow CO + Pt(s)$	-	10^{13}	125500
8d $CO_2(s) \rightarrow CO_2 + Pt(s)$	-	10^{13}	20500
9 $CO(s) + O(s) \rightarrow CO_2(s) + Pt(s)$	-	3.7×10^{17}	105000
10 $CH_4 + 2\,Pt(s) \rightarrow CH_3(s) + H(s)$	-	4.63×10^{16}	-
11 $CH_3(s) + Pt(s) \rightarrow CH_2(s) + H(s)$	-	3.7×10^{17}	20000
12 $CH_2(s) + Pt(s) \rightarrow CH(s) + H(s)$	-	3.7×10^{17}	20000
13 $CH(s) + Pt(s) \rightarrow C(s) + H(s)$	-	3.7×10^{17}	20000
14+ $C(s) + O(s) \rightarrow CO(s) + Pt(s)$	-	3.7×10^{17}	62800
14- $CO(s) + Pt(s) \rightarrow C(s) + O(s)$	-	10^{14}	184000

Table 2. Deutschmann model of surface combustion of catalyzed methane on Pt. S_{ia} is the sticking factor, A_i is a pre-exponential factor, and E^{act}_i is the activation energy for the reaction.

Where (s) describe the adsorbed status of species into the catalytic plate and Pt(s) represent the presence of a void in the solid matrix to house a chemical radical. The subscripts a/d indicate that they are species adsorption/desorption reactions, respectively. Deutschmann's model of catalytic combustion of CH_4 do not include reactions with nitrogen, given its low reactivity at the temperatures of the catalytic wall and its very low coefficient of accommodation.

For its application to the PAR model, the complete set of reactions of the Deutschmann mechanism is not necessary. Reactions 10 to 13 (marked in gray) correspond to successive steps in the dehydrogenation of methane. Therefore, these reactions will not take place in the catalytic plates of a PAR in the containment chamber as long as there is no CH_4 in the containment atmosphere, as normally occurs. On the other hand, reaction IV (also indicated in gray) would correspond to the adsorption of the OH radical from the gas stream. As homogeneous reactions have been neglected from the model, this reaction is eliminated from the modeling. Finally, taking into account the direct and inverse reactions: 1a/1d, 2a/2d, 3a/3d, 7a/7d, and 14+/14-, the 20 reactions scheme narrow to 10 (Jimenez, 2007) (Mellado Ramirez, 2002).

In this model, desorption reactions are defined through a general Arrhenius law, $k_{id} = A_i \exp\left(-E_{act}^i/RT\right)$. On the other hand, species adsorption reactions are modelled through the sticking coefficients $k_{ia} = S_{ia}/[\left(2\pi RTW_j\right)^{1/2}\Gamma]$. Meanwhile, the remaining catalytic reactions, that describe reactions between species adsorbed on the surface, are described as general Langmuir-Hinshelwood type mechanisms.

With these parameters, it is possible to develop a numerical model consisting of an equation system made of 14 equations described through time. These equations represent (Jimenez, 2007):

- Variations of the fraction of free voids on the surface as a function of the adsorption / desorption and reaction rates of the other species, ${}^{d\Theta_v}/_{dt}$
- Variations in the surface concentrations of each of the 7 species adsorbed on the plate as a function of the reaction and adsorption/desorption rates, ${}^{d\Theta_{i=H,O,vap,OH,CO,CO2,C}}/_{dt}$
- Variations in the composition of the gaseous stream near the wall because of diffusion and adsorption / desorption of species, ${}^{dX_{i=H2,O2,vap,CO,CO2}}/_{dt}$
- Increase in the temperature of the catalytic plate through the energy balance because of the heat of chemical reaction, convection, and radiation, ${}^{dT_w}/_{dt}$

These equations contain 14 parameters that are considered constant at any given time step and must be added as input into the numerical model:

- The superficial concentrations of the species $\Theta_{j=H,O,OH,vap,CO,CO_2,C}$

- The gas stream concentrations in molar fraction of gases $X^{w}_{H_2,O_2,vap,CO,CO_2}$
- The average temperature of the plate T_w

To solve this equation system, it must be treated as a non-linear system of differential equations $\frac{dX}{dt} = F(X)$ being X the vector of variables and F the function matrix of the system equations. So, the solution scheme for this system has the following way (Jimenez, 2007).

$$X_{n+1} = X_n + \left[I - \Delta t \left. \frac{\partial F}{\partial X} \right|_{X_n} \right]^{-1} \Delta t\, F(X_n)$$

The inversion of the matrix $(I - \Delta t\, J)$ has been achieved by the use of the DGETRF, DGETRI, DGEMV and other auxiliary libraries of the LAPack collection (LAPack Linear Algebra Package (3.0), 2000). A standalone version of the model has been produced and implemented into the integral severe accident code MELCOR 1.8.5 to carry out several parameter analysis and validation exercises.

3.2.6.2. Validation

The proposed model is able to simulate the H2/CO recombination phenomena characteristic of parallel-plate passive autocatalytic recombiners through a Deutschmann simplified method solving the non-linear system of differential equations. The transient model can approach both the heating phase of the PAR and its shut-down as well as the dynamic changes within the surrounding atmosphere.

After the model's implementation within the MELCOR code (Jimenez, 2007), validation calculations have been performed to check the coupling of the full transient model with the main calculation flow by MELCOR. Specifically, these results were compared with the results from the Battelle Model Containment tests of the Zx series. Results show accurate predictions and a better performance than traditional methods in integral codes, i.e., empirical correlations, which are also much case-specific. Influence of CO presence in the mixture on the PAR performance is also addressed in this model although, at the time, there were not enough experiments to validate the results obtained with PARUPM.

The Gx series from the Battelle Model Containment (BMC)

In the Gx series of experiments, a Siemens plate recombiner (precursors of the Framatome-ANP design) made of stainless steel coated with Pt was used, arranged in a subset of compartments of the BMC totalling a free volume of 209 m^3.

Although detailed results of the evolution of the experiments are not available, it was possible to access some experimental results, provided by Heitsch in the validation of his analysis of the Gx6 and Gx8 experiments performed with the CFX-4.1 code (Heitsch, 2000).

Comparing the result of the Gx6 and Gx8 with the simulations run in PARUPM for a quasi-static approximation, it is found that there is a good correlation of the proposed model with the experimental and numerical results. It should be noted that the simulation (Heitsch, 2000) did not take into account the heat lost in the plate by radiation, hence the operating point of the PAR takes place in higher temperature conditions.

The Zx series from the Battelle Model Containment (BMC)

Transient simulations of the Zx02 and Zx08 experiments at the BMC have been applied in this way for testing the dynamic behaviour of the new model and comparing results with existing models, based on correlations. The Zx series of tests were performed at the Battelle Model Containment in Germany (Kanzleiter, 1997) and consisted of an arrange of three real design recombiners situated in different rooms of the BMC facility.

Comparing the results obtained with the Zx08 test and the results simulated with PARUPM show quite a good agreement, but recombination rate is overpredicted with the model after the rapid start-up. Also, maximum value is predicted but anticipated quite early and during the descending slope, recombination rate stands below experiment. This might be an effect of the early intense hydrogen depletion occurred during the PAR warm-up phase (Jimenez, 2007).

For the Zx02 test (Kanzleiter, 1997), there is a slight deviation in the PARUPM code predictions that overestimate the H_2 recombination rate compared to the experimental value. This could indicate that the hydrogen concentration is close to the limit to start the reaction (Jimenez, 2007).

REKO-3 experiments from FZJ

The model PARUPM has also been compared to the experiments carried out by FZJ in the REKO-3 facility (Drinovac, 2006). The main characteristic of these experiments is that they are carried out in conditions of forced flow, in order to characterize the flow rate of the different species that passes through the recombiner. The objective of the REKO-3 experiments is the investigation of the detailed processes that take place in plate-type recombiners (reaction kinetics, catalyst temperatures, heat transfer, etc.), for which it is mandatory to have a strict control of the conditions of the gas stream.

Although the REKO-3 installation corresponds to a forced and controlled flow configuration in the injection lines and the model proposed in PARUPM is developed under the configuration of a channel flow driven by natural convection, it has been considered highly useful a comparison between these experiments and the model (Jimenez, 2007).

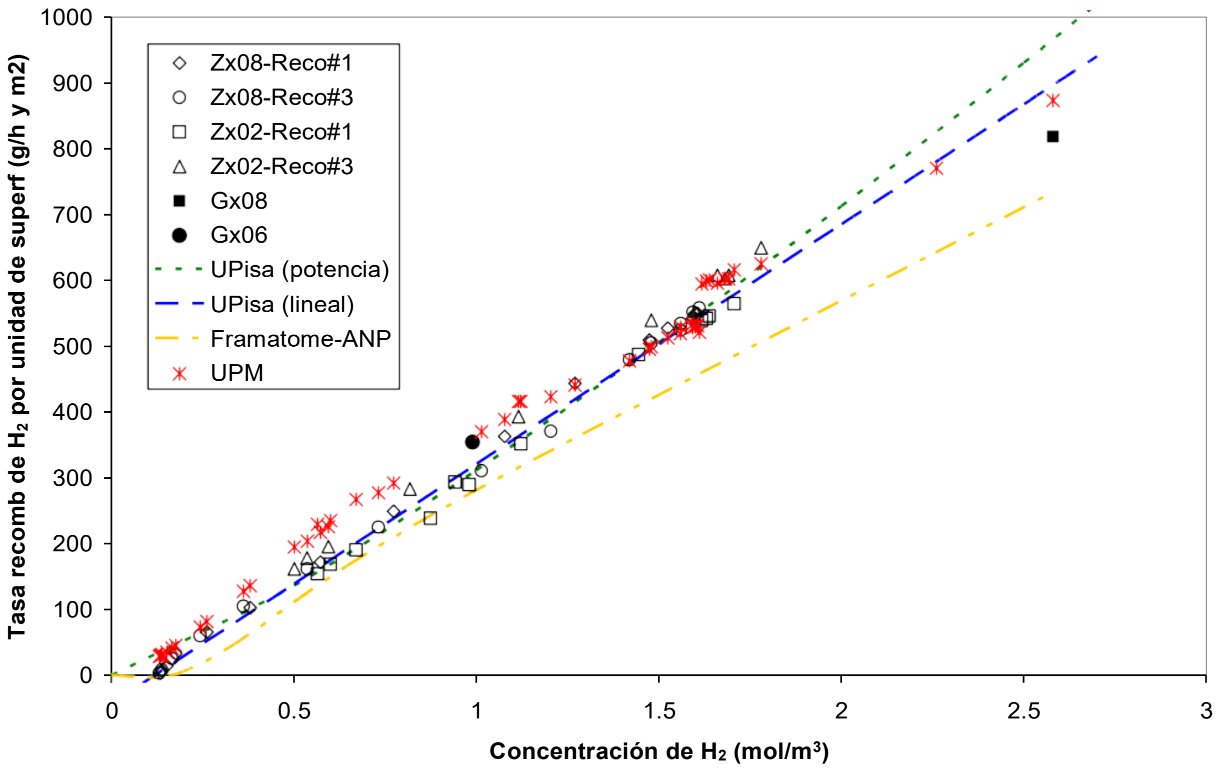
A series of conclusions can be extracted from this validation exercise, that are enumerated below:

- Even if the REKO-3 experiments correspond to conditions of forced flow, they can be simulated with the PARUPM model, but with certain limitations.

- If the REKO-3 experiments are admitted as representative of the homologous situations in natural convection, the PARUPM model shows that the characteristic length L_c of the scale of ascending forces is of the order of the plate length L (between 0.4 and 1.0 times L), with a value closer to 0.4 L.
- Just as other experiments and correlations show, the PARUPM model also predicts a behaviour of the recombination rate that is practically proportional to the volumetric flow rate of hydrogen through the channel in this range of conditions

3.2.7. SPARK

The SPARK code is a numerical tool dedicated to catalytic chemical reactor-type applications. It solves the 2D steady-state Navier-Stokes equations in the vorticity-velocity formulation by including detailed gas phase and surface chemistry, multicomponent transport, and surface heat radiation (Meynet, Bentaïb, & Giovangigli, 2014). This code has been developed at IRSN with optimized function libraries for the evaluation of thermochemical and transport properties, and



molar production rates.

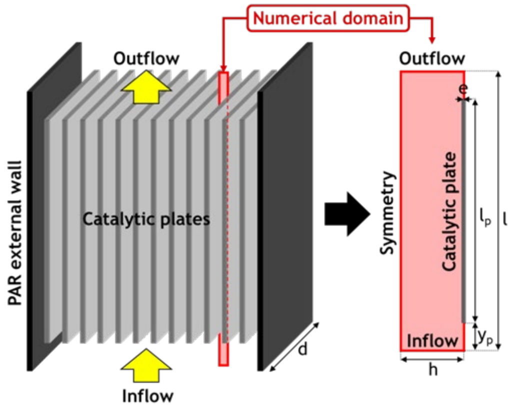


Figure 10 – SPARK numerical domain

The PAR modelling in SPARK supposes laminar flow and very thin catalytic plates, so that there is no turbulence model and the transverse solid heat conduction is neglected. Then, energy balance at the catalytic surface can be expressed as:

$$\lambda\partial_x T = \partial_y(\hat{\lambda}\,\partial_y T)\,e - \sum_{k=1}^{n} h_k M_k \hat{\omega}_k - q^{rad} ,$$

where λ and $\hat{\lambda}$ are respectively the gas and solid thermal conductivity, T the temperature, e the thickness of the catalytic sheet, h_k the specific enthalpy of the k^{th} species, M_k its molar mass, $\hat{\omega}_k$ its molar surface production rate, n the number of gaseous species and q^{rad} the radiative heat flux. The span-wise variation of the radiation is neglected so that the catalytic sheets are segmented by two-dimensional strips. The inlet and outlet are taken as black surfaces respectively at the injection temperature and the average outlet temperature. The horizontal strips are considered as diffuse gray surfaces at local catalyst temperature with an emissivity $\varepsilon_i = 0.7$. In parallel, mass balance of gas phase species at the catalytic surface yields:

$$\rho Y_k U_k = - M_k \hat{\omega}_k \quad \text{for} \quad k = 1 \ldots n ,$$

where ρ is the density of the mixture, Y_k the mass fraction of the k^{th} species and U_k its diffusion velocity evaluated by the detailed transport modelling:

$$U_k = -\sum_{l=1}^{n} D_{kl}\partial_k X_l - \theta_k \partial_x \log T \quad \text{for} \quad k = 1 \ldots n ,$$

where X_l is the molar fraction of the l^{th} species, D_{kl} the species diffusion coefficients and θ_k the thermal diffusion coefficient of the k^{th} species. This formulation includes the multicomponent diffusion (i.e. each species diffuses in relation to all the other species) and the thermal species diffusion (i.e. Soret effect). The molar production rates are evaluated thanks to detailed chemical mechanisms for H_2 and CO oxidation over platinum catalyst (Deutschmann, Schmidt, Behrendt,

& Warnat, 1996) and in the gas phase. The latter were validated with detailed experiments within a catalytic reactor at Paul Scherrer Institute.

The SPARK code had been validated intensively based on REKO tests (Chakraborty, et al., 2017) (Klauck M. , et al., 2014) and THAI test (Meynet, Bentaïb, & Giovangigli, 2014). More recently, the surface chemistry models had been extended to address H_2 and CO oxidation over palladium catalyst. This extension is under validation.

3.3. Conclusion

To model PARs behaviour, several approaches were developed ranging from engineering correlations to more details CFD models taking into account all relevant phenomena as thermal radiation, detailed chemical reactions on the surface and in the gas.

The engineering correlations are usually implemented in the safety tools (both LP and CFD) and help performing scenarios analysis to assess the PAR design. On the other hand, the PAR detailed models help understanding the phenomena that affect the PAR operation and provide then ways to improve the engineering correlation (PAR ignition limit definition for example).

Both engineering and detailed models were validated on experiments dealing with hydrogen. Their validation on conditions with carbon monoxide is still unsatisfactory due to the lack of adequate experiments.

Moreover, deeper investigations are required to improve the knowledge related to CO poisoning of catalysts. For these purpose, laboratory experiments with quantification of species and catalyst surface conditions together with detailed models for chemical reaction, fluid mechanics and mass transport are needed to refine and update the existing chemical kinetics schemes.

4. Reactor application and PAR sizing

To fulfil the requirements adopted to manage the hydrogen risk (see IDL2), especially after the Stress Tests derived from the Fukushima Dai-ichi accident, the number of PARs was determined based on numerical simulations of representative severe accident scenarios. For this purpose, LP, 3D and CFD codes has been used to find the appropriate number and the detailed location of the PARs inside the containment, (Meynet, Bentaib, Bleyer, & Caroli, 2008) (Bentaib, Caroli, Chaumont, & Chevalier-Jabet, 2010). For this purpose, the selected severe accidents scenarios consider only in-vessel conditions, normally. Thus, PAR sizing performance needs to be revaluated considering scenarios that include both in and ex-vessel phases. To do so, dedicated data and modelling improvement are foreseen in WP3 and WP4 of the AMHYCO project. (J. Fontanet, 2016)

5. General Conclusion and remaining open issues

Both past and recent experimental programs were conducted to improve the knowledge on PAR behavior in representative severe accident conditions. The past experimental programs addressed the PARs global behavior and were focused mostly on determining the PARs efficiency. Whereas, the recent programs were focused on deeper investigation on phenomena affecting PARs behavior. Thus, separate and integral tests were conducted at "meso" and large-scale facilities providing details that help improving the PAR models. Even if most of the performed experiments are relevant to in vessel conditions, recent investigations were performed to provide data concerning PARs behavior in conditions with presence of CO and lack of oxygen that are relevant for severe accident late phases (Bentaib A. , 2019).

Actually, several experimental programs have been conducted to study the effect of carbon monoxide on PAR operation. The observations range from CO conversion to CO_2 without any interference with the hydrogen recombination to full catalyst deactivation due to catalyst poisoning. Until now, the conditions for the transition between both regimes are unclear. Consequently, the experimental program in WP3, based on relevant late phase conditions issued from WP2, has to provide corresponding data regarding:

- the conditions (gas composition, including oxygen starvation) leading to catalyst poisoning by CO
- the role of containment temperature and pressure on the catalyst poisoning conditions
- the sensitivity of different catalysts (e.g. platinum- or palladium-based) with regard to poisoning

Further potential mechanisms of PAR deactivation to be investigated (e.g. cable fires) need to be deduced from analysis of relevant accident scenarios.

In parallel and in order to model PARs behaviour, several approaches were developed ranging from engineering correlations to more details CFD models taking into account all relevant phenomena as thermal radiation, detailed chemical reactions on the surface and in the gas. The engineering correlations are usually implemented in the safety tools (both LP and CFD) and help performing scenarios analysis to assess the PAR design. On the other hand, the PAR detailed models help understanding the phenomena that affect the PAR operation and provide then ways to improve the engineering correlation (PAR ignition limit definition for example).

Both engineering and detailed models were validated on experiments dealing with hydrogen. Their validation on conditions with carbon monoxide is still unsatisfactory due to the lack of adequate experiments. To this end, WP3 will provide detailed data to improve the PARs behaviour modelling in conditions relevant to severe accident late phases. Deeper investigations are foreseen to improve the knowledge related to CO poisoning of catalysts.

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Chapter 2:

Review of the existing PWR SAMGs regarding containment risk management

1. Introduction

In case of an accident in a nuclear facility, proper actions and strategies are designed to be taken to avoid or minimize the core damage and, eventually, the release of radioactive material to the environment. Three main categories of actions and procedures are then developed:

- The Emergency Operating Procedures (EOPs) to prevent or delay the core damage (i.e. to prevent severe accident conditions).
- The Severe Accident Management Guidelines (SAMGs) to mitigate the accident consequences with these objectives:
    - to terminate the progress of core damage once it has started and retain the core within the reactor vessel;
    - to preserve the containment integrity [1] as long as possible;
    - to minimize on-site/off-site radioactive releases;
    - to achieve a long-term safe and stable condition;
- The Emergency Plan (EP) to protect the safety and health of workers and general public.

To maintain the containment integrity as long as possible, the SAMGs provide guidance for a best use of the existing plant equipment to limit the consequences of phenomena such as: steam explosion, direct containment heating, hydrogen combustion, containment pressurization and molten core-concrete interaction.

Regarding the hydrogen combustion risk, as it may endanger the containment integrity and lead then to significant radioactive releases, dedicated actions and procedures were developed, as part of the SAMGs, to address this issue. The development of such actions and guidelines depends on the nuclear facility design, on the considered safety equipment and on the adopted requirement in each country.

These guidelines are developed by utilities and validated through the probabilistic studies of level 2 (PSA L2) by considering representative severe accident scenarios taking into account the severity levels of the plant states together with states of operability/ inoperability of safety systems and safety features, dedicated for severe accident management.

The aim of this report is to provide a summary on the requirements, commonly adopted in PWR technologies, to implement the hydrogen mitigation measures and on the adopted considerations of the use of engineering systems (i.e., spray, containment venting, air coolers, suppression pool, latch systems) in severe accident management strategies.

[1] Keep the containment pressure within the design domain

2. SAMGs and Hydrogen Risk

During the course of a severe accident (SA) in a light water nuclear reactor, large amounts of hydrogen (H_2) could be generated and released into the containment during reactor core degradation. Additional burnable gases (CO) may be released into the containment in case of molten core-concrete interaction (MCCI). This could subsequently raise a combustion hazard that may cause high pressure peaks that could challenge the reactor containment and lead to the damage of surrounding buildings and to the loss of safety equipment needed for the accident management.

To prevent the hydrogen explosion hazard and limit its consequences, most of the adopted mitigation strategies are based on the implementation of Passive Autocatalytic Recombiners (PARs) and igniters. Other systems like sprays or fan coolers might also affect the hydrogen distribution and the induced pressure and temperature loads in case of combustion.

The SAMGs related to hydrogen risk management rely on the use of the mentioned systems and on the gas monitoring setup when implemented. They recommend either immediate or delayed actions based on the considered accident and its progression. The use of specific SAMGs depends on the accident type, on the indicated instrumentation values, when available, and on the best understanding of the accident progression.

For this purpose, dedicated Diagnostic Process Guideline (DPG), and computational aids (CAs) were developed by utilities taking into account the nuclear facility design and specifics and the adopted requirement in each country. The Diagnostic Process Guidelines (DPG) permit choosing the appropriate actions and prioritizing their implementation. The DPG Parameter Worksheet is updated regularly to take into account the accident evolution. As an example, the structure of the PWROG SAMGs is illustrated in Figure 1 and Figure 2 and PWR-KWU in Figure 3. In these figures, the hydrogen risk is identified with the related mitigation strategy (SAG-7) and the computational aid (CA-3) used to check the containment atmosphere flammability.

As the SAMGs are linked to the reactor design and are not public, only a survey on the adopted requirement, the related safety equipment and on the use of the monitoring system will be provided with the aim to focus on gas explosion management during severe accidents late phases.

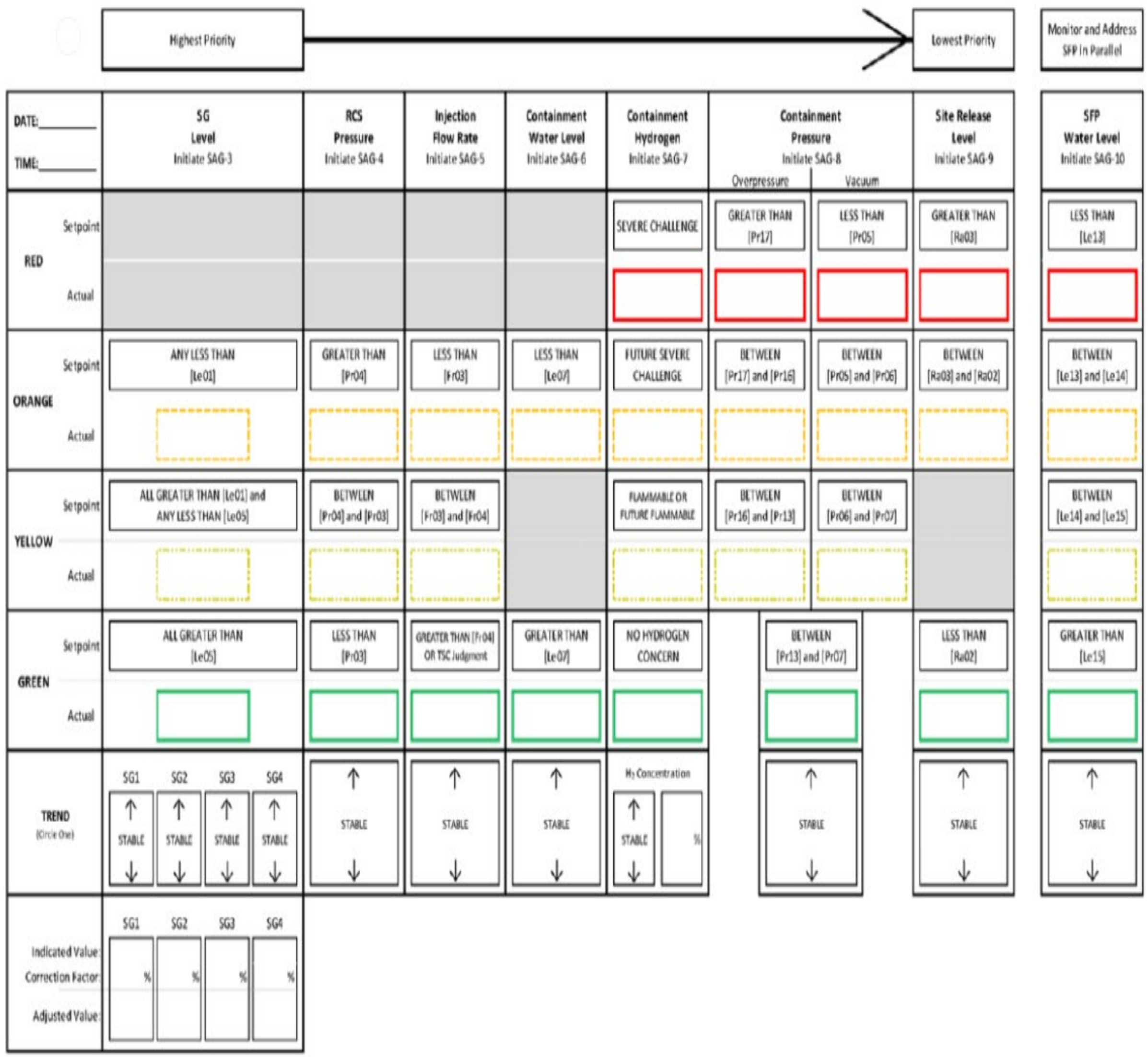


Figure 11: Sample parameter worksheet used in the diagnostic process guideline (DPG) for PWR SAMG2016 (NEA/CSNI/R(2017)16)

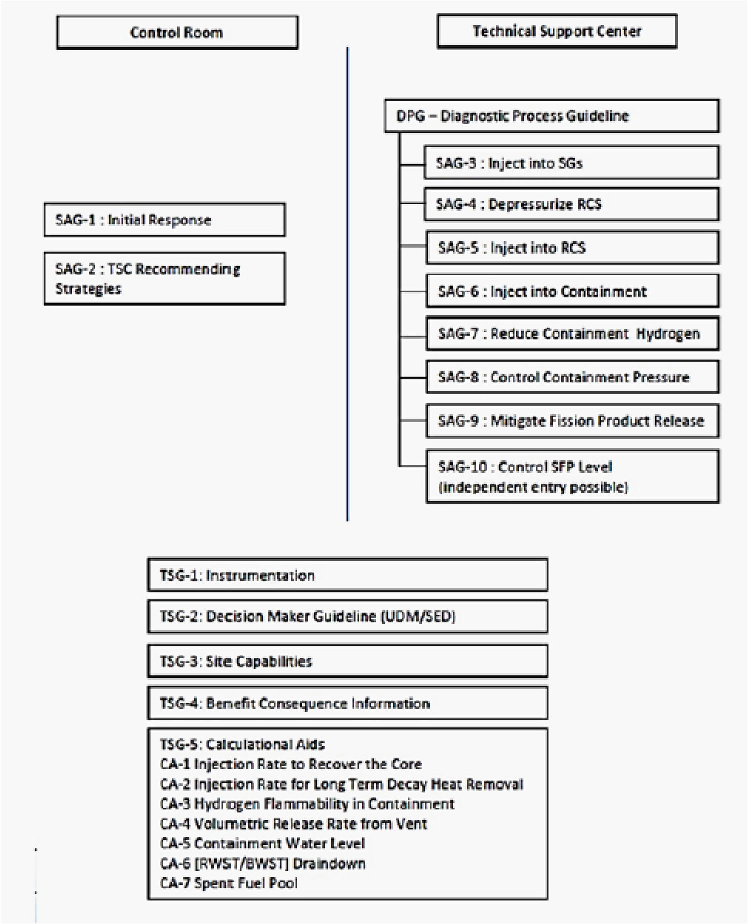
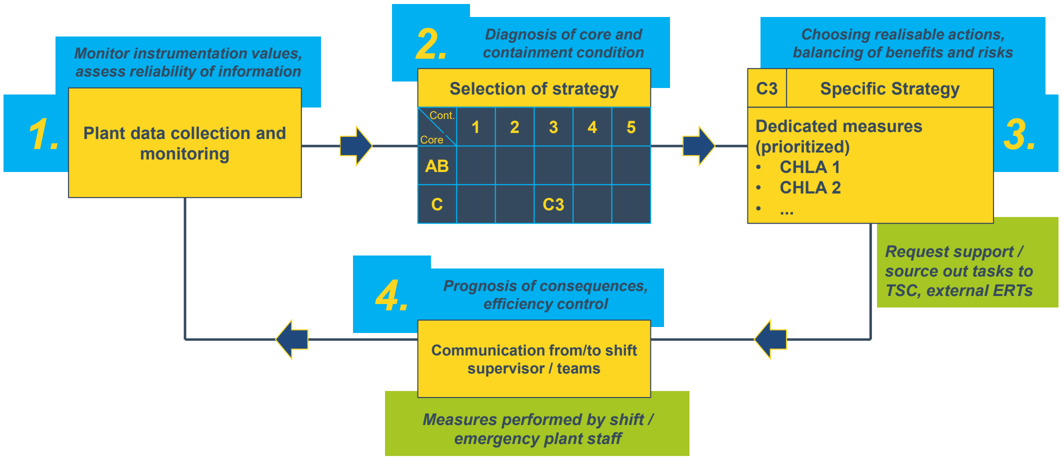


Figure 12: Example of PWROG SAMGs 2016 structure (Gajdoš, 2017)



2.1. Hydrogen Mitigation Measures Requirement

The choice of mitigation means is mainly related to the containment design. Hence, PARs or igniters are used for PWR large dry containments. Before their implementation, national requirements are defined to achieve the expected safety goals of preserving the containment integrity to avoid large fission products release to the environment.

After Fukushima Daiichi accidents, the OECD-Working Group on Analysis and Management of Accidents (WGAMA) proposed to write a status report on hydrogen generation, transport and mitigation under severe accident conditions. The Status Report on "Hydrogen Management and Related Computer Codes" was finally published in June 2014 (Liang, Sonnenkalb, Bentaib, & Sergioni, 2014). The information contained in the report covered the related information obtained in the frame of international OECD or EC programs and presents a detailed survey of the requirements commonly adopted in western countries. Table 1, summarises the national requirements for hydrogen management inside the containment.

Table 3: Adopted requirement per country [2]

Country/NPPs	**Adopted Requirements** **inside the containment building**
Belgium/PWRs	Avoid combustions challenging the containment integrity. Design criteria: mean H_2 < 4 vol.% for DBA, mean H_2 < 5 vol.% for SA, **no criterion for local H2 concentration**
Canada/CANDU 6	mean H2 < 6 vol.% for DBA**, 8 vol.% for BDBA/SA, P<3.35 bar** (a) (failure of airlock seals); demonstrate containment function to be maintained.
Canada/Multi-unit	mean H2 < 4 vol.% for DBA, **8 vol.%** for BDBA; no hydrogen concern during short term hydrogen release to avoid global combustions challenging the containment integrity
Czech Republic	Design of hydrogen removal system based on evolution of hydrogen concentrations, criteria for FA and DDT, and AICC pressure
Finland	Gas burns that may jeopardise containment leak tightness shall be prevented
France/PWR900 France/PWR1300 France/PWR1450	For all fleet, **mean H2 < 8 vol.%, local H2 <10 vol.%,** PAICC < 5 bar PAICC < 4.8-5.2 bar PAICC < 5.3 bar

[2] literal wording has been taken from the reference (Liang, Sonnenkalb, Bentaib, & Sergioni, 2014)

Germany/PWR	Avoid global combustions challenging the containment integrity
Japan/PWRs	Criteria for preventing the destructive detonation are interpreted as maintaining the **mean and local hydrogen concentration at 13 vol.%** or less without steam condition or the mean and **local oxygen concentration at 5 vol.% or less.**
Korea/PWRs/PHWRs	**Mean H2 < 10 vol.%**; **local H2 concentration should be low** to avoid widescale FA or DDT. For static combustion load (AICC), KEPIC requirements for containment integrity (such as the Factored Load Category of ASME, Sec. III) should be satisfied
Spain	Eliminate the possibility of deflagration or detonations that threaten the containment integrity
The Netherlands/PWR 500	Avoid global combustions challenging the containment integrity

From the previous table, it can be concluded:

- The adopted requirements address only in-vessel conditions.
- Only few countries adopt quantitative criteria for the requirement.
- All the requirements aim to preserve the containment integrity.

2.2. Hydrogen Mitigation Systems

The hydrogen mitigation systems commonly implemented in the PWR consists of the use of one or a combination of the following approaches:

- the deliberate ignition of the mixture using igniters,
- the consumption of hydrogen using PARs or thermal recombiners,
- the hydrogen dilution in the containment atmosphere of high concentration locations by using atmosphere mixing systems.

2.2.1. Active Deliberate Ignition

To prevent hydrogen accumulation, in several NPPs igniters are implemented inside the containment to keep the hydrogen concentrations relatively low that the pressure and temperature loads induced by combustion cannot endanger the containment integrity. To this end, the number of igniters, their location and initiation time are designed appropriately for the effective control of hydrogen concentration.

Three main igniter's technologies are used in NPP:

1) the glow plug igniters, based on electrical resistance heaters with hot surface temperatures of about 800 – 900°C, that can be operated manually (on and off), automatically (in response to LOCA signals) or semi-automatically (automatically but turned off by the operator),
2) the spark igniters that do not need high power from the outside and are maintained by a battery power and
3) the catalytic igniter that uses the heat of the hydrogen-oxygen catalytic reaction to initiate a combustion.

The advantages and drawbacks of each of the mentioned technologies are recalled in Table 2.

Table 4: comparison of igniters for hydrogen control in NPP (Bentaib & Gupta, 2021)

Type	Advantages	drawbacks
Glow plug igniters	-ignite over widest range of compositions, - continuous availability -robust -operator controlled	- rely on AC power, - high-power requirement -containment penetration
Spark igniters	-battery powered, do not rely on AC power -easily back-fitted, no connections required	-intermittent operation (in 5s intervals, -not operator controlled, -weaker ignition source than for glow-plug igniters, -unavailable in long term -rely on triggering from LOCA signals
Catalytic igniters	-self powered, use heat of H_2-0_2 reaction to produce ignition temperature - easily back-fitted, no connections required	-operates over narrower range of compositions than do either spark or glow-plug igniters; -response to changing conditions not instantaneous; -potential for poisoning or fouling -combined with recombiners, subject to common cause failure. -not operator controlled

2.2.2. Passive Hydrogen Recombination

To cope with hydrogen production rates in a severe accident with core damage, PARs were back-fitted within the containment. Typical nominal rates for hydrogen depletion for the PARs are in the range up to 100 to 200 kg/h for the whole containment building. Nevertheless, studies of representative accident sequences indicate that the hydrogen release may exceed the PARs depletion capacity. In these cases, the installation of PARs is focused on preventing or minimizing the possibilities of containment integrity challenges due to flammable gases explosions.

The PARs start without any operator action, so there are no actions required in the SAMGs. The PARs deplete H_2 as well as CO and thereby also O_2. Typically, the mass of hydrogen generated by core degradation will consume not more than half of the oxygen inside of the containment. After a possible RPV failure, the MCCI starts and produces additional H_2 and CO. The expected release of combustible gases will lead to a consumption of the entire residual oxygen up to the point where the PARs cannot recombine the combustible gases anymore (oxygen starvation). It is possible that after the consumption of oxygen still significant amounts of combustible gases are produced and stored in the containment, although do not lead to a containment challenge because no combustions nor explosions can be produced. However, this has to be considered for the FCVS operation, when the containment atmosphere may be mixed with air again, e.g., in the vent stack or on top of the dedicated exhaust pipe. Moreover, the non-condensable gas release leads to an increase of pressure inside the containment. The containment over-pressurization may promote the H_2/CO migration from the primary containment to connected buildings, where formation of flammable atmospheres may also result in gas explosions. Thus, dedicated measures need to be implemented to avoid such risk.

2.2.3.Active Hydrogen Recombination

Connected to the active hydrogen mixing system, containment air is forced through an active thermal hydrogen recombiner. The purpose of this active recombiner system (preceding the back-fitting with PARs) is the mitigation of the limited hydrogen release during a design basis large-break LOCA and the subsequently expected radiolysis gas production. As the capacity of the (still existing) active thermal recombiner system is rather low, by far outperformed by the now installed PARs, **the active recombiners are not further credited for hydrogen mitigation in severe accidents**.

2.2.4.Atmosphere Mixing System

PWR-KWU and EPR containments are accessible during power operation. Therefore, the containment is divided as so called two-room-containment into accessible service compartments and not accessible equipment compartments. These two types of compartments are separated in two ventilation system zones. The ventilation system keeps the equipment compartments at lower pressure (higher sub-pressure). This creates a defined direction of the air flow from compartments with low risk of fission product release to compartments with higher risk.

In case of a design-basis LOCA, that is, inside of the equipment compartments, the separation of the two ventilation zones is ended by rupture foils on top of the steam generator houses. These rupture foils prevent a significant pressure difference between the different containment compartments. The opening of these rupture foils guarantees the pressure relief, but not a good convective mixing of the containment, necessary for dilution of hydrogen within the containment. Thus, for the long-term treatment of hydrogen in the PWR-KWU after a design-basis LOCA incident, an active dedicated hydrogen mixing system is available. This system takes atmosphere from the accessible rooms and blows it by fans into the steam generator houses. The system can open the rupture foils by the pressure difference created by its fans and ensure well-mixing of the atmosphere in the equipment and accessible rooms. Similarly, a dedicated mixing system, called mixing dampers, is implemented in the EPR containment. Thereby flaps are opened in the lower building part to enable upward convection through the equipment compartments and downward flow in the outer containment areas.

The following table, issued for (Liang, Sonnenkalb, Bentaib, & Sergioni, 2014), summarizes the adopted hydrogen mitigation measures in different countries:

Table 5: Implemented hydrogen mitigation measures per country

Country/NPPs	Hydrogen Mitigation Measures
Canada/CANDU 6 (Point Lepreau)	19 AECL PAR [3]; Local air cooler and dousing
Canada/Bruce (A &B)	64 **glow plug** with 22 AECL PAR each station; Local air cooler and dousing
Canada/Pickering A	24 **glow plug** with 20 AECL PAR for each unit; Local air cooler and dousing
Canada/Pickering B	64 **glow plug** with 120 AECL PAR; Local air cooler and dousing
Canada/Darlington	232 **glow plug** with 34 AECL PAR; Local air cooler and dousing
France/PWR900	24 AREVA PARs (111.6 kg/h at 1.5 bar and 4% H_2)
France/PWR1300	116 (50 without chimney and 66 with chimney) AECL PARs (109 kg/s at 80°C and 4% H_2)
France/PWR1450	
German/PWR KONVOI	65 AREVA PARs (~190 kg/h at 1.5 bar and 4 vol.% H_2)
German/PWR Pre-KONVOI	90 NIS PARs (~190 kg/h at 1.5 bar and 4 vol.% H_2)
German/BWR-72	78 NIS PAR in drywell and wetwell (~133 kg/h at 3 bar and 4 vol.% H_2) wetwell inerted by N_2
The Netherlands/PWR 500	22 Siemens/KWU PARs (119 kg/h at 1 bar)

[3] In Canada, all AECL PARs are required to self-start at 2% H_2 and 100°C regardless of catalyst degradation level, self-stop at 0.5-0.6% H_2 with capacity of 0.8 kg/h/per PAR at 20°C and 4% H_2.

Spain/PWR-KWU-1000	32 AREVA PAR (142.6 kg/h at 1.5 bar and 4 vol.% H_2)
Spain/PWR-Westinghouse 1000	19-22 AREVA/NIS PAR (80-120 kg/h at 1.5 bar and 4 vol.% H_2)
Slovenia/W 2-loop PWR	22 PARs, NIS Type 44

It has to be noticed that the mitigation measures, as presented in Table 2, were implemented to satisfy the requirements presented in Table 1. Their implementation had been validated based on severe accident scenarios considering only in-vessel phases.

2.3. Considerations of Systems and Events on Hydrogen Behaviour

During severe accidents, several engineering systems as sprays, local air cooler, venting systems, rupture discs, mixing dumpers or blow-up panels could be used to reduce containment pressure and temperature. However, operation of these systems can have an impact on H2/CO distribution and combustion if ignition occurs. They may reduce their maximum concentration values due to enhanced mixing or through the increase in the total available volume, for the containment with accessible and not accessible zones. On the other hand, the sprays and air cooler actuation may lead to an increase of the hydrogen concentration due to steam removal.

To this end, various requirements and considerations (in the SAMGs) have been defined by different countries in use of these systems in case of severe accident. The following table summarizes these considerations for each of these engineering systems: sprays actuation, venting systems, local air cooler, blow-up panels.

Table 6: Requirements for Operation of Spray System

Country/NPP	Nominal water spray (kg/s)	Criteria for spray actuation and termination	SAMG recommendation
Belgium/PWR1000	Varies among units (125 to 150 kg/s) per train; 3 trains	Varies between units between 2.1 and 3.1 bar (a)	
Canada/CANDU6	6800kg/s maximum with all 6 headers on	1.4bar(on), 0.7bar(off)	
Canada/multi-units Vacuum building	Varies among stations as high as 5750 kg/s	Pressure increase in the vacuum building caused by the opening of the pressure relief vault (2,5 kPa)	License have criteria (SAMG entry conditions) for which such systems are used during a SA
Finland/Loovisa VVER 440	550 kg/s for internal spray, 35 kg/s for external spray	P>1.17 bar (a) for internal spray and P>1.7 bar(a) for external spray	
Finland/Olkiluoto 3 -EPR	180 ks/s if both pumps are operating	Manually activated in accident situation	

France PWR900 PWR1300 PWR1450 EPR		 P>2.6 bar P>2.5 bar P>2.5 bar P>2.6 bar	 For the GENII NPPs, 6 hours delay after core degradation start For the EPR, 3 hours delay after core degradation start
The Netherlands PWR500	50 m^3/h	Manually activated in BDBA	Not used in case of high hydrogen concentrations
Spain PWR W-1000	PWR-W (no fan coolers) varies between ≈170-230 kg/s PWR-W (fan coolers) ≈ 100 kg/s **Recirculation phase:** 10% increase of the mass flow rate	P>1.7 bar	Switch off of the spray when containment pressurization is recommended to avoid flammable cloud formation.
Swiss KBB (PWR)	110kg/s	P>1.31 bar (g)	
Slovenia, W 2-loop PWR,	68 kg/s	P > 1.6 bar (g)	It is also used within Alternative Heat Removal System, manually activated.

Table 7: Requirements for Operation of heat removal through Containment Venting system

Country/NPP	**Nominal mass flow rate (kg/s)**	**Criteria for CHRS opening**	**SAMG recommendation**
Belgium/PWR1000		3bar (ON), 2 bar (OFF)	
Canada/CANDU6 (FCV)			
Canada/multi-units EFADS	149 m^3/h (peak to 790 m^3/h depending on sub atmospheric holds up period)		FCV upgrade as in CANDU 6 for Bruce and Darlington
Finland/Loovisa VVER 440			
Finland/Olkiluoto 3 -EPR		Opened manually if necessary. Not needed if other SAM systems work properly	
France PWR900 PWR1300 PWR1450 EPR	3.5 m^3/h	P>5 bar	At least 24 h after core degradation start
The Netherlands PWR500	4.5 kg/s steam at 4.8 bar (a) and 138°C	P>4.8 bar (a)	
Swiss KBB (PWR)	5.2 kg/s	P>4.2 bar (g)	Venting can be initiated earlier or later over the active path of the FCVS on behalf of emergency staff and /or in accordance with the Swiss emergency organisations

Spain PWR W-1000	Diameter of SFVC pipes: 20 cm (8”)	There is not a fixed value to open the FCVS base on containment pressure. Instead, a range around the design containment (Pd) pressure is established (approximately Pd ±20%). If containment pressure is in this range, the FCVS may be opened In any case, FCVS shall be opened at the highest value of the range (typically: Pd + 20%).	Venting in Spanish NPP is always filtered. The decision is taken by the on-site Emergency Director taking into account the containment pressure but also other considerations.
Slovenia, W 2-loop PWR,	7 kg/s	P > 5 bar (g)	Venting can be initiated earlier if the evaluation (dose calculation) shows that it is beneficial. Manual venting must be initiated if passive venting fails on 5 bar (g).

Table 8: Requirements for Operation of Local Air Coolers

Country/NPP	Cooler location	Criteria for cooler actuation and termination	SAMG recommendation
Belgium/PWR1000	Primary containment , peripheral or upper zone	P>1.3 bar (a)	
Canada/CANDU6	Fuelling machine vaults, boiler room, dome and other accessible areas	To maintain the temperature between 41°C and 55 °C in the inaccessible areas	Emergency mitigation equipment with external sources of electrical power and heat sinks
Canada/multi-units	Reactor vault	~38 MW heat removal during a LOCA	
The Netherlands PWR500	Inside the containment	Cooling of containment atmosphere during normal operation	Heat removal by air coolers is limited or terminated in the presence of hydrogen
Spain PWR W-1000	Within containment outside the missile shield	Safety injection signal	
Swiss KBB (PWR)		P>0.131 bar (g), safety injection signal	

Table 9: Requirements for Latch System, Blow-out Panels and Doors

Country/NPP	Type of devices	Criteria	Passive/Active
Belgium/PWR1000			
Canada/CANDU6	Blow up panels between accessible and inaccessible area	ΔP>6.9 kPa	Passive
Canada/multi-units	Explosive panels		Passive
Finland/Loovisa VVER 440	Forcing open the ice condenser doors (lower inlet, intermediate deck and top deck doors)	Core exit temperature > 450°C	Active (Manually opened with pressurized nitrogen cylinders (no electricity needed)
Finland/Olkiluoto 3 -EPR	Rupture foils in the ceilings of the SG towers and mixing dampers in the lower part	ΔP>50 mbar or T>90°C	Passive
France EPR	Rupture foils in the ceilings of the SG towers and mixing dampers in the lower part		Passive
The Netherlands PWR500	Burst membranes between the component compartment and the dome	Differential pressure in case of H2, 12 panels can be opened by hand	Passive Active
Spain/PWR-KWU-1000	Blow out panels between SG and dome	ΔP>0.5 bar	Passive
Swiss KBB (PWR)			

2.4. Hydrogen Instrumentation

The emergency procedures as safety injection, spray or filtered venting system activation may depend directly on insights in the hydrogen concentration inside the reactor containment. Thus, hydrogen monitoring systems had been implemented in several NPPs as PWRs: Beznau (Swiss), Doel (Belgium), Ascó and Vandellòs II (Spain), Gösgen (Swiss), Kanzaï (Japan), Ringhals (Sweden) and Tihange (Belgium), VVER-1000 such as Kozloduy 5-6 (Bulgaria) and VVER 440-213 such as Paks (Hungaria), as well as German Konvoi PWRs. The typical numbers of used sensors is between 5 and 12.

Two measurements techniques are mainly used: gas sampling or based on catalytic reaction.

When the catalytic reaction measurement techniques are considered, the hydrogen concentration is deduced based on the increase of temperature induced by the catalytic reaction on Pt/Pd sensors. The Beznau plant in Switzerland, the Doel units 3 and 4 in Belgium, and the Kozloduy plant in Bulgaria are using this system to measure hydrogen concentration (Plank, Mandl, Roth-Seefrid, Weber, & Kluegel, 2005). Nevertheless, these systems do not operate under conditions of the late phases of a severe accident, where oxygen is lacking and the carbon monoxide is present in the containment atmosphere. In fact, the oxygen lack leads to the catalytic reaction reduction and consequently to the temperature increase limitation. The simultaneous presence of carbon monoxide and hydrogen in the containment atmosphere make difficult the deduction of the hydrogen and carbon monoxide concentration based on temperature measurement.

The second mostly used hydrogen measurement technique is based on sampling. Generally, the sample extraction monitors that draw a gas sample through a sampling line are located outside containment, where the gas sample is analyzed and then returned to the containment. Sampled gases are analyzed using mass spectrometer or thermal conductivity detector outside the containment. These methods are accurate and have been used in several NPPs in Germany and in Japan. These systems allow long-term availability during a severe accident as the hydrogen monitors are located outside containment and not exposed to the hostile conditions inside the containment. Nonetheless, these measurement techniques have several drawbacks (Plank, Mandl, Roth-Seefrid, Weber, & Kluegel, 2005) (BMU, 2015) as:

(1) The need of containment penetration which increases the risk of containment leakage.

(2) The gases sampling process which may lead to hydrogen dilution. Actually, gas difference pressure between the pipe inlet and outlet may affect the measurement accuracy.

(3) The time delay induced by sampling process analysis.

(4) The need to protect the sampling system installed outside to avoid any radiation exposure to personnel.

3. Conclusions

As mentioned previously, the hydrogen mitigation strategies were developed to preserve the containment integrity. The related measures were designed to satisfy the requirements adopted in each country. They were designed and validated based on severe accidents considering mainly in-vessel phases.

From the survey, we can conclude that

- the adopted requirements address only in-vessel conditions. Their extension to ex-vessel conditions need to be established for the containment and the auxiliary buildings connected to the containment,
- all the adopted requirements aim to preserve the containment integrity. The availability of the safety systems, as sprays or venting line, needed to manage the severe accident late phases need to be addressed in the extended requirements,
- only few countries adopt quantitative criteria for the requirement,
- the mitigation means are designed accordingly to the adopted requirements for in-vessel conditions.
- only few existing SAMG recommendations concern the use of safety systems (CHRS, sprays and coolers) in case of severe accident late phases.,
- the existing monitoring systems don't measure carbon monoxide content.

To extend the existing SAMG to severe accident late phases management, the following input are expected from the work packages 3 and 4:

- Flammability limits and flame acceleration criteria for representative containment and auxiliary atmosphere in late phases. These inputs will help the requirement extension to severe accident late phases.
- PARs performances based on representative scenarios that can help assessing the existing PARs design, with hydrogen recombination rate of 100 to 200 kg/h, to satisfy the requirements in late phases.
- Data on H_2-CO flame interaction with safety systems, as spray, coolers, including the cold water injection in the sump, or venting line, to provide recommendation on their actuation in late phases.
- Data on the combustible gas migration from containment to auxiliary buildings during the containment pressurization in late phases. These input data will help establishing requirements and recommendation (for example, the use of venting) to prevent gas explosion in auxiliary buildings.

- Indication on the use of gas monitoring systems to actuate safety systems as spray, coolers and CHRS.

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Chapter 3:

Review of the existing H_2/CO combustion risk engineering correlations

1. Introduction

During the course of a severe accident (SA) in a light water nuclear reactor, large amounts of hydrogen could be generated and released into the containment during reactor core degradation. Additional combustible gases (H2 and CO) may be released into the containment in case of molten core/concrete interaction (MCCI). This could subsequently raise a combustion hazard. As observed during the Fukushima accidents, hydrogen combustion could cause high pressure peaks that could challenge the reactor buildings. A hydrogen explosion may also be a safety concern in spent fuel storage areas, where flammable conditions may be reached if adequate ventilation is not provided. In this case, the hydrogen explosion may lead to radioactive products dispersion into the environment.

To evaluate the consequences that the H_2/CO combustion may have on the containment and on the safety equipment, empirical correlations and engineering models are used to determine the flammable clouds, the possibility to flame acceleration and the pressure and temperature loads.

The aim of this document is to provide a survey of these correlations and engineering models and their validation status. This survey will be used in WP3 as input to perform additional experiments needed to improve these models and correlations.

2. Empirical correlations

As mentioned above, several empirical correlations have been developed, based on experimental results, to derive limits indicating the propensity of a mixture to develop sustainable flame (flammability limits) and conduct to fast flame regime (flame acceleration limits) or to detonation (deflagration to detonation limits).

2.1. Flammability limits

2.1.1. In vessel conditions

During the course of a severe accident, hydrogen is released and diffuses in the nuclear power plant building (NPP). Since it diffuses in the containment filled with air, it eventually reaches concentrations for which a flame can be ignited. However, not only hydrogen is produced, but also water vapor. As such, the mixture, in the early stages, is likely non-combustible. In fact, one has to consider the history of the pressure and temperature in order to evaluate the risk of forming a combustible mixture. One of the basic parameters of premixed combustion relevant to this risk is the flammability limit and its variation with the thermodynamic conditions.

Among the several methods that exist to determine the flammability limits, the spherical bomb method is often used to conduct flammability limit studies for H2/air diluted or not with steam for various initial conditions of temperature and pressure. A criterion to identify these flammability limits is necessary. Indeed, for a mixture containing hydrogen, air and water vapor, the classification between flammable and non-flammable mixtures will rely on a given parameter that discriminates between the two possibilities: once a sufficient energy is provided (generally a local deposition via an electric spark), either (i) a flame is produced which will propagate inside the vessel and induce a pressure increase; or (ii) the ignition kernel fades away and no sustainable flame is formed. Hence, there are two main parameters to identify the flammability potential of the mixture: (i) by monitoring the flame inception and propagation inside the vessel visually or/and (ii) by monitoring the pressure inside the vessel. In the second case, if the flame is weak and travels mainly in the upward direction, the pressure increase can be very limited and is sometimes barely measured (Cheikhravat, Chaumeix, Bentaib, & Paillard, Flammability limits of hydrogen-Air mixtures, 2012; K. N'Guessan, 2019). To overcome this limitation, the identification of a successful ignition was based on the images recorded by a high-speed camera in the work done at CNRS/ICARE (Cheikhravat, et al., 2015). Moreover, the spherical bomb is also equipped with a high frequency pressure transducer which allows the monitoring of the pressure increase in case of a successful ignition and flame propagation. The limit that separates the flammable zone from the non-combustible mixture, as shown in Figure 1, represents the limit of total flammability limit without any combustion being triggered.

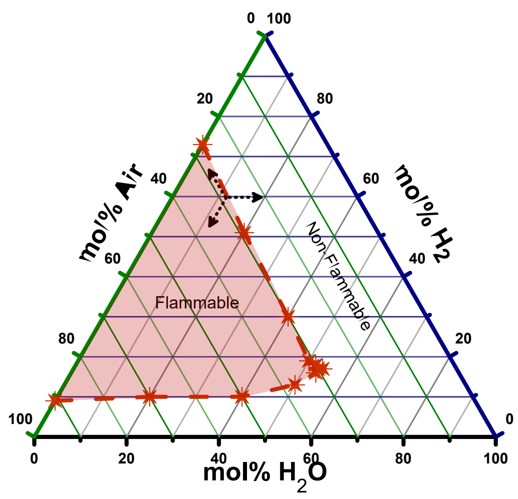


Figure 14: Flammability limit of H_2/air/H_2O_{vap} mixtures initially at 1 bar and 100°C (Cheikhravat, et al., 2015).

In fact, close to the lower flammability domain, a flame can be ignited, but the combustion occurs only in a limited range: the flame ignited at the centre of the vessel will propagate in the upward direction only; it is not able to propagate in the downward direction and hardly on the horizontal one. This behaviour is due to the fact that H2 is a very light combustible and the flame in this domain is very weak, it is not able to overcome the gravity, but the buoyancy is a favouring factor in the upward propagation. Hence, a closer look in the lower flammability limit (LFL) shows that one can define a second limit between the partial combustion with upward propagation and the total combustion domain as shown in Figure 2 for H2/air mixtures at different initial temperatures and at an initial pressure of 2.5 bar.

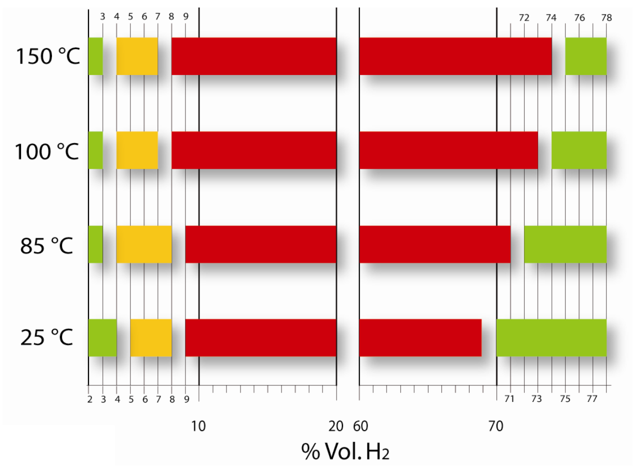


Figure 15: Flammability limits diagrams of H_2/air mixtures between 25°C and 150°C at an initial pressure of 2.5 bar. Green zone: no combustion; orange zone: partial combustion; red zone: complete combustion (Cheikhravat, Chaumeix, Bentaib, & Paillard, Flammability limits of hydrogen-Air mixtures, 2012).

The identification of the region, in terms of mixture composition, for which the combustion is incomplete, is very important since the combustion overpressure that can be reached will depend not only on the real conditions (composition, initial temperature and pressure inside the vessel) but also on the regime of propagation. As it has been shown in our previous work (Cheikhravat, Chaumeix, Bentaib, & Paillard, 2012; Goulier, Lefebvre, Idir, Bentaib, & Chaumeix, 2017) , close to the flammability limit, for hydrogen content between 4 and 9 %, even with a successful ignition and flame propagation, the maximum pressure due to the combustion is limited and well below the theoretical value that one would estimate based on complete adiabatic isochoric combustion (Fig. 3). This is due to the fact that the flame does not propagate in the entire volume but travels only in upward direction. Above 9 % of H2 and up to almost the upper flammability limit (UFL), the maximum pressure is very close to the calculated one which is again an indicator that the flame propagates in the entire volume.

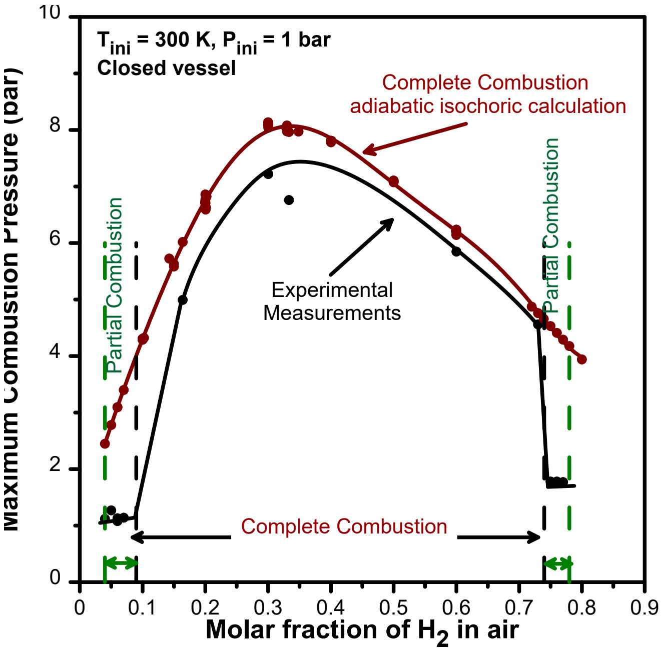


Figure 16: Maximum combustion pressure measured (black line and symbols) and calculated (red line and symbols) in case of H_2/air mixtures initially at 1 bar and 300 K (Cheikhravat, Chaumeix, Bentaib, & Paillard, 2012)

Another important issue is the effect of the medium state in terms of turbulence on the flammability limit. The question is if there is a certain gas motion in the vessel which can be represented by a given turbulence level, which will significantly affect the LFL. As a new preliminary investigation, the effect of turbulence on the lower flammability limits has been examined in a spherical vessel in which an initial homogeneous and isotropic turbulence is generated. More details on the setup and methodology can be found in (Goulier, Chaumeix, Halter, Meynet, & Bentaïb, Experimental study of laminar and turbulent flame speed of a spherical flame in a fan-stirred closed vessel for hydrogen safety application, 2017; Goulier, Chaumeix, Halter, Meynet, & A., Experimental study on turbulent expanding flames of lean hydrogen/air mixtures, 2017). Since the lower flammability limit is sensitive to the initial temperature, the lower flammability limit in this case was found equal to 4.4 % (molar percentage of hydrogen) as the initial temperature for these experiments was equal to 293 K. As it is summarized in Figure 4 , the lower flammability limit increases with the turbulent intensity. When u' increases from 0 (quiescent mixture) to 2.81 m/s, the minimum molar percentage of hydrogen below which no ignition was obtained varies from 4.4 to 5.6 %.

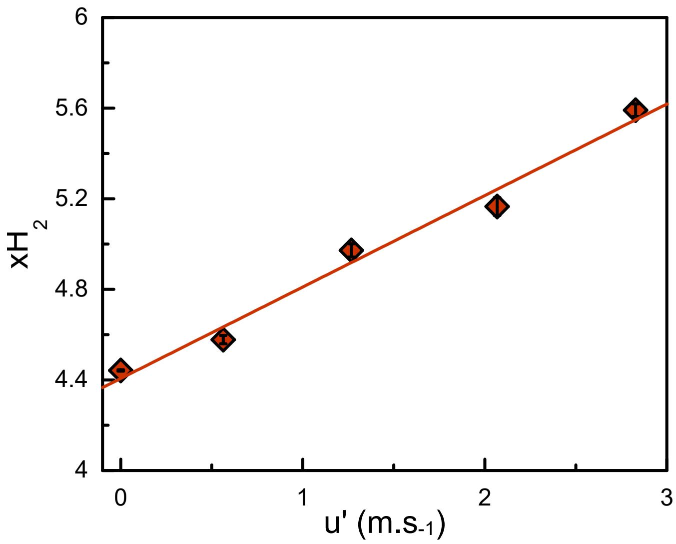


Figure 17: Evolution of the Lower Flammability Limit with the initial turbulence intensity generated in a closed spherical vessel. The mixture was constituted of H_2+air initially at 1 bar and 293 K (Grosseuvres, et al., 2017).

This preliminary study shows the importance of considering not only the thermodynamic conditions when evaluating the possible initiation of combustion, but also the turbulence in the building must be assessed.

2.1.2. Ex-vessel conditions

After the beginning of the ex-vessel phase with molten core concrete interaction (MCCI) and concrete erosion, H2, CO and CO2 are released from the melt pool, coming from the concrete composition. The rate of CO and CO2 production depends strongly on the type of concrete and the water bound in the concrete.

CO is a burnable gas with a rather high density, but with much less reaction energy per kg in case of combustion compared to hydrogen (but with similar lower heating value per mole). It is distributed with the convection flow and in case of combustion it is burned simultaneously with hydrogen. It is recombined by the recombiners as well. Thus, it contributes to the oxygen consumption and influences the duration of oxygen availability and overall mixture flammability. A general difficulty in the processing of CO combustion or H2/CO mixture is that not all the methods developed in the context of hydrogen combustion are available (for example, criteria for FA or DDT). In the following, a survey of available data for CO-H2 flammability limits is given.

The flammability limits of CO/air, at atmospheric pressure, have been reported by Coward and Jones 1952 (Coward & Jones, 1952) in humid air (air saturated with water vapor at 18-19°C), the LFL was found to be equal to 12.9% of CO and the UFL equal to 74.2%. In the case of dry air, the flammability domain is strongly reduced, the LFL and UFL are then 15.8% and 68.5% respectively. Moreover, larger ignitions are needed to ignite dry CO/air mixtures. The effect of the vessel size has also to be considered when reporting the flammability limits of CO/air.

The direction of propagation is also important and is worth reporting. However, only the compilation of (Coward & Jones, 1952) reports such values as summarized in the following table.

Table 10: Flammability limit of CO/air initially at atmospheric pressure and ambient temperature from the literature (Coward & Jones, 1952).

LFL (%CO), air saturated with water			**UFL (%CO), air saturated with water**		
Downward	Horizontal	Upward	Downward	Horizontal	Upward
15	13.5	12.5	71	-	74

These flammability limits can be compared to the values reported in (Karim, Wierzba, & Boon, 1984; Wierzba & Kilchyk, Flammability limits of hydrogen–carbon monoxide mixtures at moderately elevated temperatures, 2001; Shang, Gang, Zi, & Zhuo, 2020).

Table 11: Flammability limit of CO/air initially at atmospheric pressure and ambient temperature from the literature.

Reference	**LFL (%CO)**	**UFL (%CO)**
(Coward & Jones, 1952)	12.9 (humid air) 15.8 (dry air)	74.2 (humid air) 68.5 (dry air)
(Karim, Wierzba, & Boon, 1984)	13.75	Not measured
(Wierzba & Kilchyk, 2001)	13.6	72.3
(Shang, Gang, Zi, & Zhuo, 2020)	12.8	Not measured

It is important to mention that the presence of impurities can modify the combustion properties of CO. As reported in the early work (Coward & Jones, 1952), the presence of 20 ppm of iron carbonyl raises the LFL 15% to 18% while the UFL decreases from 69% to 43%. Iron carbonyl would form whenever iron is in contact with CO.

The flammability limits of H_2/CO in air have been measured by several authors (Wierzba & Kilchyk, 2001; Van den Schoor, et al., 2009; Grune, et al., 2015; Shang, Gang, Zi, & Zhuo, 2020)...

(Van den Schoor, et al., 2009) have studied the flammability limits of H_2/CO air for three different $H_2/(H_2+CO)$ ratios: 0.44, 0.62 and 0.71 for an initial temperature varying between 25°C and 200°C. Their results are summarized in Table 3. For a fixed initial temperature, the addition of CO induces the raise in the LFL, while the addition of 60% of N_2 seems to induce a decrease of the LFL which is not what would be expected. It is not clear from this work the reason behind the peculiar behavior at 60% of N_2.

Table 12: LFL of different H_2/CO/Air/N_2 mixtures at different initial temperatures adapted from (Van den Schoor, et al., 2009)

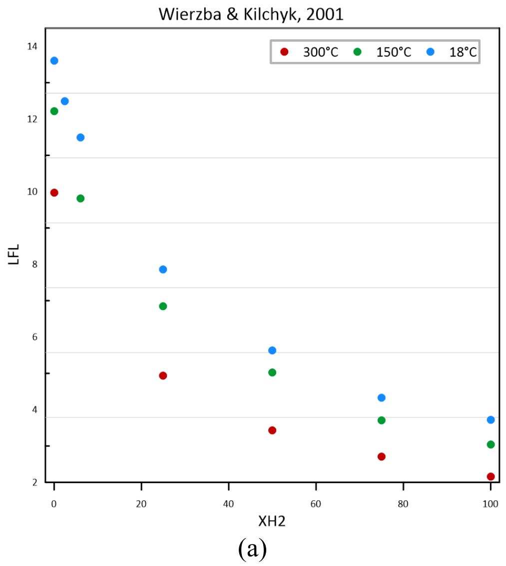
$x_{H2}/(x_{H2}+x_{CO})$		0.44			0.62			0.71		
T(°C)		**25**	**100**	**200**	**25**	**100**	**200**	**25**	**100**	**200**
N2 (mol%)	0	6	5.4	4.4	4.8	4.4	4.2	4.4	4	3.8
	60	5.8	5	4.2	4.8	4.2	3.6	4.6	4	3.4
	70		5	4.4	5	4	3.6	4.6	4	
	71	6		5				4.6		
	71.5	not found		not found	5			4.8		
	72				5.2					
	74								4	
	75		5.2						4.2	
	75.5		not found			4.2				
	76					4.4				
	79						3.6			3.4
	79.5						3.8			>3.8

The UFL limits were also determined and the results are summarized in Table 4. The change in the initial temperature raises the UFL while the addition of N_2 decreases it strongly.

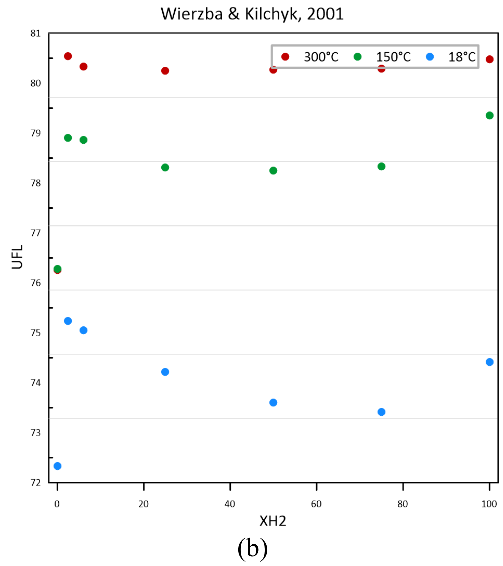
Table 13: UFL of different H_2/CO/air/N_2 mixtures at different initial temperatures adapted from (Van den Schoor, et al., 2009)

$x_{H2}/(x_{H2}+x_{CO})$		0.44			0.62			0.71		
T(°C)		25	100	200	25	100	200	25	100	200
N_2(mol%)	0	74.8	77.2	80.4	75	76.8	80	74.4	76	80.4
	40	37.2	39.2	42.2	36.6	38.6	42.4	36.4	38.8	42.4
	60	18.6	20.8	23.8	18.4	20.6	23.4	17.8	20	24.4

(Wierzba & Kilchyk, 2001) determined the flammability limits of H_2/CO/Air for a temperature range between 18°C and 300°C, the results are summarized in Figure 5. Similar trends were found in previous studies. The increase of the initial temperature is responsible for an increase of the flammability domain and the addition of CO induces a decrease of the flammability domain. In this study one can see that a minor addition of H_2 has a very strong influence on the UFL for which the UFL is much higher than either pure fuels and there is no clear evidence which mechanism is responsible for such behaviour. This result is contra intuitive from the fundamental understanding. When a flammability limits is reached, it is in fact the result of complex phenomena that take place: (i) a complex chemistry involving H, C and O atoms, (ii) the heat losses that are modified from the pure fuels (no CO_2 in the burnt gases for H_2 and no H_2O in the burnt gases of CO), (iii) the modification of the effective Lewis number (and subsequently Markstein number) which will be responsible for a deviation of the burnt gases temperature from the equilibrium one and hence modify the reaction rates and the radiative heat losses.



(a)



(b)

Figure 18: Flammability limits of H_2/CO/air measured by (Wierzba & Kilchyk, 2001): (a): LFL; (b): UFL.

Coudoro (Coudoro, 2012) has measured the flammability limits of a 50% H_2 + 50% CO fuel in air at ambient temperature and at two different initial pressures: 1 and 2 bar. The LFL at 1 bar was found equal to 6.07%±0.01 and increased only marginally to 6.20%±0.04 when the pressure was raised to 2 bar. The UFL was found to be equal to 71.16%±0.02 and was not affected by the increase of the pressure to 2 bar.

Figure 6 illustrates the evolution of the LFL as a function of the amount of H_2 in the binary fuel mixture for different studies from the literature. The general trend of the variation of the LFL with the initial temperature and with $H_2/(H_2+CO)$ ratio. However, there are some discrepancies that need to be addressed.

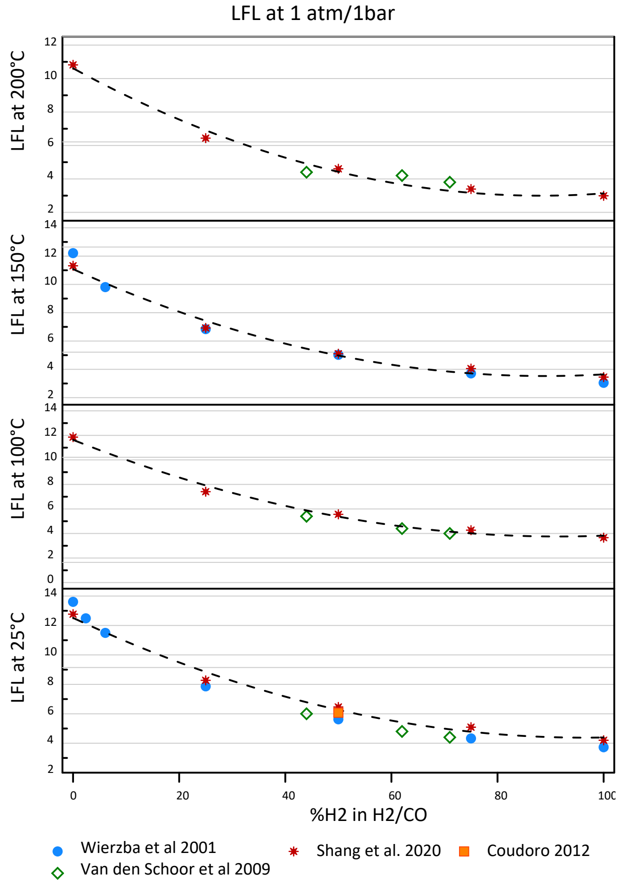


Figure 19: Comparison of the LFL of H_2/CO/air mixtures from different (Wierzba & Kilchyk, 2001; Van den Schoor, et al., 2009; Shang, Gang, Zi, & Zhuo, 2020; Coudoro, 2012) .

For the UFL, the number of studies is more limited and as one can see Figure 7, thein Figure 7, there is a very large discrepancy between the different studies in the literature.

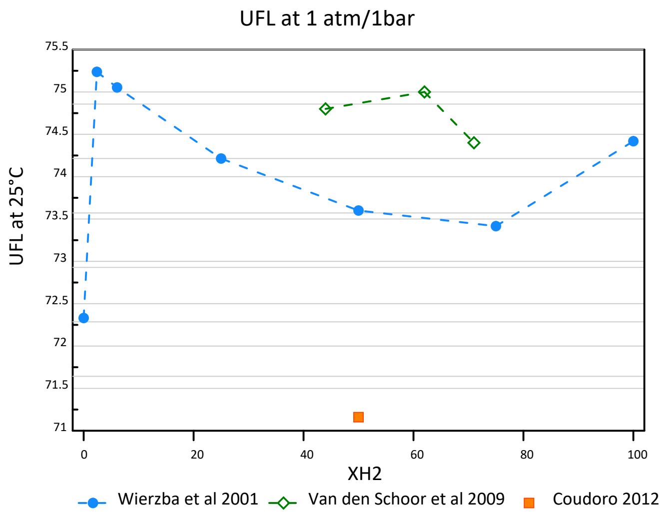


Figure 20: Comparison of the UFL of H2/CO/air mixtures from different studies (Wierzba & Kilchyk, 2001; Van den Schoor, et al., 2009; Coudoro, 2012)

(Grune, et al., 2015) studied the flammability limits of $H_2/CO/O_2$ mixtures diluted by $N_2/CO_2/60\%H_2O_{vap}$ at two different initial temperature, namely 170°C and 250°C. The CO percentage has been varied between 0 and 20% while H_2 was limited to a maximum of 3% in the mixture which is very low. The following ternary diagram have been plotted. The conclusion is that, regardless of the initial temperature or H_2/CO ratio:

(i) for lean mixtures, if the mixture contains less than 10%(CO+H_2) no ignition can occur

(ii) for rich mixtures, if the oxygen content is less than 3% of O_2, no ignition can occur.

However, one has to be very cautious with this conclusion as it applies only for these specific mixtures with %H_2 in H_2/CO is limited to a maximum of 3%. One can see from the previous works that for larger amounts of H_2 in the binary fuel, this conclusion does not hold as the LFL is below 10%.

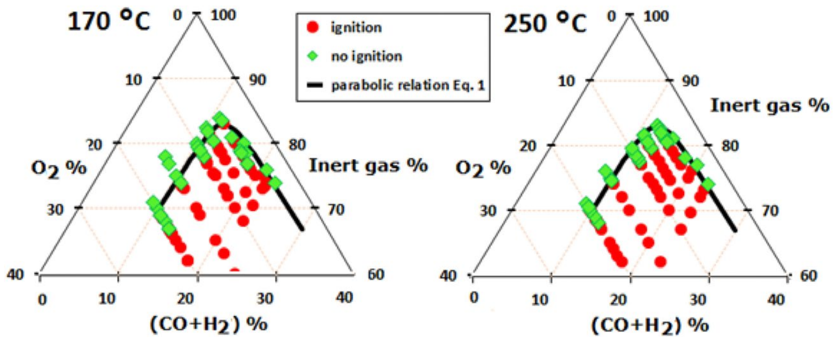


Figure 21: Ternary diagram for {CO+(0 to 3%H_2)}/O_2/Inert gas at 1 bar. Inert=N_2 or CO_2 or H_2O_{vap} from (Grune, et al., 2015).

On the other hand, regarding the correlations, for the LFL, the Le Châtelier Rule is very often used and can be expressed for H2/CO mixtures as:

$$1/LFL_{mix} = (x_{H2}/LFL_{H2}) + (xCO/LFL_{CO})$$

With xi, the polar percent of the species i in the binary mixture.

It is then important to have a good knowledge of the LFL limit of the pure species. At ambient temperature, there is a very good agreement between the experimental values and the one derived using the Le Châtelier rule (Figure 9 (Hustad & Sønju, 1988)).

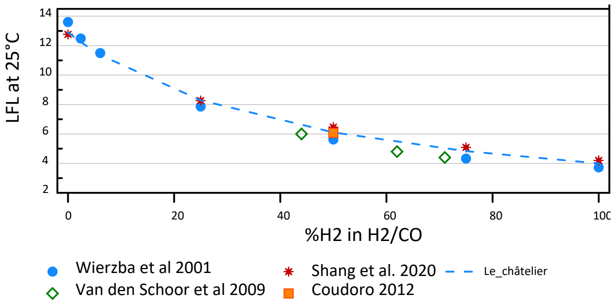


Figure 22: Comparison between the LFL limits in the literature and the Le Châtelier rule. The mixtures are initially at ambient temperature and pressure. Data are (Wierzba & Kilchyk, 2001; Coudoro, 2012; Van den Schoor, et al., 2009; Shang, Gang, Zi, & Zhuo, 2020).

(Hustad & Sønju, 1988) proposed an expression of the flammability limit that considers the initial temperature:

$$\frac{1}{LFL_{mix}} = \frac{\%H2}{5 \cdot [1 - 0.00129 \cdot (T_{ini} - 25)]} + \frac{\%CO}{15 \cdot [1 - 0.00095 \cdot (T_{ini} - 25)]}$$

This correlation was used with the literature data and is plotted in Figure 10 and shows that this correlation overestimates the flammability limits of H2/CO/air for almost all conditions and is not suitable for H2/CO as pointed out by (Kim, Jeon, Song, & Kim, 2020) and showing that in order to accurately predict the flammability limits of H2/CO, heat transfer must be considered.

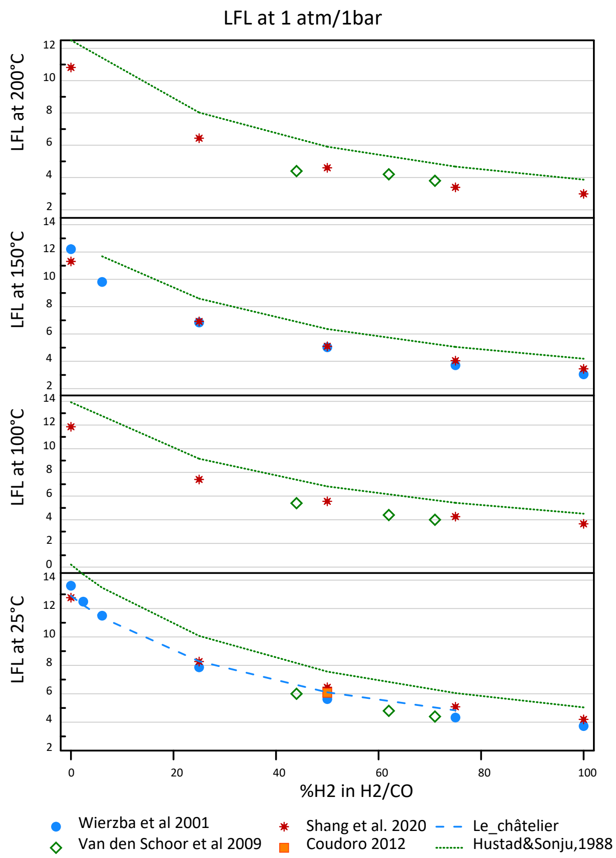


Figure 23: Comparison between the LFL limits in the literature and the Le Châtelier and (Hustad & Sønju, 1988) correlations. The mixtures are initially at ambient temperature and pressure. Data are from (Wierzba & Kilchyk2001; Coudoro, 2012; Van den Schoor, et al., 2009; Shang, Gang, Zi, & Zhuo, 2020).

For the upper flammability limit, the Le Châtelier is not suitable and moreover, the data in the literature need to be better assessed.

2.2. Flame acceleration criteria

The flame acceleration criteria are used to discriminate a priori between (i) mixtures that have the potential to accelerate strongly, and hence induce a large pressure overload (fast flames) and (ii) mixtures that cannot sustain a strong acceleration and as a consequence will induce a limited overpressure if at all (slow flames). For this purpose, numerous experimental results, carried out in different facilities (see Figure 11), were used to delimit the transition between slow and fast flames in H2/air mixtures based on the ratio, σ, between the density of fresh gas and burnt gas at constant pressure. In the review of (Ciccarelli & Dorofeev, 2008), the main mechanism for flame acceleration is described: the flame acceleration in a closed vessel with obstacles is due to the positive feedback between: (i) the expansion of the burnt gases that induces a flow motion in the fresh gases ahead of the flame inducing a turbulence and (ii) the subsequent increase in the flame surface as it moves in these accelerated fresh gases which will lead to a further increase of the flame speed. The increase of the flame speed following this chemistry-turbulence interaction (in other words the geometry) is assessed through the reactivity of the mixture (activation energy, Zeldovich number) and the geometry (integral length scale, turbulence intensity). By considering experiments with the integral length scale normalized by the flame thickness ratio that is large enough, the geometry effect can be ruled out from the criterion that has been proposed (sigma criterion). Moreover, in the slow/quenched regime, the energy release which is a combined effect of flame surface area, chemistry and turbulence, is limited and is not capable of generating strong compression waves. As such the parameters that are important for the slow to fast flame regimes is based on combustion parameters namely the density ratio and the activation energy or Zeldovich number

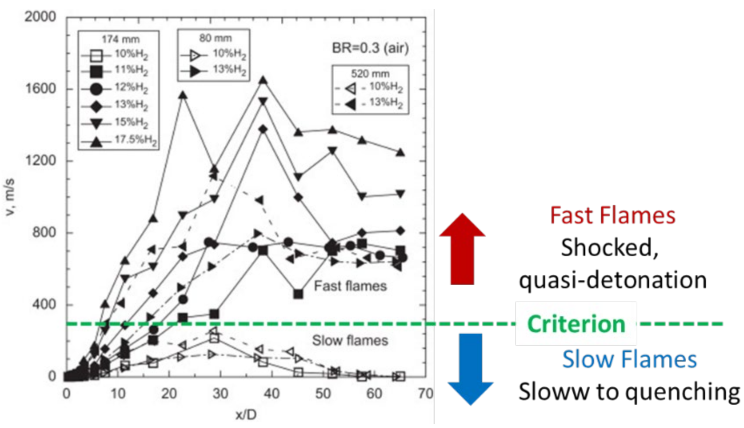


Figure 24 : Classification of slow and accelerated flame propagation regimes in H2/air mixtures adapted from (Ciccarelli & Dorofeev, 2008)

Thus, the established criterion depends only on the gas mixture and does not depend on the geometry in which the flame propagates. It provides a necessary condition for the onset of flame acceleration, but not sufficient, hence it does not allow us to predict the speed reached by the flame for a given mixture and geometric configuration.

Following the established criteria, accelerated propagations are possible if:

$$\sigma > (3{,}5 \sim 4) \quad \text{where} \quad \beta.(Le-1) > -2$$
$$\sigma > \sigma^{*}(\beta) \quad \text{where} \quad \beta.(Le-1) < -2$$

where

$\beta \cong \frac{\sigma - 1}{\sigma}\frac{E_a}{RT_u}$ represents the Zeldovich number and gives information about the reactivity of the mixture

And Le is the Lewis number.

The established flame acceleration (FA) criterion was extended to multi-compartment geometry in framework of EU-HYCOM project (2000-2003) (Breitung, et al., 2005) (W. Breitung, 2005). Originally, the criterion was developed on the basis of tests in obstructed tubes with constant cross sections including cases of elevated T and P and of steam dilution. The criterion gives a description of mixture properties that provide potential for effective flame acceleration (FA) in tubes with obstacles. Correlations for the critical expansion ratio σ (ratio of densities of reactants and products) were suggested in a form of σ > σ*(Ea/RTu), where Ea is the effective activation energy, R is the gas constant and Tu the initial mixture temperature (CSNI Group of Experts, State of the art report' flame acceleration and deflagration to detonation transition in Nuclear Safety, 2000; Dorofeev, et al., 1999)

The effective activation energy for H2-air-steam mixtures was assumed to be a function of equivalence ratio ϕ. This gives a correlation for the critical σ* in the form of σ* = σ*(Tu, ϕ). The accuracy of the criterion was estimated as ± 8% in critical σ*-value. For hydrogen-air mixtures at normal initial temperature and pressure, this gives the critical composition of 10.5 ± 1.3 % vol. of hydrogen.

In cases of complex flow geometry, combustion processes can be affected by the change of cross-section along the flame path, or by lateral venting. Thus, the venting decreases the effective expansion of the products, and a more energetic mixture (larger σ) is necessary for strong FA. Thus, the effect of lateral venting on σ*-value had been expressed as follow:

$\sigma^* = \sigma^*_0 (1 + 2.24\alpha)$; where α stands for the ratio of the lateral surface opening per the cross-section flame path. Figure 12 shows the lateral venting effect on critical σ* value based on experiments performed on RUT facility (see Figure 13) in framework of HYCOM project.

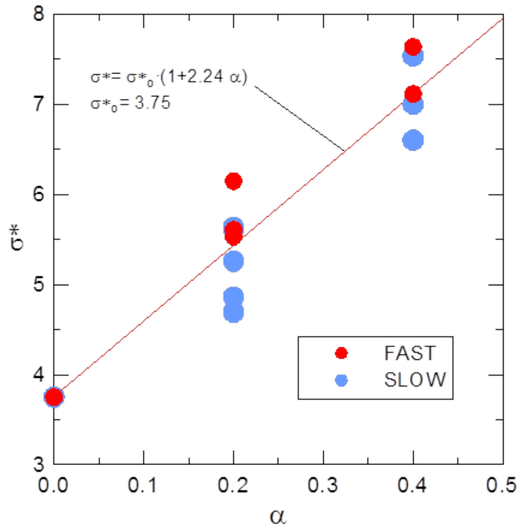


Figure 25: lateral venting effect on the FA criterion from Fig.11

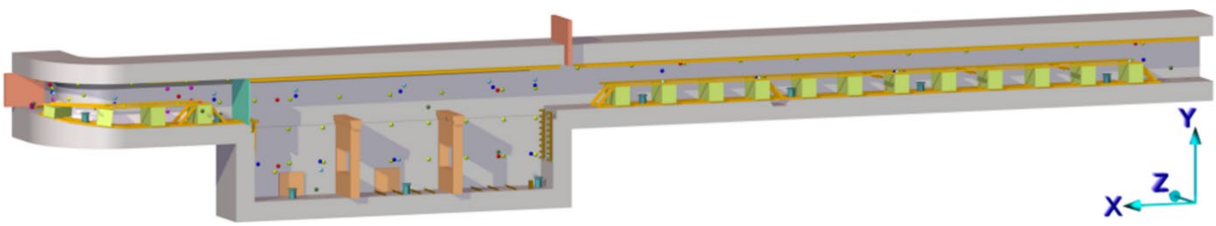


Figure 26: RUT facility scheme (65 m length, height 6 m, canyon length 15m, depth 2.5 m)

In the opposite situation, reduction of cross-section along the flame path can promote the FA. Thus, large flame area in the wide section of RUT generates an excess volume of hot products acting as a gas piston, which pushes the flame along the left channel as in the Figure 14.

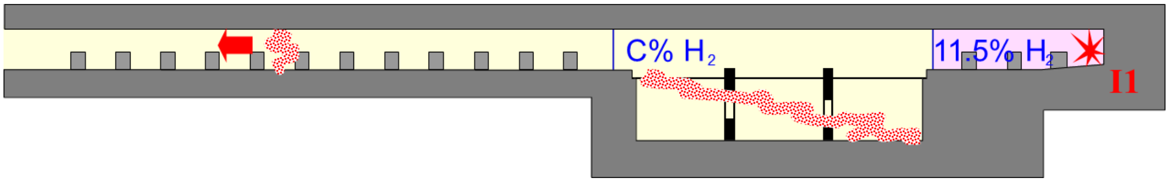


Figure 27: RUT facility scheme – Piston effect on flame acceleration

It was indeed observed that the flame accelerated strongly in this channel for tests with 10% H2. High overpressures were generated in this case. The results show, however, that the decrease of H2 concentration down to 9% results in a very weak combustion process with low overpressures, even though the flame is pushed through the channel by the additional gas piston (Breitung, et al., 2005). (W. Breitung, 2005),Concerning the uncertainty range of the σ-criterion, the promoting effect of flow geometry on FA was found to be limited in strength, the existing uncertainty range of the σ-criterion cannot be significantly reduced. This range covers the possible promoting effect of multi-compartment geometry, which should be considered in reactor applications. It may be suggested that the application of the σ-criterion should be combined with CFD analysis, if further reduction of uncertainties is desired.

More recently, the work of Malet (Malet, 2005) and H. Cheikhravat (Cheikhravat H. , 2009) has allowed to refine the results obtained in the HYCOM project and to initiate its extension to stratified mixtures with a negative gradient (ignition in the rich zone). In this case, the flame accelerates in a similar way as in a homogeneous mixture with the same molar concentration of hydrogen as in the ignition zone of the stratified mixture.

The criteria thus developed did not consider the effect of the initial temperature. This aspect was investigated in the framework of the thesis of R. Grosseuvres (Grosseuvres R. , 2018). The work carried out in this way has made it possible to highlight the impact of temperature on flame acceleration (see Figure 15a) and to extend the acceleration criterion to consider the effect of the initial temperature (Figure 15b).

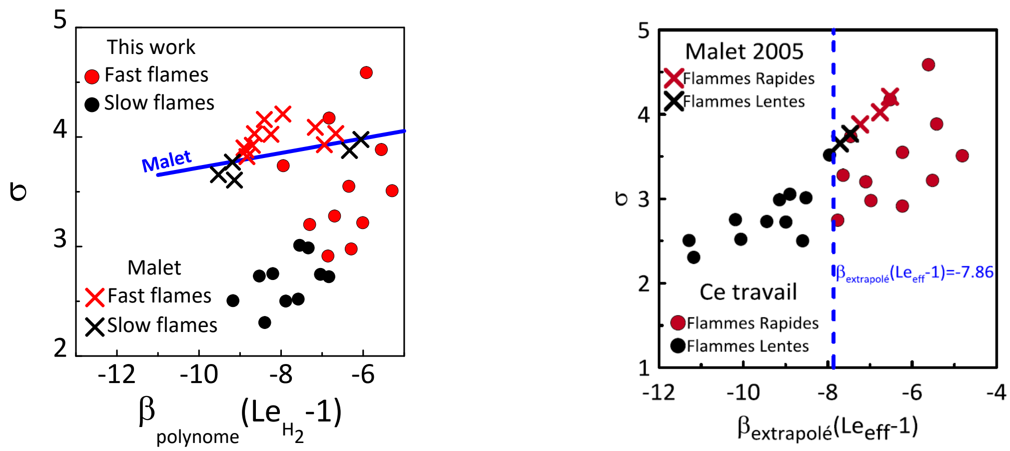


Figure 28: Flame acceleration criteria. (a) F. Malet thesis (Malet, 2005); (b) R. Grosseuvres thesis (Grosseuvres R. , 2018).

Concerning the fast flame transition in H2/CO mixtures, at ICARE a preliminary study has been performed by Coudoro (Coudoro, 2012) during his PhD thesis for a mixture 50%H_2+50%CO in ENACCEF 1. The total fuel percent was varied between 10% and 14% and the blockage ratio varied from 0 (smooth tube) to 0.63. The limit between slow and fast flame was found to be higher than for H_2/air mixtures in the same conditions (13.7% of 50H_2/50CO in air, versus 11% of H_2 in air

(Figure 16). The criterion developed for H_2/Air/H_2O_{vap} mixtures could not be used for H_2/CO mixtures in this study.

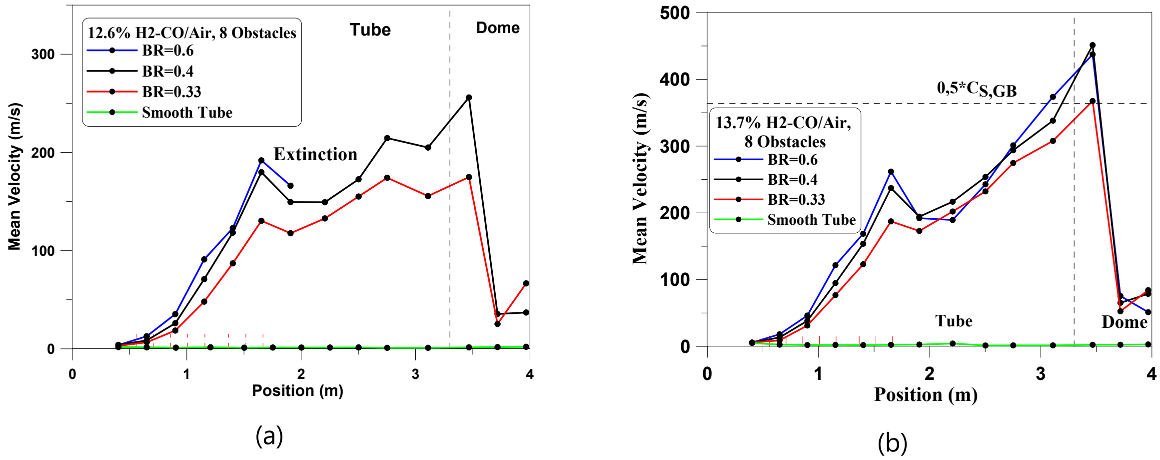


Figure 29: Flame propagation speed for {$50H_2$+50CO}/air initially at 1 bar and 298 K in ENACCEF 1 (Coudoro, 2012).

To verify the extension of the sigma criterion, the Zeldovich number and the effective Lewis number for the binary mixtures must be determined. Both of these parameters rely on the good knowledge of the laminar flame speed and a detailed kinetic mechanism (Grosseuvres, Comandini, Bentaib, & N., 2019). The definition adopted for both parameters is still subject to debate and need a specific effort to come-up with these values in the range of applicability of ex-vessel accident conditions.

2.3. Deflagration-Detonation transition criteria

This section presents an overview of the DDT criteria for both in and ex vessel phases of a severe accident.

The criterion for DDT is based on the knowledge of the detonation cell size as Dorofeev and his group summarized in (Ciccarelli & Dorofeev, 2008) have shown that a mixture can undergo a DDT if the characteristic size of a room filled with combustible mixture, L is greater than 7 times the cell size: L>7xλ. This criterion is used in most of practical applications to determine the likelihood of a DDT in large scale plants.

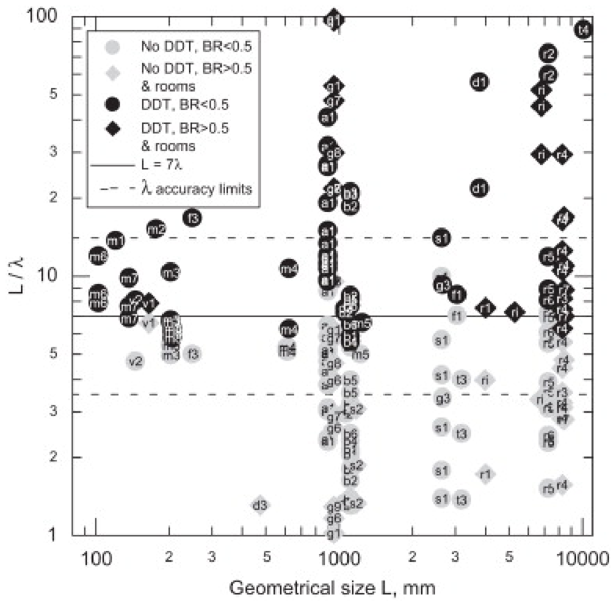


Figure 30: Summary of detonation onset conditions for H_2/air/H_2O_{vap} mixtures from (Ciccarelli & Dorofeev, 2008).

The detonation of H_2/CO mixtures has recently been the subject of a few studies. (Chen, et al., 2019) has determined the effect of N_2 and 10% CO addition to the detonation of H_2/air mixtures. As illustrated in Figure 18, the detonation cell size decreases for lean mixtures when 10%of CO is added to the mixture, while it increases on the rich side.

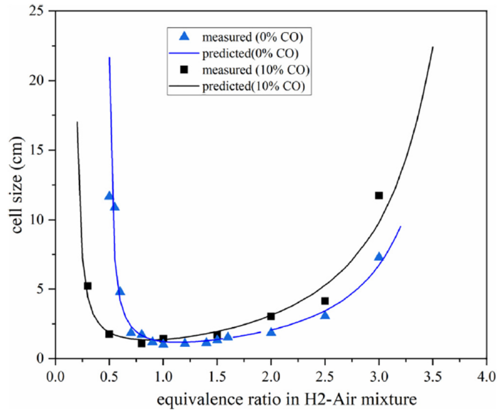


Figure 31: Detonation cell size of H_2/CO/air mixtures initially at 1 bar and 393 K (Chen, et al., 2019).

This result indicates that the detonability domain in the lean region should be carefully investigated before considering that the detonability domain will be reduced when adding CO. If indeed this is the case for rich mixtures, it is not valid on the lean side. The detonation limit corresponding to the 78 mm i.d. detonation tube used for this study is reported in Figure 19 illustrating the promoter effect on the lean side and the inhibitor effect on the rich side.

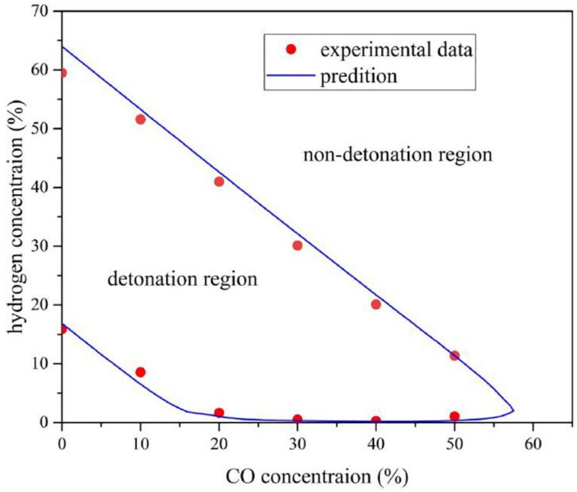


Figure 32: Detonation domain of {90H$_2$/10CO}/air mixtures, initially at 1 bar and 293 K, determined in a 78 mm i.d. tube, from (Chen, et al., 2019).

In a very recent study by (Heilbronn, Barfuss, & Sattelmayer, 2021), the run-up distance to the detonation has been measured for H$_2$/air, (50H$_2$/50CO)/air and (75H$_2$/25CO)/air mixtures at an initial pressure of 1 bar and ambient temperature. The results are summarized in Figure 20. From these preliminary results it is difficult to draw a clear picture of the DDT in H$_2$/CO/air mixtures as acknowledged by the authors that more investigations are needed.

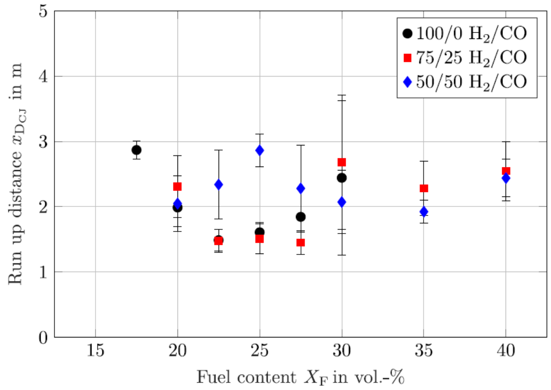


Figure 33: Run-up distance to the CJ detonation from (Heilbronn, Barfuss, & Sattelmayer, 2021).

2.4. Conclusions

The ability to predict the most important parameters for H_2/CO combustion based on the knowledge of H_2/Air/Diluents mixtures relies on the knowledge of fundamental parameters of H_2/CO.

The literature survey showed that data on LFL for H_2/CO based mixtures at elevated temperatures, but for an initial pressure of 1 bar and/or 11 atm exist and agree fairly well, despite some points need to be revised yet. On the contrary for the UFL, the few data in the literature show large discrepancy both on the absolute values and on the trend.

The effect of the initial pressure is not yet addressed and should be investigated. The effect of steam and carbon dioxide is also missing for an initial pressure higher than the atmospheric one.

For the Flame acceleration, only two studies were relevant to ex-vessel conditions. Both of them were preliminary studies from which it was not possible to draw a clear picture on how the flame acceleration criterion can be extended from pure H_2 to a mixture of H_2/CO. For this criterion validation and/or extension to ex-vessel conditions, there is a need to determine the Zeldovich number and the effective Lewis number for a binary fuel mixture. Moreover, flame acceleration experiments should be extended to larger scales in order to adequately analyze the phenomena. The data are too scarce to address adequately this very important issue

A similar conclusion can be drawn for the H2/CO detonability. Only recently, data were published on the detonation cell size of 90%H2/10%CO mixtures with air. These preliminary results indicate that for lean mixtures, the detonation limit may be larger for CO/H2 mixtures than for H2 mixtures. There are not enough data to draw a clear conclusion. In this regime, larger scale experiments are desirable.

3. Review of H_2/CO combustion engineering models

If the flame acceleration criteria are not met, the dynamic pressure loads are excluded and the pressure load is evaluated by considering a complete isochoric combustion process. In the contrary, where the flame acceleration criteria are met, the combustion induced loads are evaluated using appropriate combustion models.

This section presents the correlation and engineering models mostly used by the nuclear community.

3.1. Empirical models

The pressure resulting from the H2/CO combustion depends on the flammable cloud size, the mixture composition and the geometry. This pressure is proportional to the amount of hydrogen and carbon monoxide burnt. Its upper boundary, when the flame acceleration criteria are not met, is the pressure P_{AICC} assumed adiabatic isochoric complete combustion (AICC).

The P_{AICC} is determined from an energy balance in an adiabatic, isochoric closed system under the hypothesis of complete combustion (Breitung W. , The analysis of Hydrogen behaviour in severe accident, 1997).

$$\sum_A \left(n_A c_{v,A}\right)_b T_b^{AICC} = \sum_A \left(n_A c_{v,A}\right)_u T_u + n_{H_2,q} q_{H_2} + n_{CO,q} q_{CO}$$

where $C_{v,A}$ stands for the specific heat at constant volume and n_A the number of moles of the species "A" in the mixture (O_2, N_2, H_2, H_2O, CO and CO_2). T_u represents the initial temperature (unburned gas mixture) and T_b^{AICC} is the resulting temperature of the burned gas by considering AICC combustion. Last two terms in the RHS express the energy release by H_2 and CO reaction. The T_b^{AICC} is calculated through an iterative method. The AICC pressure is calculated finally by considering a mixture of ideal gases in the equation:

$$P_{AICC} = p_u \left(\frac{T_b^{AICC}}{T_u}\right)\left(\frac{n_b}{n_u}\right)$$

When FA or DDT criteria are satisfied, flame may accelerate and transition to detonation may occurs. In the case of detonation onset, the maximum pressure developed is bounded by the Chapman-Jouguet pressure (p_{CJ}) and the maximum pressure peak comes from the reflected shock wave ($p_{CJ\text{-}RF}$) (Breitung, 1997).
These three theoretical pressure magnitudes, AICC, CJ and CJ-RF, show the same dependence with the equivalence ratio, whereby Breitung (1997) proposed the following simple relationships to approach them in nuclear safety analysis:

$$P_{CJ} = 1.8(\pm 0.08) P_{AICC} \quad \text{and} \quad P_{CJ-RF} = 4.1(\pm 0.3) p_{AICC}$$

The peaks, AICC, CJ and CJ-RF, provide an instantaneous estimation of the pressure upper bound may be reached in case of hydrogen and carbon monoxide combustion. They are mainly used as indicators to identify severe accident scenarios that could lead to high combustion pressure loads. The assessment of the combustion pressure loads consequences on the structure need an evaluation of the pressure impulse (the pressure evolution versus time) provided by the engineering models.

Simplified computer modules have been developed to estimate expected combustion regimes and pressure loads from H2/CO mixtures to help with PSA level 2 analyses in containments (Robledo, Martín-Valdepeñas, Jiménez, & Martín-Fuertes, 2005)(Robledo et al, 2005).

3.2. Engineering models

The pressure time evolution depends on the flame propagation inside the reactor containment. The flame propagation process is complex and rely the interaction of turbulence and chemistry. For the engineering models, the chemistry is considered simple and global and the turbulence is simplified. Two main approaches are then developed.

3.2.1. Global combustion models

The global combustion models are based on mass and energy balance assuming the following:

1. the containment atmosphere is supposed homogenous,
2. the combustion completeness coefficients α_{H2} and α_{CO} are user parameters,
3. the heat losses Q_{loss} is a user parameter,
4. the combustion duration Δt is a user parameter.

Depending on the oxygen content, the hydrogen and carbon monoxide combustion model may be written as follow:

$$\begin{cases} \dfrac{dm_{H2}}{dt} = -\dfrac{(1-\alpha_{H2})m_{H2_{ini}}}{\Delta t} \\ \dfrac{dm_{CO}}{dt} = -\dfrac{(1-\alpha_{CO})m_{CO_{ini}}}{\Delta t} \end{cases}$$ in case of sufficient oxygen content and

$$\begin{cases} \dfrac{dm_{H2}}{dt} = -\dfrac{m_{O2_{ini}}}{16\Delta t} \\ \dfrac{dm_{CO}}{dt} = -\dfrac{14m_{O2_{ini}}}{16\Delta t} \end{cases}$$ if not

m_{H2}, m_{H2ini}; m_{CO}, m_{COini} and m_{O2}, m_{O2ini} stand for the mass and initial mass of hydrogen (resp. of carbon monoxide and oxygen). The energy released by time unit due to combustion in the compartment is given then:

$$E_{comb} = -\frac{dm_{H2}}{dt}.Q_{H_2} - \frac{dm_{CO}}{dt}.Q_{CO} + Q_{Loss}$$

Q_{H_2} is the energy released by mass unit of hydrogen and Q_{CO} is the energy released by mass unit of carbon monoxide.

3.2.2. Burning velocity model

As the combustion duration is fixed by user, the global combustion may either under or overestimate the pressure impulse. To overcome this limitation, the burning velocity models (BVM) aim at characterizing the flame front burning velocity.

For this purpose, the flame velocity is calculated as function of gas composition. This approach is adopted in MELCORMELCOR code. More sophisticated approach is implemented in ASTEC and COCOSYS code. It consists in calculating the flame speed as function of gas composition, turbulence level, temperature and pressure. These two approaches are presented below:

3.2.2.1. MELCOR combustion model

MELCOR combustion model uses a piecewise function to calculate the flame speed. The used expression writes as follow:

VF = Vbase * Cdil

where Vbase stands for the flame velocity in dry air using the following expressions:

- 0.0 ≤ Ymax ≤ Y1 (default Y1 = 0.1) Vbase = C1 + Ymax * C2- Y1 < Ymax ≤ Y2 (default Y2 = 0.2) – Vbase = [C1 + (C2 - C3) / Y1] * Ymax + C3

and Cdil represents the diluent effect on flame speed. The coefficients C_i are constants set to address both hydrogen and carbon monoxide combustion.

3.2.2.2. ASTEC combustion model

In the ASTEC code, flame propagation is modelled using CPA-FRONT combustion model. Only hydrogen combustion is modelled. The flame propagation is modelled inside the junctions. The H2-combustion itself (mass transfer from H2 and O2 to steam, distribution of combustion heat) takes place in the zones.

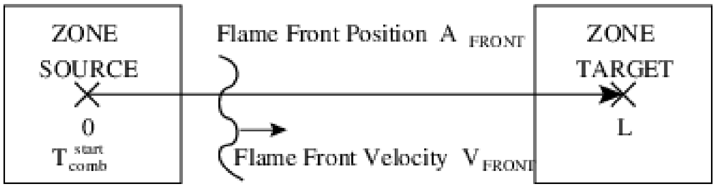


Figure 34 : CPA-FRONT Flame propagation principle.

The flame front burning speed is then estimated as sum of gas speed and turbulent flame speed:

$$\mathrm{V}_{FRONT} = S_t + U_{gas}$$

Where U_{gas} stands for the gas velocity in the junction and S_t represents the turbulent flame front speed issued from the Peters correlation:

$$S_t = S_l\ (1 + \sigma_{Peters}) \text{ where } \sigma_{Peters} = \frac{\sqrt{\left(0.39\frac{l_t}{\delta}\right)^2 + 8\times 0.39\frac{l_t u\prime}{\delta\, S_l}} - 0.39\frac{l_t}{\delta}}{2}$$

- S_l is the laminar flame speed. Several correlations are available in the ASTEC code:
  - ✓ Liu-McF for the classical Liu Mac Farlane model
  - ✓ Liu-CNRS for the correlation developed by CNRS (Malet, 2005)
  - ✓ USER option offering the possibility to use different correlation
    - u′ represents the root-mean-square (RMS) velocity fluctuations given by

$$u' = \left|U_{gas}\right|\ REYFAC\ Re^{REYEXP}$$

where $Re = \frac{\rho\left|U_{gas}\right|\sqrt{S_{junc}}}{\mu}$ stands for the Reynolds number while REYFAC and REYEXP are user parameters.

- ➢ l_t represents the turbulence integral scale estimated based on the zone floor and the junction section area Sjunc;
- ➢ δ stands for the flame thickness and μ for the dynamic viscosity.

3.2.3. Outcomes from international benchmark (ISP49, SARNET, MITHYGENE, SAMHYCO-NET, …)

All the recent benchmark organized under the auspices of OECD (ISP49) or in the framework of European project (SARNET or SAMHYCO-NET) or at national level (MITHYGENE) considered hydrogen flame propagation in both homogenous and stratified mixtures. All the engineering used models were based on the burning velocity model.

From the ISP49 outcomes, it could be noticed that the simulations with LP codes utilizing BVM combustion model demonstrated satisfactory prediction of the flame speed and can be considered as perspective basis for further model development. Moreover, it was found that depending on the combustion regime and/or selection of the experiment a quite wide range of conclusions can be derived:

- For slow combustion regime, typical for the unobstructed open, e.g., in the dome area, the majority of the codes and participants demonstrated reasonable accuracy of prediction of the vertical flame speed, while noticeable scatter of the pressure growth rate predictions for both LP and CFD.
- For flame acceleration and fast combustion regime, typical for the obstructed areas as, steam generator casemates, the majority of the models was able to reproduce the trajectory of the flame with satisfactory accuracy and qualitatively reproduce the short pressure peak, thus confirming their ability to tolerably simulate accelerated and decelerated flames.
- For flame quenching, no one of the participants used a quenching model, therefore none of the simulations was able to predict the experimentally observed flame quenching process.

Similarly, the MITHYGENE and the SAMHYCO-NET benchmarks outcomes highlighted the ability of the LP codes utilizing BVM combustion model to predict reasonably the flame speed and the pressure build up. Nonetheless, the results show that the flame speed maximum value is generally over predicted. This indicates that there are still limitations and weaknesses in the combustion models used in the different codes. These limitations concern the chemistry part, the turbulent combustion model and the coupling between the two models. An improvement of the combustion models is necessary in order to obtain consistent results between the flame regime and the pressure build-up predicted for a given configuration. Therefore, further investigations are still needed, also because scaling from experimental facilities to actual containments remains an open issue.

3.3. Conclusion

The empirical models are often used in the probabilistic studies and permit the evaluation of the maximum pressure peak that the combustion may induced. Both hydrogen and carbon monoxide combustion are considered. These models assume complete combustion and, consequently, they do not address conditions of oxygen starvation, typical of the severe accident late phases. Dedicated developments are then needed to address the incompleteness of the combustion.

The engineering models offer the possibility to calculate the pressure loads during the combustion process. Moreover, the global combustion models include both the hydrogen and carbon monoxide combustion and consider the effect that low oxygen may have. These models are suitable to have a first estimation of the pressure and temperature combustion loads. These results have to be improved using BVM models. These latter demonstrate their ability to address both slow and fast hydrogen combustion regimes. Their extension to typical severe accidents late phase needs:

- further investigation of laminar flame propagation considering representative conditions of the severe accident late phases. These investigations will help establishing laminar flame speed correlation and determine the relevant parameter to extend the flame acceleration criteria, for mixtures based on H_2/CO/air diluted with H_2Ovap and CO_2.
- development of turbulent flame speed in representative conditions of the severe accident late phases, for mixtures
- additional investigation on the effect that thermal radiation may have on the flame speed,
- validation of the obtained model based on slow and fast flame tests,
- Validation on large scale experiments is a must

4. Example of reactor application

Several studies were conducted using both empirical and engineering models. As example of these studies, the evaluation that PARs may have on the hydrogen risk in the reactor containment (Bentaib, Caroli, Chaumont, & Chevalier-Jabet, 2010) and the analysis of scenario corresponding to a Loss of offsite power (LOOP) situation and seal leaks of the primary pumps (Phoudiah, et al., 2011) (Bentaib, Caroli, Chaumont, & Chevalier-Jabet, 2010) and the analysis of scenario corresponding to a loss of offsite power (LOOP) situation and seal leaks of the primary pumps (Phoudiah, et al., 2011) . Both studies showed the beneficial effect of recombiners as igniters.

4.1. Evaluation of PARs effect on hydrogen risk

In the framework Level 2 Probabilistic Safety Assessment (PSA-2), the effect of PARs consideration had been assessed considering the French 900 MWe reactor. For this purpose, 35 scenarios including accidents involving secondary circuit transients, accidents involving loss of steam generators feedwater, accidents involving steam generator tube ruptures SGTR, accidents involving loss of coolant LOCA and accidents involving loss of electrical power, had been considered and simulated using ASTEC code.

The flammable gas time evolution is checked by considering gas mixture in each containment zone at each time in the ternary H2-Air-Steam diagram. At each time, gas composition is represented by a point in this ternary diagram. The gas composition time evolution in each zone is then described by curve. Figure 22 shows the gas composition in a zone during the core degradation sequence by considering or not the use of PARs. This figure shows also that the use of PARs decreases the hydrogen concentration in the containment atmosphere and limits the flammable cloud size inside the reactor containment.

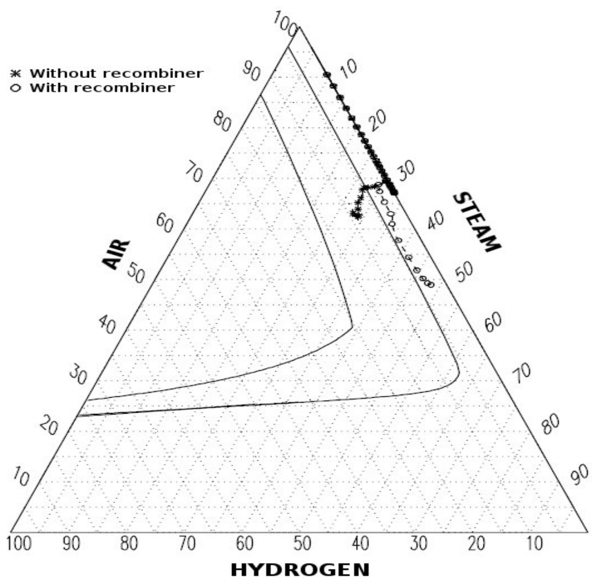


Figure 35 : Effect of PARs on gas mixture flammability
(with stars: gas composition without PARs; With circle: gas composition with PARs)

As for the flammability risk assessment, flame acceleration risk is checked by calculating and comparing the expansion σ factor, corresponding to the gas composition in each zone, to the limit value σ*. The analysis of ASTEC results show that the use of PARs leads to low hydrogen concentration and consequently to low σ values. This situation is illustrated in Figure 23 where σ values obtained with and without PARs are compared to the critical values σ* at time of high hydrogen release for each zone.

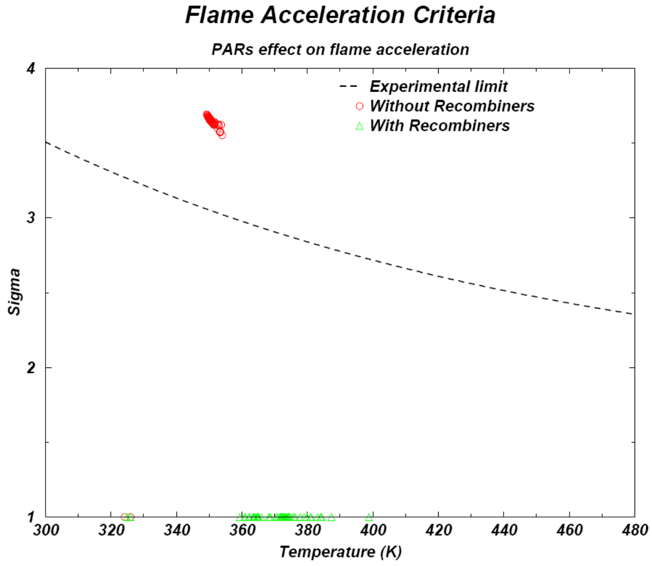


Figure 36: PARs effect on Flame acceleration (in red: gas composition without PARs; in green: gas composition with PARs)

Before performing combustion calculation, ignition sources have to be defined. The ignition must be either predicted mechanistically (self ignition) or must be postulated with respect to time and location. In this last case, ignition time is usually chosen to induce high pressure load. Figure 24 shows the pressure maximal values obtained by considering adiabatic isochoric complete combustion for different core degradation sequences.

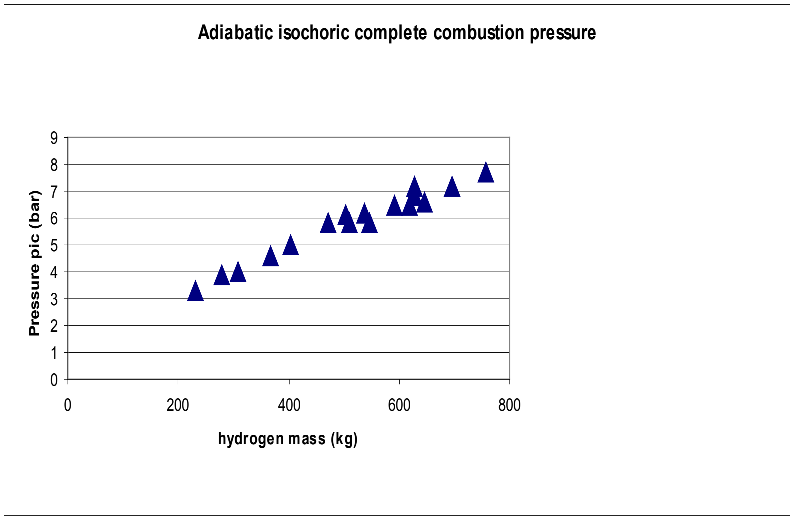


Figure 37: PAICC pressure versus hydrogen mass

Figure 24 shows also that the "probabilistic" ignition sources could lead to high pressure values beyond the containment pressure design of 6.5 bars. To perform more realistic pressure load assessment, engineering combustion are used as for the following example.

4.2. Hydrogen risk assessment considering LOOP scenario

For this study, Loss of offsite power (LOOP) scenario on French 1300 MWe reactor is considered. The leak size is estimated to be equal to 0,55'' for each pump. This scenario had been simulated using ASTEC LP code. The loss of offsite power leads the reactor trip actuation following by the turbine trip. Safety injection (liquid water) starts at low pressure (<121 bar). After 3 hours, containment pressure reaches 2.6 bar leading to automatic spray activation in direct mode and in recirculation mode 1 h 30 min later. At this time, safety injection was lost leading to a sharp decrease of the primary pressure. Later on, core degradation starts leading to hydrogen release in the reactor containment. The released liquid water, steam vapor and hydrogen mass and mass flow rate are presented in the following figures.

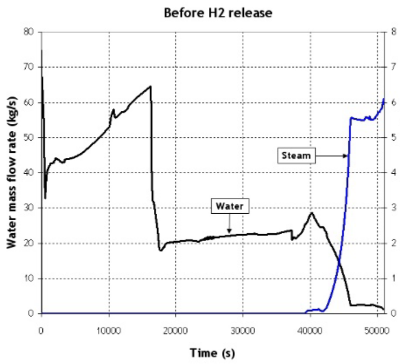


Figure 38: steam and liquid water mass flow rate released in the containment before the hydrogen release

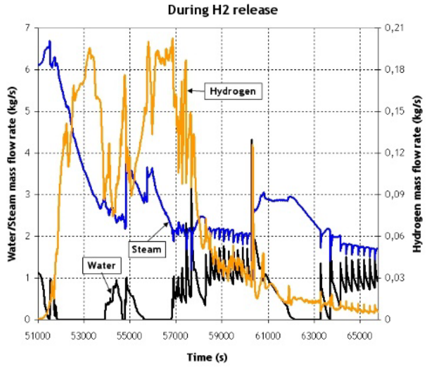


Figure 39: hydrogen, steam and water mass flow rate released in the containment during degradation phase

The analysis of the containment atmosphere composition during the accident transient shows the beneficial effect of PARs. Indeed, hydrogen concentrations remain low and stay under the concentration limit for flame acceleration regime. Nevertheless, flammable cloud had been observed as shown in Figure 27 figure.

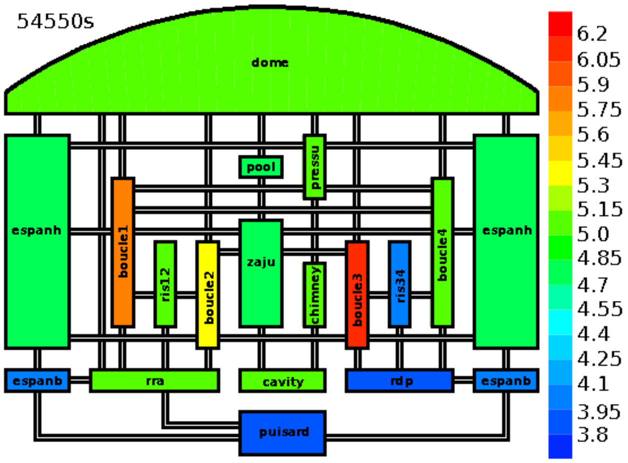


Figure 40: hydrogen concentration distribution at t= 54550s

As hydrogen concentrations exceed the PAR ignition limit in several zones, combustion has been calculated using CPA-FRONT model in ASTEC. This model calculates laminar and turbulent flame front velocities for the actual thermohydraulic state in a connecting junction between two zones. Due to the fact that ignition induced by PARs occurs for low hydrogen concentration, the pressure remains low and below the containment pressure design. Moreover, the maximal overpressure in the dome induced by hydrogen combustion is lower than 0.44 bar (see Figure 28 Fig.7).

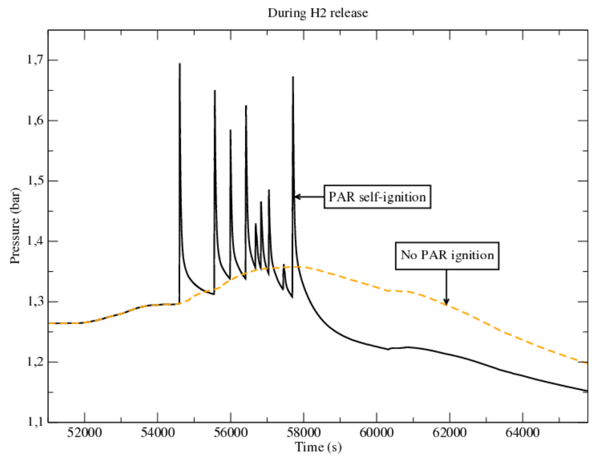


Figure 41 : dome pressure evolution with time

Furthermore, the pressure induced by a complete, adiabatic and isochoric combustion (AICC) is presented in Figure 29. In the case of PAR self-ignition, the combustion calculated by CPA-FRONT is not complete for this kind of hydrogen concentration. That is why the combustion stops even if hydrogen is remaining and the overpressure induced in the dome reaches only 0.4 bar instead of 2 bars for an AICC combustion.

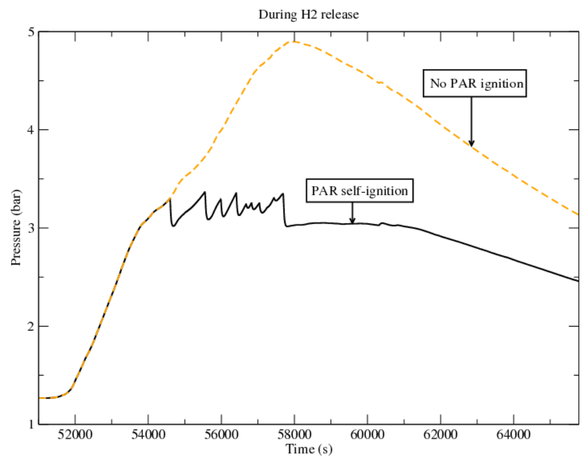


Figure 42: AICC pressure evolution with time

From the previous figure 29, one can observe that the AICC pressure calculated by adopting PAR self-ignition limit stays below 3.5 bars while the AICC pressure obtained using the classical flammability limit reaches 5 bars.

5. Conclusion

This document provides a critical assessment of the H2/ CO combustion engineering correlations and models and their validation status. Thus, a survey of flammability limit and flame acceleration criteria relevant to severe accident late phases conditions is provided. In addition, the status of empirical and engineering combustion models, commonly used in nuclear field, is given.

The literature survey showed that:

- For flammability limits, the available data on LFL for H2/CO based mixtures at elevated temperatures, but for an initial pressure of 1 bar and/or 1 atm exist and agree fairly well, despite some points that need to be revised. On the contrary for the UFL, the few data in the literature show large discrepancy both on the absolute values and on the trend. The effect of the initial pressure is not addressed and should be investigated. The effect of steam and carbon dioxide is also missing for an initial pressure higher than the atmospheric one.

- For the Flame acceleration, only two studies were relevant to ex-vessel conditions. Both of them were preliminary studies from which it was not possible to draw a clear picture on how the flame acceleration criterion can be extended for pure H2 to a mixture of H2/CO. For this criterion validation and/or extension to ex-vessel conditions, there is a need to determine the Zeldovich number and the effective Lewis number for a binary fuel mixture.
- For the H_2/CO detonability, only recently, data were published on the detonation cell size of 90%H2/10%CO mixtures with air. These preliminary results indicate that for lean mixtures, the detonation limit may be larger for CO/H2 mixtures than for H2 mixtures. There are not enough data to draw a clear conclusion,
- Fundamental data on flame propagation are still missing to upgrade the existing combustion models ability to address representative severe accident late phase conditions,
- There is a strong need for experiments at large scale for H2/CO based mixtures. These data are needed for proper code validation for the prediction of the combustion regimes and the associated pressure loads.

Thus, additional experimental and theoretical investigations are needed to fill the observed knowledge gaps. This issue will be addressed in the framework of the WP3 of the AMHYCO project. Consequently, the experimental program in WP3 has to provide corresponding both fundamental data, as laminar flame speed or turbulent flame speed, and “applicative” correlations, as flammability limits or flame acceleration criteria. The obtained experimental results will help improving the existing engineering combustion models to cover the conditions expected in the late phases of severe accident.

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Chapter 4:

Review Of The Containment Equipment Qualification Criteria And Instrumentation Surveillance Under Severe Accident Conditions

1. Introduction: Purpose and Target group

Over the last decades, much insight and experience has been gained in the field of equipment and instrument qualification under DBA and SA conditions. Harsh environments developed during an abnormal operation scenario can subject safety-related items of a NPP to service conditions that may far exceed their design specifications. Adequate programmes to assure the availability and performance of these components need to be developed and deployed. Following that aim, a wide technical basis arose to generate efficient tools and regulations to harmonize the approaches taken, whether in the experimental and industry level or in the analytical simulations performed worldwide. Nevertheless, differences appear when splitting the problem of electrical and mechanical equipment qualification into the two main domains of study, DBA and SA.

Equipment and I&C elements to be qualified for their use under DBE conditions follow experimental and analytical testing programmes comprised in an Environmental Qualification process. This EQ enterprise is supported by a rather extended frame of regulations and good practices established in the industry since 1980, with standards in constant revision. An EQ process will give all the outcome necessary to evaluate if the performance of the equipment will be impaired, for what enveloping profiles of the main stressors (temperature, pressure, radiation, humidity, etc.) are derived and compared to the expected conditions that could be developed in a containment environment during a transient scenario.

On the other hand, DEC/SA qualification of equipment and instrumentation follow the path of the assessment of survivability under the plausible harsher conditions of the aforementioned stressors that can be developed during a SA. Few industry standardized approaches have been developed to describe the preferred methods for testing and qualifying components under the several phases of a SA. EQ regulations and conclusions have served, and serve in this review, as a starting point and technical repository to extend and solve the problem at NPPs. As in the case for DBE-EQ development, plant-specific profiles are adjusted to consider the possible conditions in each stage of conservative accidents to account for the degradation and damage to which components can be subjected, to various degrees up to complete failure. Moreover, survivability assessments sometimes rely on EQ values. Thus, to give better insight on the latter points, a more detailed explanation on the DBA EQ principles and criteria is given in this review.

In every stage of a SA, and for a long period after the onset of the events, information from accident monitoring instrumentation is needed to assess the course of action of the SAM measures and to confirm the possibilities in the use, or replacement, of equipment located in vital areas. Without a proper qualification, the protection against harsh environments cannot be assured, nor the functionality and efficiency, so a thorough evaluation of the reliability, by physical and computational means, is needed to support the development of documents such as SAMG guidelines and Deterministic/Probabilistic Safety Analysis reports.

Objectives

In this report, a state-of-the-art revision of the main criteria and principles of Equipment Qualification under Design Basis conditions and Survivability Assessment of electrical and I&C equipment under Severe Accident scenarios, is undertaken. The information compiled herein aims to serve as a technical repository of not only the standards and characteristics of each field of qualification, but also of relevant real data gathered from experimental and analytical programmes performed in European and non-European PWR NPPs.

Structure of the chapter

The chapter is divided into two sections, regarding environmental qualification for DBA scenarios and equipment survivability assessment for SA conditions, respectively.

Section 1.1 reviews the principles of EQ and seismic EQ, expounding the characteristics of the service conditions and major stressors that can arise and explaining the process of qualification and the parametrical profiles important for plant safety. **Sections 1.2** and **1.3** follow the historical evolution of EQ standards and the current state of international regulation. **Section 1.4** contains relevant plant-specific data of the main variables used in EQ programmes and tests for a variety of PWRs and some other NPPs in several countries. **Section 1.5** gives a brief review of the different approaches of the analytical assessment of EQ with computer codes, starting from the industry preferred Lumped Parameter approach and following with the 3D and CFD integral modelling analyses. **Section 1.6** reviews some experiments and industrial tests performed on EQ programs for DBE qualification, while depicting some lessons learned in EQ testing and giving examples of nuclear class qualified components. Finally, **Section 1.7** enumerates some novel EQ approaches.

Section 2.1 reviews the principles of Survivability Assessment under SA criteria, defining the most common functional requirements and processes for the demonstration of equipment and I&C reliable performance. SA harsh-conditions parameters environmental profiles are reviewed as well as some methodologies applied for the assessments. **Section 2.2** copes with the regulatory frame surrounding SA survivability assessment and its connections with the EQ standards. **Section 2.3** contains relevant plant-specific SA qualification data for temperature and pressure enveloping profiles for SA survivability assessments for a variety of PWRs and some other NPPs in several countries. **Section 2.4** and **2.5** reproduce the same topics as in Sections 1.5 and 1.6, now for the case of survivability assessment of electrical equipment and I&C. **Sections 2.6** and **2.7** review some common implemented approaches and the most relevant international efforts in the field of SA equipment and instrumentation survivability under severe scenarios.

For the effective comprehension of the terminology used in this section, the reader is advised to consult the glossary at the end of this document.

2. Containment Equipment Qualification criteria under Design Basis Events

In the present section, a review of the general criteria applied to the qualification of containment equipment under Design Basis scenarios will be conducted, focusing on the regulations adopted in Europe and USA concerning the specifics of the environmental qualification (EQ) of components, equipment and instrumentation within the qualification programmes in PWRs (W, KWU, VVER).

The purpose of the information displayed throughout this review is to act as a technical data repository concerning the limiting variables that have a leading role in the qualification of equipment located in PWR containments. To fulfill this aim, testing experiences, experiments and code-based analyses will be addressed in order to extract sufficient references of temperature, pressure and other values comprising the environmental profiles used in the industry to qualify equipment and instrumentation under a wide range of conditions.

Those values, as well as those reviewed in the section concerning severe accident scenarios and equipment and instrumentation surveillance, will be of importance when undertaking simulations, conducted in further WP´s of AMHYCO project. A thoroughly research is in process to acquire international data that would support the calculations and other future issues.

The bulk of regulatory and technical information is derived from the specifics of class 1E electrical equipment of NPPs (cabling, I&C items, transmitters, etc.), although mechanical items (like motor operated valves, seals, gaskets, etc.) will also play a role in determining profiles and data important to the qualification of components in containments. Although EQ is going to be addressed here for every type of component, mechanical EQ particularities will be reviewed in a subsection.

2.1. Principles of Environmental Qualification under DBA/LDB

In this subsection, general definitions and concerns over containment equipment and instrumentation environmental qualification under Licensing Design Basis and Design Basis Accident scenarios will be provided, as an introductory glossary of terms and principles applied in the various programmes, models and experiments developed worldwide and issued in this report for technical query purposes.

Regarding EQ, it is established that safety-related equipment and instrumentation must perform its function within any environmental conditions enveloped by a design-basis-event spectrum, testing their adequate performance under a plant design envelope basis concerning levels of temperature, pressure, radiation and other limiting variables that can affect direct or indirect safety-related items in a NPP containment (EPRI, 2010). These DBE or LDB conditions are not as harsh as those developed during a SA, so it is important to highlight the requirements and the regulations that apply to this matter.

The principles of qualification will be here defined as those standardized in the industry. For instance, the Institute of Electrical and Electronics Engineers (IEEE) sees equipment qualification as “the generation and maintenance of evidence to assure that the equipment will operate on demand, to meet the system performance requirements during normal and abnormal service conditions and postulated design basis events” (IEEE, 1983), concept applied to both electrical and mechanical items under conditions with the potential to produce unique or simultaneous common-cause failures, such as the scenario of a seismic event causing unavailability of equipment in spite of their design diversity, redundancy or physical separation.

The aforementioned generation and maintenance of evidence in qualifying equipment is seen as a responsibility that lies with the plant licensee, who has the role of preserving the qualified status throughout the installed life of the components. Nevertheless, decisions on whether to use generic environmental profiles, provided by the specialized manuals, or to use plant specific profiles calculated by each NPP and country regulatory body, are always an open issue, as plant specific values can be lower thus being more attractive to use. This issue is for instance stated in NRC´s Regulatory Guide 1.89 and in the latest IEEE for class 1E equipment manual (International Electrochemical Commission & Institute of Electrical and Electronics Engineers, 2016; Regulatory Guide 1.89, 1984),

2.1.1. Service conditions and plant safety

Regarding all items important to safety in a NPP, namely here equipment and components which have to perform their functions when necessary and are located in a containment, the IAEA SSR-2/ Requirements (IAEA, 2012) state that a qualification program shall be implemented to verify that capability in the prevailing environmental conditions, throughout their design life and with due account taken of plant conditions during maintenance and testing, among others. Moreover, the process of EQ involves the demonstration of necessary functionalities under all service conditions associated with all plant design states, as referred in (IAEA, 2011).

The variety of systems, structures and components (SSC´s) important to safety and directly or indirectly supportive of the performance of safety functions (functional and performance requirements concerning reactor cooling, containment isolation and integrity, etc.) will operate under a wide range of service conditions. These can be environmental conditions, external to the equipment like radiation or induced vibration, operational conditions, internal to the equipment or associated with its physical or electrical interfaces, and abnormal conditions, like SBO, failure of HVAC systems or leaks of steam from valves and other small process piping. Both these conditions and the safety functions must be assessed to identify all qualification acceptance criteria, which are inherently related to all significant operational and environmental stresses, including those resulting from DBE´s.

Qualification would then reduce or eliminate the outcome of common-cause failures occurring due to design, operational, environmental or human factor initiators. Common examples of induced failures are those resulting from earthquakes (field of seismic qualification) or postulated accidents, such as Main Steam Line Break (MSLB) & Large Brake Loss Of Coolant Accident (LBLOCA) (HELB´s), which create harsh-environmental conditions and introduce significant amounts of stressors to multiple components in the form of temperature or pressure, having the potential of reducing their functional capability to unacceptable levels.

The scope of EQ is then to address all topics affecting the suitability of each equipment, I&C and SSC for its intended function. The main issues to be treated may be classified as (IAEA, 2016):

- Suitability and correctness of functions and performance
- Environmental qualification over harsh and mild environments
- Qualification for the effects of internal and external hazards
- EMC qualification

Some of these points are to be discussed in the following subsections.

Relative to the second issue pointed out, it is mandatory to define the harshness of the environment where the qualification will be developed. Moreover, during Postulated Initiating Events (PIE´s), environmental conditions can change in each zone of the plant and the containment, so operational conditions may be quite different than those present during transients or normal operation. EPRI´s Nuclear Power Plant Equipment Qualification Reference Manual define two types of zones subjected to EQ, in accordance with IAEA standards (IAEA, 2010):

- **Harsh Environments EQ:** these conditions are usually produced by pipe break accidents, during and following HELB´s inside (LOCA or MSLB) and outside (MSLB) containment. Most countries require a demonstration of compliance for any safety equipment performing safety-related functions under these conditions, considering any aging effects resulting in degradation which could promote equipment failure during harsh environments. The most recognized methods to demonstrate harsh-EQ are of the type-testing class. It is important to note that the whole inside of any containment is generally considered as a harsh zone, while auxiliary buildings can have certain regions which are considered harsh for EQ evaluations.
- **Mild Environments EQ:** existing in plant areas not affected significantly by an accident. This means that conditions do not significantly vary in those specific zones

and equipment should not experience significant differences in performance as a result of a PIE (DBE), except for a seismic event (IEEE, 1983). To provide for required functionality of equipment in these conditions, general practices range from conservative design practices and proven equipment designs, to manufacturing production tests and pre-operational equipment and systems tests, with appropriate QA controls over all component´s life cycle.

Some countries, e.g. U.S.A., do not require formalized mild-EQ programs for their equipment (unlike France and Germany (IAEA, 2010)), and support qualification in regulations like NUREG-0588, which claims that this type of qualification can be established by the design/purchase specifications containing functional requirements and service conditions under normal and abnormal events, combined with well supported maintenance and surveillance programmes (Southern California Edison Company, 1981).

To summarize, service conditions, either environmental and/or operational, during PIEs may differ substantially from those of normal operation, so their severity and the class of equipment and instrumentation will determine the appropriate qualification practices to be developed.

Figure 1 shows the different response of a component between mild and harsh environments and Figure 2 shows a case of application in AREVA´s EPR reactor.

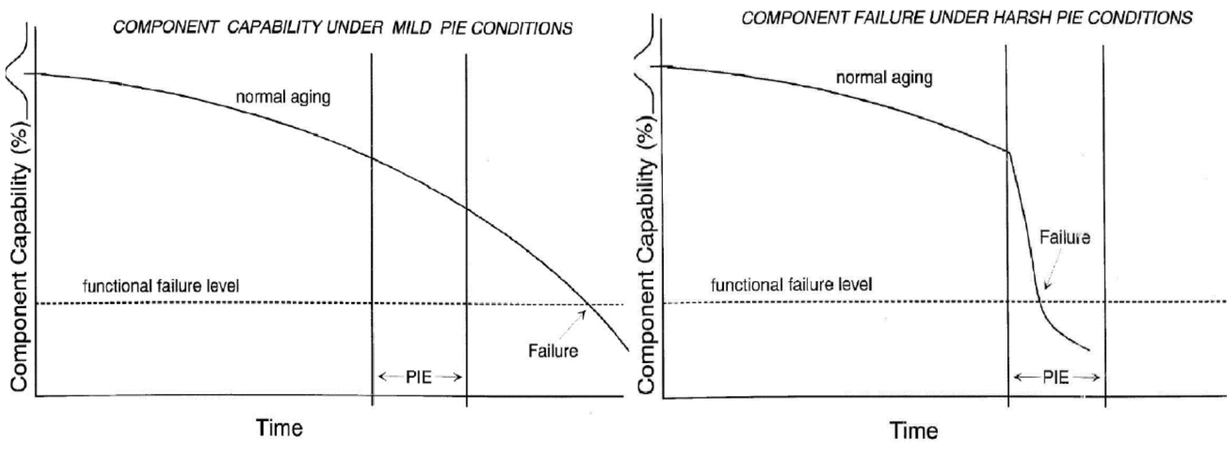


Figure 43: Mild and Harsh environments component response (IAEA, 2010)

Table 1 enumerates typical values of the important mild and harsh service conditions to be evaluated in a EQ program (SCHULZ & Dean, 2019):

Table 14: Typical mild and harsh environment conditions for LWR (SCHULZ & Dean, 2019)

	MIld	Harsh
Temperature	40 ºC	171 ºC (accident peak)
Pressure	1.013 bar	4.2 bar
Humidity	10-95% RH (non-condensing)	100% RF (condensing)
Radiation	< 10^4 rad TID	3* 10^5 (normal) – 2*10^8 (acc.) rad TID
pH Spray	N/A	Caustic 10.5 pH
Submergence	N/A	None

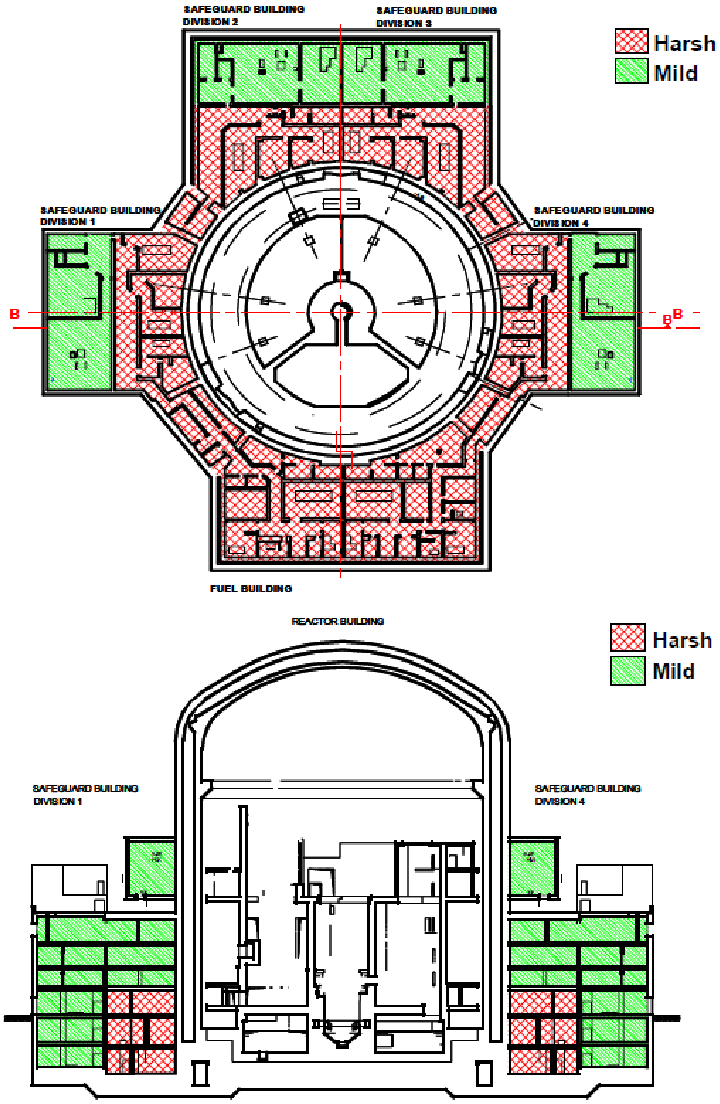


Figure 44: Use of Harsh and Mild Zones in Safeguard Buildings of AREVA´s EPR NPP design (AREVA, 2006)

2.1.2. Enveloping profiles and Major Stressors

Significant changes in service conditions create stresses that might very well result in equipment failures, especially if the components have already been experiencing in-service degradation. Those stressors can be classified as (Karasek, 2015):

- **Environmental stressors:** temperature, pressure, humidity, steam, radiation, chemicals, vibration (induced and seismic) and electromagnetic interference.
- **Operational stressors:** power supply V/f, electrical/mechanical cycling, self-heating, process fluid effects.
- **Internal and external hazards:** fire, flooding, extreme weather, falling objects, pipe whips, components acting as missiles.

Among these, temperature and pressure are especially interesting variables in terms of EQ studies for containment safety-related equipment and instrumentation under DBE and LDB conditions both in harsh and mild zones. On the other hand, radiation cause material degradation and thermal aging after long periods, e.g., alterations on semiconductor devices of digital I&C systems through ionization. Vibration can cause fatigue and failure in active and passive components, resulting in wear, loose parts or cyclic damage.

Some of the most important effects of these operational major stressors are (EPRI, 2010):

- Affected performance and aging characteristics of electrical equipment due to variations in their electrical parameters.
- Electrical and mechanical stresses due to loading conditions as well as to intermittent operation of equipment.
- Material cyclic fatigue.
- Heat rises due to ohmic heating and higher service temperatures.
- Higher than local ambient service temperatures of equipment due to process fluid heating effects.

To assess all stressors, environmental qualification and design conditions envelopes are created based on analyses of the containment response to a spectrum of HELBs and related scenarios. The outcome of the analyses is a variety of enveloping profiles of temperature, pressure, etc., that indicate the peak values reached in each containment evaluated (plant-specific containments or NPP-type specific evaluations). These envelopes are the key elements to be consulted during simulation´s Verification & Validation stages, and will be presented all along this report, either in the form of graphics or discrete values.

2.1.2.1. Temperature and pressure effects and enveloping profiles

Temperature gradients may change material characteristics by gradually, chemically and physically, thermally aging the components. The effects caused in electrical equipment by harsh environments and thus, high temperatures, are: lower dielectric and mechanical strength and insulation resistance, changes in semiconductor devices characteristics, increases in electronic circuits failure rates, melting of thermoplastics and differential expansion, among others (IAEA, 2010). Quick pressure variations affect equipment by causing additional loads on parts and components. Those loads, if sufficiently heavy, might cause structural failure on a SSC and crush or damage enclosures and force external environment conditions into the components.

Figure 3 shows an example of the differences in local temperature that can be present in an electrical equipment during a transient.

Figure 4 depicts a typical temperature and pressure enveloping profile for DBA-EQ purposes. In this case, the envelope is that for Kori NPP units 3 & 4 (Kwi Hyun Seo et al., 2006).

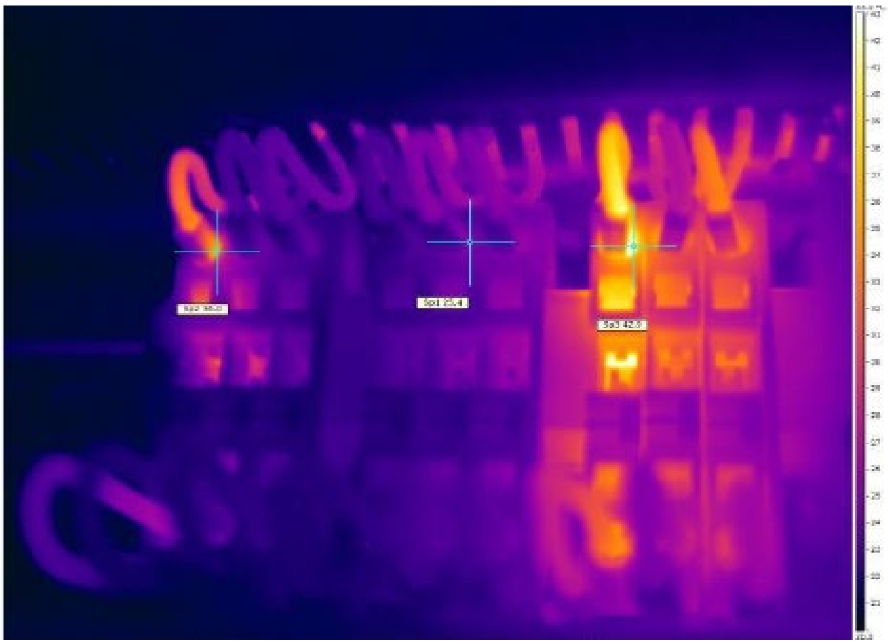


Figure 45: Example of differences in the local temperatures in an overheated electrical equipment (Karasek, 2015)

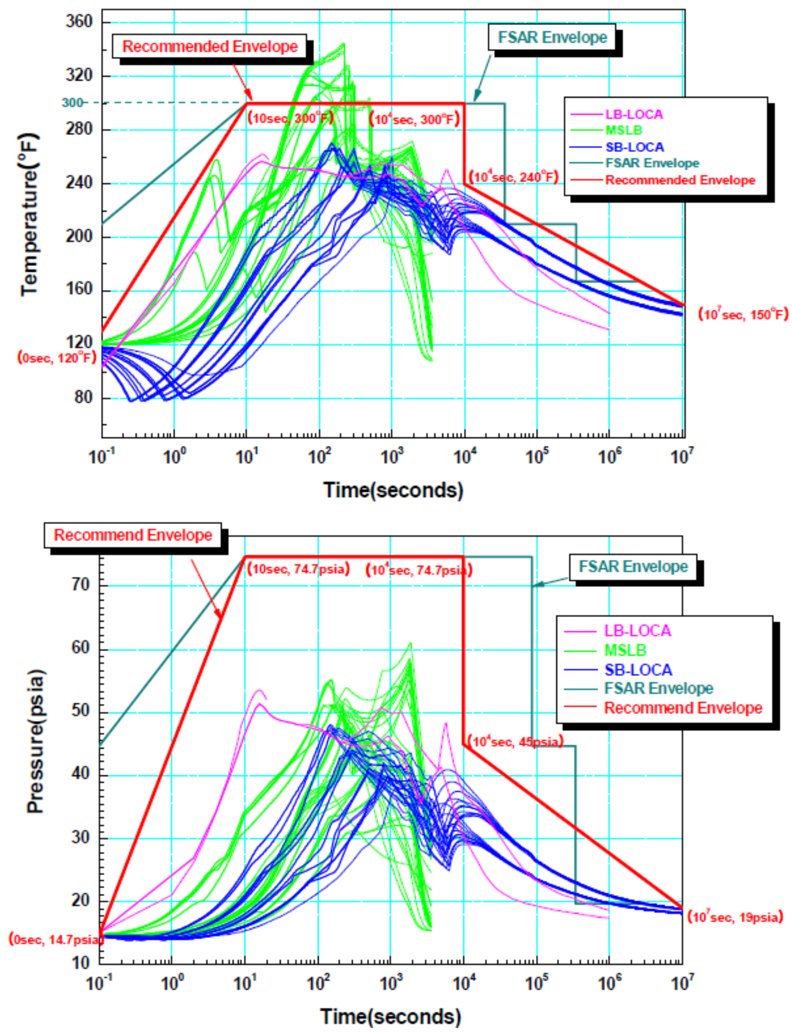


Figure 46: Temperature and Pressure envelopes for EQ of Kori NPP 3&4 under DBA conditions (Kwi Hyun Seo et al., 2006)

2.1.2.2. Steam and humidity effects

In the event of, for instance, a HELB, the exposure to high-temperature saturated steam combines temperature and humidity effects that can cause corrosion affecting not only metallic surfaces but also electrical terminations and contacts. Water sprays can come from piping or component leaks, deliberate releases or inadvertent fire suppression system actuations, to name a few. Also, if an item is subject to being submerged, it must be qualified to the submergence depth anticipated or moved above the flood plain. Lastly, chemical sprays are to be noticed as they can appear in the most energetic transients and produce undesirable effects.

2.1.2.3. Seismic EQ

Seismic qualification is required for equipment in mild environmental conditions. Its functional qualification is integrated into a structured equipment qualification program that is similar to the harsh-EQ electrical one and most countries require formalized qualification to establish equipment performance during seismic events, for both electrical and mechanical equipment. That qualification also generally includes both structural integrity (cabinets, fixture points, etc.) and operability and functional capability, e.g. analysis of simple systems like check valves (IAEA, 2010).

Testing is the most frequently used seismic EQ method. It encompasses the possibility to verify functional requirements and test complex specimens limited by the size. It is also frequent that tests and experiments are to be performed by simulations on vibration/shake tables.

The top level regulation for seismic qualification for electrical class 1E equipment is IEEE 344 and it is complemented by IEC 60908 rule (Y. Lee et al., 2011) and RG 1.100. Equipment must demonstrate that their safety functions are not compromised during and after a SSE (maximum possible earthquake at the location) and also previously to a number of OBEs (maximum reasonably expected earthquake at the location). Thus, analyses should simulate the conditions of such seismic scenarios to give figures that enable EQ of electrical, I&C and mechanical components under reasonable enveloping profiles of the variables of interest. Figure 5 gives a graphic example of seismic EQ envelopes.

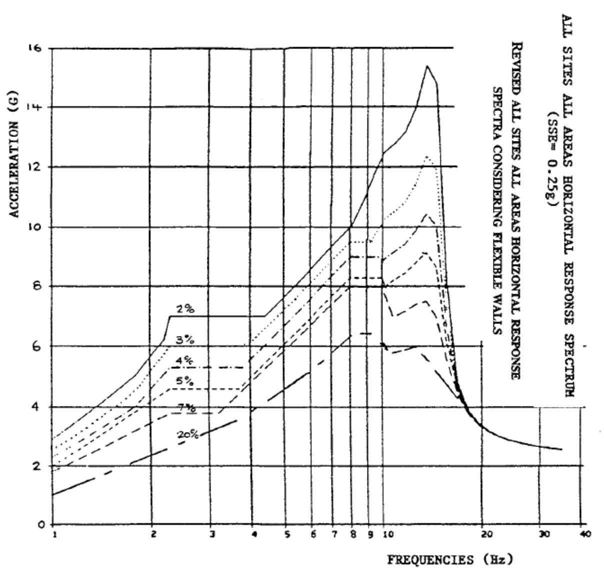


Figure 47: Horizontal seismic spectrum used in U.K. for EQ of pressure transmitters (European Commission, 1996)

2.1.3. Environmental Qualification as a process

The qualification process is intended to significantly minimize the probability of common-cause environmental failures, typically performing the equipment qualification process on a device-by-device basis (EPRI, 2010). The equipment qualification should be based on a selection of various methods, as recommended in IAEA standards (IAEA, 2016; Karasek, 2015):

- Type testing of supplied equipment
- Use of engineering and manufacturing processes in compliance with recognized standards
- Reliability demonstration and past experience in similar applications
- Analyses to extrapolate test results or operating experience under relevant conditions
- Evaluation of manufacturer during production processes and inspection of components during manufacture

The specific combination of methods and regulations that apply will vary from component to component and the safety-relationship of the systems under evaluation. For instance, qualification evidence based upon operating experience for directly related systems is usually combined with type testing and testing of supplied equipment. The aforementioned type testing method (in a simultaneous, sequential or separate basis) is normally preferred for qualification of electrical and I&C equipment whose complexity and variety of failure modes require aging and accident simulations performed on limited samplings of "types" of equipment, for example under harsh conditions (Karasek, 2015).

Testing will go hand in hand with different forms of analysis, probing similar or testing identical items under similar conditions with supporting analyses, which can be assessed in combination with partial type-test data supporting the analytical assumptions and conclusions. Such is the case that applicable standards and regulations recognize and endorse experience as a valid method to address EQ, whenever sufficient data is available (limiting cases arise for harsh-environment equipment that has in reality experienced harsh conditions).

The process of qualification is exemplified in Figure 6. Equipment and service condition information vital to EQ is to be defined during plant design and subsequent modifications of it. Together with the EQ-related basis and the EQML of components subjected to qualification (the scope of EQ), it is important to define performance requirements and EQ acceptance criteria for normal, abnormal and accident environmental conditions, plus power and signal conditions which can raise (Southern California Edison Company, 1981). This, ultimately, will permit appropriate considerations during aging simulations all over the qualification program.

Qualification verification phase should then be successful if the next sequential activities are accomplished: EQ specification and plan approval, data collection and qualification report evaluation and approval. Nevertheless, test results are often based on generic enveloping conditions and do not always address plant-specific environmental conditions, so additional analyses or complementary approaches might be required by some regulatory bodies to demonstrate specific applicability in a set of equipment, regarding environments, configuration, or maintenance practices.

As a sample of a typical plant-specific evaluation list of deliverables, the next list provides a glimpse on the documentation effort necessary (EPRI, 2010):

- "Qualification Criteria and Standards and Test report Overview"
- "Required environmental, performance and operational conditions"
- "Similarity of tested and installed equipment"
- "Configuration limitations and requirements"
- "Acceptance criteria and Performance requirements"
- "Test Sequences and Anomalies"
- "Aging Simulations and Qualified Life"
- "Accident conditions and Margin & Conservatism"

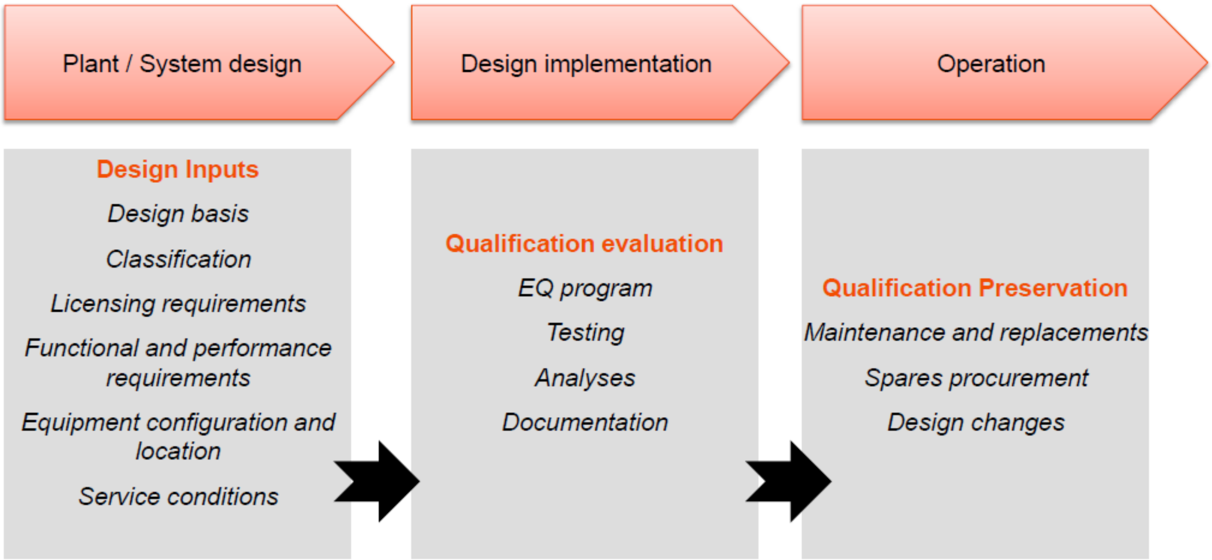


Figure 48: General scheme of a qualification process (Karasek, 2015)

2.1.4. Components Aging issue

Many components within NPPs, like safety-related cables, are especially vulnerable to adverse conditions during and after DBAs (NEA, 2018), and the assessment of their condition of installation need a myriad of condition indicators to effectively assess the aging stressor factors. This is an issue recurrent when considering LTO of NPPs, as EQ has to be re-evaluated through costly programmes and much equipment have had a qualified life of less than 40 years (Gonzalez, 2012).

Aging can be a common-cause failure mechanism if the population of components is allowed to reach the wear-out phase, often described in "bathtub" failure rate curves and other indications on the stages of electric and mechanical components. If the curves from the specifications mark a compromising phase, components should enter a replacement scheme, which is also one of the mild-EQ objectives.

As stated in IAEA´s SSR 2/1 Req. 31 on Aging Management (IAEA, 2012): "The design life of items important to safety at a nuclear power plant shall be determined. Appropriate margins shall be provided in the design to take due account of relevant mechanisms of ageing, neutron embrittlement and wear out and of the potential for age related degradation, to ensure the capability of items important to safety to perform their necessary safety functions throughout their design life".

To accomplish such a requirement, an efficient methodology should identify aging stressors and mechanisms (and methods to address them), use analytical models and/or accelerated aging tests, establish a qualified-life estimate and specify surveillance maintenance and replacement activities. Together with a well-suited corrective action program to preclude age-related degradation, information from on-going qualification is crucial to increase or decrease the qualified life of components.

2.1.5. Mechanical Environmental Qualification

Electrical equipment is more sensitive than mechanical equipment to accident conditions and related aging mechanisms, therefore EQ for electrical components is required by virtually all IAEA Member States but EQ for mechanical components is only required by some members, e.g., France and Germany (IAEA, 2010).

Mechanical equipment have characteristics that contribute to their greater environmental tolerance; also, normal operation combined with fabrication, preoperational and periodic tests during operation, can demonstrate performance under normal service conditions, that being the reason for codes and standards not addressing functionality of active components under normal and DBE conditions. For instance, valves or pumps are exposed, and designed, to normal process scenarios typically far more severe than accident conditions. Moreover, they are fabricated principally of metallic alloys virtually unaffected by HELB type environmental conditions, remaining practically functional after degradation of certain organic (non-metallic) components like seals and gaskets.

Nevertheless, failure of non-metallic components of mechanical equipment can hamper the safety performance, something especially critical if operational service conditions during PIE´s are substantially different from those occurring during normal operation and functional tests, for when selective environmental qualification programmes shall be implemented.

2.2. Historical review of EQ and International Regulation

To better understand the principles and needs surrounding EQ of containment components under design basis conditions, it is recommended to review the evolution of equipment qualification and its regulation since the beginning of nuclear plants licensing history. To our purposes, only the most important guides, manual and regulatory documents will be addressed, but exhaustive references will appear in order to compile the extensive regulatory literature on the matter. The focus will be put in safety-related electrical equipment, although regulations and guides relative to mechanical components will be also commented.

2.2.1. Evolution of Standards

In the early days of licensing reviews of plants, namely before 1971, the regulatory requirements were defined as "standards of acceptability", unique to each new plant review and generally not formalized. Licensing was then an ad hoc process and designers just procured the highest-quality industrial grade equipment available (Jordan, 1973).

By 1971, methodology takes form and informal standards were formalized as the "General Design Criteria" (GDCs), followed by the issue of pioneering Regulatory Guides and Standard Review Plans from the recently created NRC, which identified the need to ensure operability of certain classes of equipment when called upon to perform a safety function (NRC, 2015). For electrical equipment, the first of a series of dedicated manuals of safety-class equipment is born: IEEE 323-1971, from the previous efforts of this institute since 1967 to develop standards for EQ and to provide more guidance on methods to qualify under normal/abnormal/accident conditions and the combination of them (type testing, operating experience, code analyses…).

IEEE Std 323 is the top-level qualification standard for electrical equipment and instrumentation ("class 1E") and will be of reference to equipment located inside and outside the containment, for the purposes of this project. The document was revised in 1974, adding aging qualifying requirements and margins, (IEEE, 1974). Subsequent incorporation of knowledge, experience and enhancements gave birth to the revisions of 1983, 2003 and 2016, this last one being today´s reference, as explained in further sections of this report (IEEE, 1983, 2003; International Electrochemical Commission & Institute of Electrical and Electronics Engineers, 2016).

In 1984, a cornerstone is laid with the publication of NRC´s RG 1.89, frame of reference of the regulation (Regulatory Guide 1.89, 1984), and that endorses IEEE guides therefore supporting virtually all qualifications undertaken under the new an well recognized standards. The relation between IEEE standards and RG 1.89 is key to make the U.S. regulatory framework an international one, something even more sponsored with the imbrication of guideline 10 CFR 50.49 (IEEE 323 Rev. 1983 incorporated CFR´s methods to qualify under mild/harsh environments, facilitating the integration of other IEEE Stds. such as IEEE 627-1980). Going a bit backwards, it should be pointed out that NRC established in 1979 a series of EQ criteria concerning all operative NPPs, a regulatory process compiled in DOR Guidelines and NUREG-0588 (NRC, 1981). This frame was of the utmost importance in many NPPs following license review but it was then harmonized with the publication of 10 CFR 50.49 in 1983 (NRC, 1983).

Revisions of the standards have proven to be fruitful over the decades. IEEE 323 Rev. 2003 reflected major EQ developments in the nuclear power filed, defining updated requirements on environmental zoning, introducing condition-based qualification and its application to license renewal, recommending new methods on thermal aging analysis and defining requirements for qualified life extension.

Nowadays, the current “licensing basis” for each NPP cites the version of any codes and standards that apply to a given site, so end-users of the manuals have to identify which regulations apply to their purpose. For example, many U.S. operating reactors are still committed to the IEEE Std. 323-1974 level, even though industry standards have been in constant evolution, offering attractive new approaches which do not normally enter in conflict with current licensing basis (EPRI, 2010).

To summarize, Figure 7 depicts the relationship between EQ-related industry standards and the associated EQ-regulatory requirements that culminated in the issuance of 10 CFR 50.49, showing that evolution of industry standards preceded the change in the regulatory requirements. The evolution of these, reflects a shift from the original focus on equipment performance just under harsh conditions to the inclusion of aging effects and qualification margins to account for uncertainties in the process.

Table 2 summarizes the important regulation reviewed until now. Important notice is to be put into code 10 CFR 50.49 and its year of issuance, as it has influenced many decisions relative to EQ since its issuance in many countries, specially the ones that usually have adopted American regulations to their own programmes.

To gain quick knowledge of "IEEE Std. 323 for electrical class 1E equipment" evolution throughout the years, a diagram is presented in Figure 8.

Table 15: Important American EQ regulation evolution (1971 to 2016)

Document	Year of issuance	Observations
Industry standards	< 1971	High quality assurance during manufacturing
IEEE 323	1971	First specific EQ rule
IEEE 323	1974	More severe requisites added
RG 1.89	1974	NRC endorses IEEE 323-1974
DOR IE-79-01B	1980	Criteria establishment to evaluate qualifications. Development of EQMLs
NUREG-0588	1980	Reqs. For NPPs subjected to IEEE 323 1971/74
10 CFR 50.49	1983	Harsh EQ reqs. Classification of safety-relationship of equipment
IEEE 323	1983	Revision to include 10 CFR 50.49
RG 1.89	1984	Revision with guide and method to comply with 10 CFR 50.49
IEEE 323	2003-2016	New lessons learned and enhanced techniques

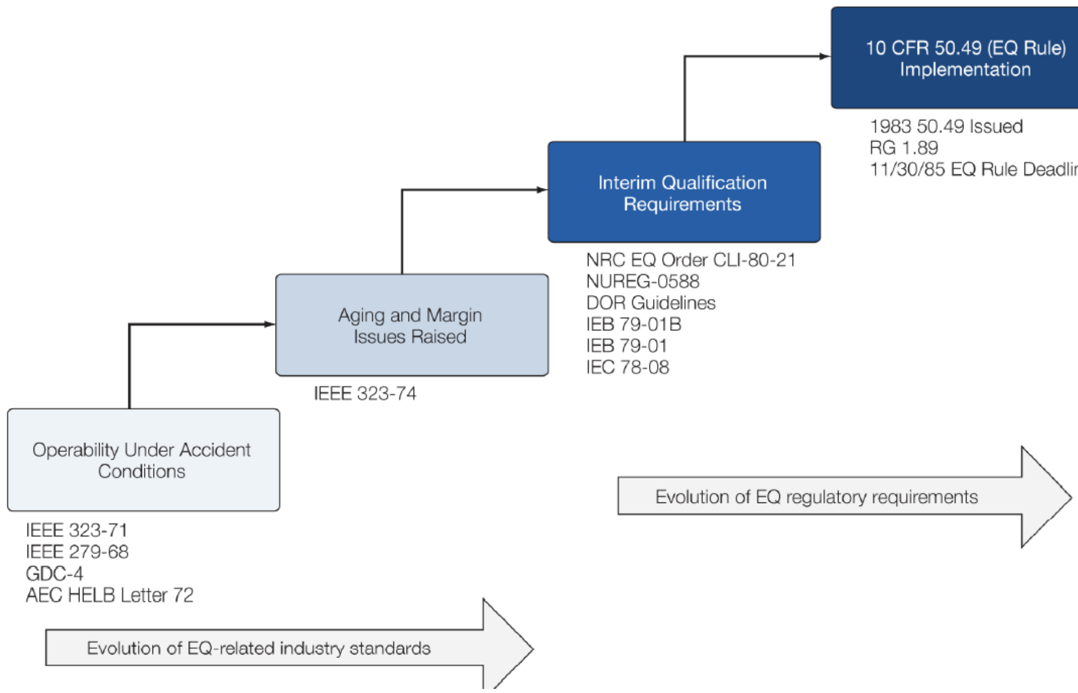


Figure 49: Evolution of EQ-related industry standards and EQ regulatory requisites (EPRI, 2010)

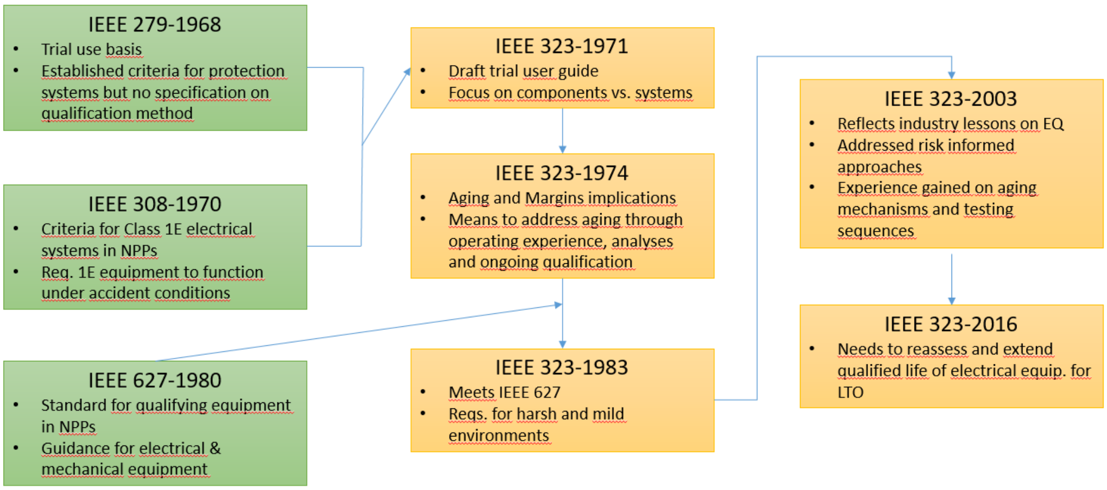


Figure 50: IEEE Std. 323 evolution (adapted from (Castleberry, 2012))

Some components qualified to European standards may be applicable for use in the U.S., as many EQ performed to foreign standards is usually evaluated against U.S. qualification standards prior to acceptance in a likewise NPP. In general, every safety-related SSC will have the same general requisites: quality group (e.g. ASME class mechanical equipment), quality warranty (as expected from regulations like 10 CFR 50 App. B.), EQ and seismic qualification, dependability (redundancy, diversity, proof capability…) and physical and electrical separation (Cid, 2014). The general principles of EQ and the main elements of methodology, although strongly linked to the characteristics of each plant, are however similar within the European countries (European Commission, 1996).

Nevertheless, specific regulations may apply when qualifying specific areas or components in an American NPP versus a European one (being comparably between any NPP to any other counterpart around the globe). To give an example, Table 3 depicts an extract of a qualification report for P/dP transmitters made by Endress+Hauser©, where the specifics of certain regulation applicable to different areas are shown, revealing regional discrepancies/preferences in the use of German regulation rather than international standards (which may very well be complementary in the case presented).

Table 16: EQ of Endress+Hauser P/dP transmitters. German vs. International regulation for some areas of application in an NPP. Taken and adapted from (Cid, 2014)

Location	German Reg.	International Reg.
Conventional area within the NPP	No qualification required	No qualification required
Safety areas for vibrations (seismic test)	EVA test contained in KTA 3505	IEEE 344 – class 2E
Area within the containment	Containment test in KTA 3505	IEEE 323 – class 1E LOCA
Reactor annulus (between containment and reinforced concrete shell)	KTA 3505 reactor annulus	IEEE 323 – class 1E

2.3. Current state of regulations

As a repository of published rules, guidance documents, industry codes, standards and recommended practices to date, this section provides a compendium of the EQ normative framework relevant to AMHYCO project, as far as for the date of redaction of this report. Any country-specific regulation will be highlighted as that. The bulk of the collection of rules herein focuses in the most important standards used worldwide and applicable to PWRs (Western-type, KWU, VVER). Generic regulations presented are US regulations, which are rather adapted to their use in the majority of occidental NPPs.

Figure 9 shows the hierarchy of documents applicable to qualification in an NPP and reliably applicable to containment EQ in the US. The licensees are responsible for translating the guidance or requirements in these documents into policies, procedures and practices within their own contractor organizations. Most of the rules contained in the scheme have been reviewed by NRC in its SRP of 2017/12 (NRC, 2017) for EQ of electrical and mechanical equipment.

A thorough list of regulations and standards, which extend the previous figure range of knowledge into sibling rules, can be consulted in (Antaki & Gilada, 2015; EPRI, 2010). An example of a hierarchical application of regulations can be found in (MHI, 2013).

A glossary of regulations is displayed in Annex B.

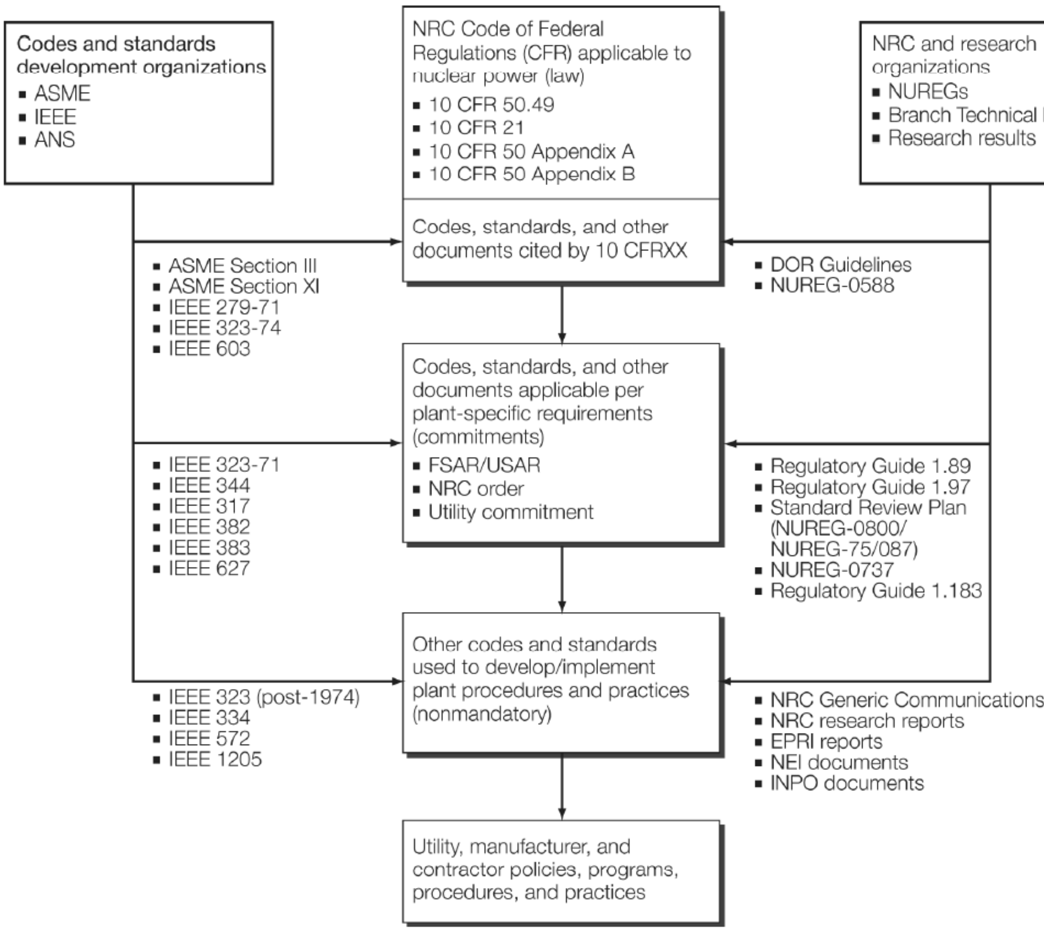


Figure 51: Hierarchy of equipment qualification requirements, standards and guidance in the US (EPRI, 2010)

2.3.1.USA Regulatory Guides

Created by US NRC, these guides serve as a guidance to licensees and applicants who want to implement specific parts of NRC´s regulation or techniques used to evaluate postulated events.

- **Regulatory Guide 1.89 - Environmental Qualification of Certain Electric Equipment Important to Safety for Nuclear Power Plants**: on Periodic Review (Rev. 1) and lastly revised in 2018, to be out for public comment by the end of the first quarter of 2021. Current status of applicability is that of 1984 version. (Navedo, 2020; NRC, 2018; NUGEQ, 2014)
- **RG´s to endorse IEEE Stds. 352/387/577/741/1205/1819/2420:** expected to have draft out for public comment by end of 2020/2021. Status: revised. (Navedo, 2020)
- **RG 1.153 - I&C Safety Criteria:** updated to endorse IEEE 603-2018. (Navedo, 2020)

2.3.2. IEEE Standards

IEEE is a worldwide organization for standardization which promotes co-operation on all questions concerning standardization in the electrical and electronic fields. For nuclear power EQ, their standards have been part of the technical EQ basis and processes for decades. **IEEE Std 323-2016** is the up-to-date review of this standard, endorsed by regulatory bodies (International Electrochemical Commission & Institute of Electrical and Electronics Engineers, 2016). The full IEEE Nuclear Power Collection of standards can be consulted in (IEEE, 2012).

The following tables show current endorsement status of IEEE standards with relation to Regulatory Guides:

Table 17: IEEE endorsed standards summary (AREVA, 2006)

IEEE Standard	Regulatory Guide Revision	Equipment Type / Subject	Latest IEEE Standard Edition
317-1983	1.63, Rev. 3	Penetrations	317-2003
323-1974	1.89, Rev. 1	Electrical /I & C	323-2003
334-1971	1.40, Rev. 0	Motors	334-2006
344-1987	1.100, Rev. 2	Seismic	344-2004
382-1974	1.73, Rev. 0	Actuators	382-2006
383-1974	1.131, P1*	Cables	383-2003
387-1974	1.9, Rev. 3	EDG	387-2001
497-2002	1.97, Rev. 4	PAM	497-2002
535-1986	1.158, Rev. 0	Batteries	535-1986
572-1985	1.156, Rev. 0	Connectors	572-2006
7-4.3.2-2003	1.152, Rev. 2	Computers	7-4.3.2-2003
None	1.180, Rev. 1	RFI/EMI	None

Table 18: IEEE non-endorsed standards (AREVA, 2006)

IEEE Standard	Subject
628-2001	Raceways
638-2006	Transformers
649-2005	MCC
650-2005	Charger/Inverter
1202-1991	Cable flame tests
1205-2000	Aging
1290-1996	MOV applications
C37.82-2004	Switchgear
C37.105-1987	Protective relays

2.4. Environmental Qualification within NPP Containments

In this section, a depiction of EQ within containments is made, reviewing and comparing different enveloping profiles comprising the values for maximum temperature and pressure used for qualification among some European and non-European NPPs. Those values can come from internationally accepted regulations and guides, experimental efforts and testing programmes or industry-related manuals and manufacturer experienced references.

An important source of data is encountered in the numerous code analyses performed by the industry, regulatory bodies, research centres, etc., whose thermal-hydraulic calculations of harsh/mild environments have permitted to extract conservative figures (e.g., maximizing temperature and pressure) for a wide range of containment types and conditions, following well known DBE scenarios and their limiting conditions. A common practice is to run several simulations varying the size, location and mass & energy release of a HELB (i.e., LOCA, MSLB) which would provide different pressure and temperature profiles, and then create an envelope of all these profiles to give birth to a representative yet conservative figure. Then, equipment qualified with an enveloping profile is to be considered valid for any plant/location specific profile that falls within the envelope (EPRI, 2010).

Table 6 will gather country/plant specific peak temperature and pressure EQ enveloping profile values. The aim is to act as a repository for technical data for further comparisons with values extracted from simulations, as well as a revision of values found in the literature. If a peak value is surpassed anytime in a simulation outcome, the claim is that the assessed EQ criteria would then be surpassed as well, independently if it is a global or a local value (see next section for further discussion on this topic). Of important notice is that each NPP can utilize generic values or to use plant, or fleet, specific parameters and enveloping profiles.

It is important to point out the peak temperature and pressure criteria for equipment and instrumentation proposed by the earliest IEEE Std. 323 (1974). These peak values, referenced in Table 6, have been used for decades in many NPPs, either as a containment global criterion or as peak local criteria for the assessment of damage in containment compartments (Jimenez et al., 2017).

Table 7 shows the margin to safety limits established by IEEE Std. 323-2016 for temperature, pressure, total radiation dose, seismic vibration and other parameters. The margins are recommended to be applied for DBE service conditions scenarios but do not apply to age conditioning. Alternate margins of uncertainty might very well be acceptable if properly justified by the end-user of the data or by the regulatory status of each country or regulatory body.

Annex A contains a rather detailed list of systems containing class 1E electrical equipment in a typical PWR NPP, namely units 2&3 of San Onofre NPP (CA, USA) (Southern California Edison Company, 1981). Containment equipment referenced there, can act as a valid example of typical electrical and mechanical equipment subjected to EQ in PWRs around the world.

Table 19: Different containment maximum temperatures and pressures in the enveloping profiles for environmental qualification used in a variety of countries, NPPs and/or Regulatory Bodies regarding DBE service conditions

Country	Max. Temperature (ºC)	Max. Pressure (bar)	Observations	Reference
Belgium	160	4.5	Doel 3&4, Tihange 2&3 units	(European Commission, 1996)
Czech Republic	127	2.5	Harsh conditions EQ for Dukovany NPP (VVER-440)	(Anguera & Weidmüller, 2019; Denk, 2019; Masopust, 2003)
Czech Republic	104	1.2	Temelin NPP (VVER-1000) EQ for HELB sequences	(UMWELTBUNDESAM, 2003)
Czech Republic / Hungary / Slovakia	IEEE 323-1983/ ASME QME 1/ OTT-87		EQ acceptance criteria for installed components post-2003 for VVER-440/1000 NPPs	(Anguera & Weidmüller, 2019; Denk, 2019; Masopust, 2003)
Finland	155	5.4	LOCA/MSLB test for Loviisa NPP (PWR-VVER)	(European Commission, 1996)
India	171	1.9	Transient MSLB profile (most conservative values obtained). ERDA & TAPS R&D (Tarapur 3&4 NPP)	(Kumar & NPCIL, 2012)
India	107	1.47	LOCA chamber test for analogic P/dp electronic transmitters under DBA conditions	(NPCIL, 2012)

Korea	150	5.13	DBA EQ envelopes for Kori 3&4 NPP (PWR-W (WH-F))	(Kwi Hyun Seo et al., 2006)
Romania	150	4	Containment envelopes for Cernavoda NPPs (CANDU-6) in harsh MSLB conditions	(Dinca & Vasile, 2019)
Slovakia	180	4.5	DBA EQ envelopes for Mochovce 3&4 NPP	(Anguera & Weidmüller, 2019; Denk, 2019; Masopust, 2003)
Slovenia	130	3.9	LOCA/MSBL for Krsko (PWR-W) NPP´s FSAR. Envelopes calculated with GOTHIC code under US regulation	(Cavlina et al., 1996; Cerjak et al., 1998)
Spain	172	-	Test chamber combined PWR/BWR profiles	(European Commission, 1996)
Sweden	170	6	Combined PWR/BWR profiles	(European Commission, 1996)
Sweden	260	-	AP1000 containment DBA combined tests profile	(Clark & Fröding, 2014)
Sweden	207	4.5	Ringhals 3&4 NPP first seconds of DBA inside containment	(VATTENFALL & OKG, 2013)
U.K.	200	4.9	2 transients' envelope	(European Commission, 1996)
Ukraine	150	4.41	Ukrainian VVER-1000 NPP fleet common harsh envelope	(Energoatom, 2019)
Ukraine	124	2	Ukrainian VVER-440 NPP fleet common harsh envelope	(Energoatom, 2019)
USA	219	4.1	AP1000 containment DBA (Design Control Document)	(NRC, 2011c; Westinghouse, 2007)

USA	178	4.1	US-APWR EQ Program. Containment enveloping profile for various DBAs	(MHI, 2013)
Worldwide IEEE Std. 323-1974	148.9	4.82	Historically used conservative general criteria for equipment and I&C for damage conditions following steam exposure from 0 s to 10 h	(IEEE, 1974)

Caution note to the reader for Table 6: Each NPP design have different maximum P & T values and enveloping profiles. Some NPP fleets share common parameters or adhere to generic profiles, while other NPPs use plant specific parameters. This is duly noted when possible in the Observations column.

Table 20: Minimal test margins recommended for DBE service conditions in IEEE Std. 323-2016 (International Electrochemical Commission & Institute of Electrical and Electronics Engineers, 2016)

Parameter	Margin	Comment
Temperature	+8 °C	Applied to peak temperature
Pressure	+10 %	Applied to peak gauge pressure profile NOTE Margin on temperature and pressure shall take into account dependence of these parameters for saturated steam.
Total radiation dose	+10 %	Applied to accident radiation dose
Electrical characteristic	±10 % ±5 %	Power supply voltage – margin added up to equipment design limits Line frequency – margin added to rated value
Equipment operating time	+10 %	Percentage value of the period of time the equipment is required to operate following the start of the event
Seismic vibration	+10 %	Value added to the seismic acceleration requirements at the mounting point of the equipment

2.5. Analytic assessment of EQ with computer codes

One of the major contributors to containment safety analyses have been the works and simulations performed in various codes. Regarding DBA analysis of equipment and instrumentation, Lumped Parameter (LP) codes have historically stood out as the industry preferred method to calculate averaged values of temperature and pressure and reflect them into enveloping profiles. Nevertheless, during the last decades, a great effort has been put into the development of 3D containment models, enablers of much more detailed simulations and of different approaches to the derivation of enveloping profiles for environmental qualification.

The basic idea, independent of the election on the approach, is to model harsh environments by thermal-hydraulic codes and include a variety of assumptions to maximize the outcoming variables. NUREG-0588 identified computer codes acceptable for defining these conditions (NRC, 1981) and guides like the ones issued by EPRI (EPRI, 2010) have been paving the way with the definition of the relations between simulated HELBs, outcoming enveloping profiles and location specific equipment profiles within containments of different NPPs.

The main difference between both types of codes and simulations (LP vs. 3D models) is the computational cost, associated in last instance to the modelling idiosyncrasy. LP´s model the containment building with a single or few computational cells and then run simulations under several DBE service conditions to give birth to conservative full-room-averaged values of temperature and pressure. Thus, the idea is to represent enveloping profiles of large volumes with a single-cell approach, totally opposite to 3D-model volumes, which are subdivided in no less than thousands of cells, providing more accurate solutions and accounting for phenomena to which LP codes are blind.

A general review of the types of codes employed by utilities, regulatory bodies, academics and the industry, is given in this section, comparing LP, 3D and CFD codes and giving examples of the outputs generated. This review is intended to complement the knowledge on the technical data displayed in the previous section and to give some insight on the simulations that will be further developed and addressed during the AMHYCO project.

2.5.1. Lumped Parameter approach

To qualify the design of the containment and its equipment against transients and accidents, traditionally Deterministic Safety Analyses within the licensing process of NPPs have relied upon LP codes to simulate conservative HELBs (LOCAs, for peak pressure determination, and MSLBs, for peak temperature, normally chosen as the transients which maximize the Mass & Energy release to the containment atmosphere from the primary and secondary cooling systems) (Phillips et al., 2009; Sehgal, 2012). To conduct the analysis and evaluate the consequences of those harsh conditions on large containment free volumes, normally of complex geometry, LP codes use correlations to simulate the small characteristic length scale physical phenomena on few computational cells that deal with the whole volumes. Therefore, LP codes model large buildings such as containments with reasonable results on global pressure and temperature limits during DBEs and with very low computational effort.

Nevertheless, phenomena as condensation, friction, conduction and convection are dealt in a particular manner. As a result, regulatory bodies and other users of the codes have had to impose biases to fully accept the LP approach and extend it as a custom. The pressure obtained by lumped containment analyses have been historically taken into account to set design parameters like the minimum in-containment free volume or like the thickness of containment walls (NRC, 2015), and the temperature evolution profiles obtained have been also taken into account as references in almost any equipment DBE EQ in the literature.

LP codes possess some hypothesis important to notice and pointed out by many authors (Corradini, 1984; Whitley et al., 1976): instantaneous fluid mixing and interaction of all thermal structures with fluid inside a control volume, no 2D/3D effects of the flow patterns and no forced convections. Accordingly, almost all containment analysis have been performed with this approach (Abdelghany et al., 2004; Duke Power Company, 2004; Ofstun, 2004).

2.5.2. 3D containment modelling approach to EQ analysis

Although LP codes are still the reference approach to perform EQ enveloping profiles in containment safety analysis, the rapid increase in computer resources and in phenomenological knowledge have arose new software tools and higher levels of accuracy, implemented to detail since many years ago in 3D codes, such as GOTHIC or GASFLOW (EPRI, 2014b; Travis et al., 2011). These new capabilities, for example, where used in 1993 to better calculate the thermal impact of a DBA in Oconee NPP and to adequate EQ profiles for MSLB accidents (Tuckman, 1994).However, international organisms also take into account these tools for applications out of DBA analysis (OECD/NEA, 2014a).

These 3D containment models track and analyse physical variables to an extent unreachable for LP models, thanks to adequate cell sizes that can model flow patterns. Comparisons of LP and 3D codes are common and can be found in references like (Bocanegra et al., 2016; Jiménez et al., 2014). 3D approaches have been tested to compare DBA simulation results against safety and EQ limits of pressure and temperature imposed by LP analyses of containments. During transients, pressure is transmitted at sonic speed all over the rooms inside a containment building, so its value becomes homogeneous almost instantly and LP codes and 3D models´ results are similar. However, temperature distribution is more heterogeneous and can result in temperature peaks, local conditions, and invisible to lumped codes, making damage assessment incorrect. These phenomena are due to the slower convective diffusive processes responsible for temperature spreading and to the three-dimensional flow patterns inside the volumes. To accurately account for these phenomena, it is necessary to make up more fine and accurate nodalizations.

Consequently, impulses arise to compare temperature limits obtained by LP models with 3D analyses that account for new parameters and phenomena like room maximum local temperature, 3D flow patterns or heat flux through specific equipment or containment walls. An example of such an analytical comparison can be found in (Jimenez et al., 2017), where EQ limits are assessed, differentiating between full-room average lumped values and GOTHIC 3D room-dependent local and temporal results. Investigations like these have indeed found that lumped analysis can be correct in terms of pressure but can also many times hide local high temperature peaks, an issue sufficiently important to considerate EQ 3D modelling analyses to complement LP ones, because 3D modelled temperatures tend to be higher than that calculated by LP codes.

Many researchers have accounted to the fact that temperature heterogeneity in the containment rooms may make invalid average values of LP models. Early example of this is the work of Cavlina et al. at Krsko NPP (Cavlina et al., 1996), evaluating HELBs with GOTHIC, using the same input data and assumptions, to perform new EQ approaches and include the envelopes obtained in the update of the NPP FSAR/USAR.

On the other hand, many NPPs have formally asked to their regulatory bodies to authorize the use of codes like GOTHIC and GASFLOW in their updated EQ programmes, as was the case of some NRC´s issuance amendments in the early 00´s in NPPs like Fort Calhoun NPP or Cooper NPP (both in the U.S.A.) (NRC, 2004; Ridenoure & NRC, 2003). A detailed methodological construct for analysing postulated PIEs such as pipe ruptures inside NPP containments with the GOTHIC code can be found in (Dominion, 2006).

Figures 10-12 show the difference between a LP approach (MELCOR code) and a 3D one (GOTHIC code) as for obtaining an enveloping profile for containment temperature. The difference is clear on how the nodalization is done and the capabilities of 3D codes to obtain local maximum temperatures against lumped averaged values on the full containment free volume. Indeed, 3D models can derive higher temperatures because they use smaller cell sizes, and the temperature field obtained is heterogeneous because different spaces are nodalizated.

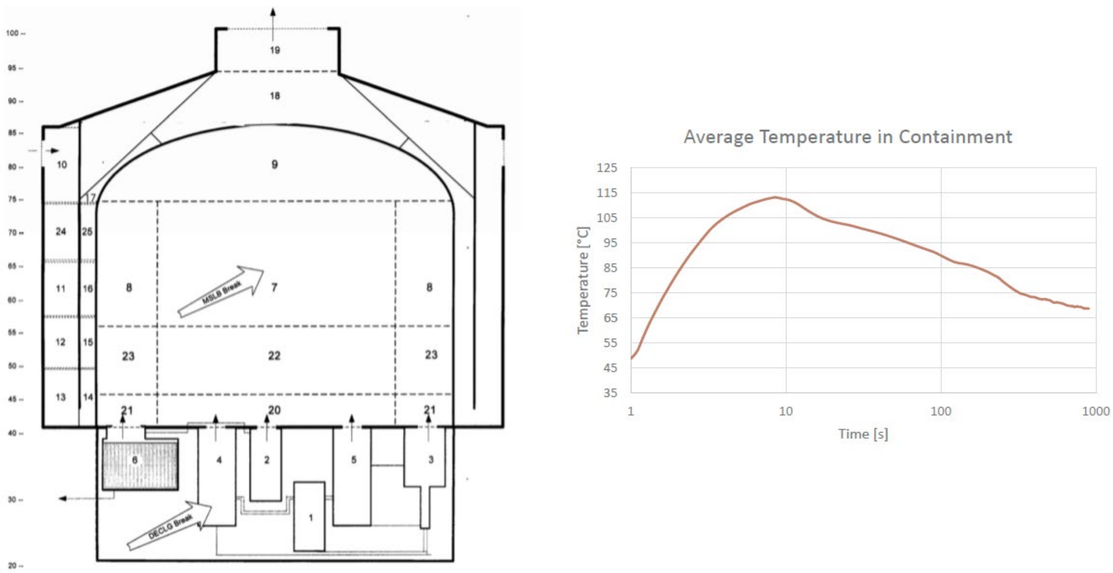


Figure 52: MELCOR based lumped nodalization of an AP1000 containment (Fernández-Cosials, 2017) **and example of the average temperature enveloping profile obtained with lumped approaches (Jimenez et al., 2017)**

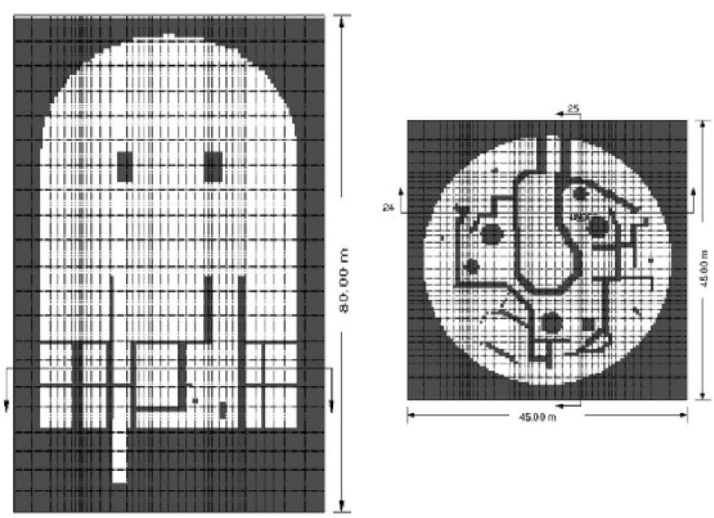


Figure 53: GOTHIC nodalization of a PWR-W containment (Jimenez et al., 2017)

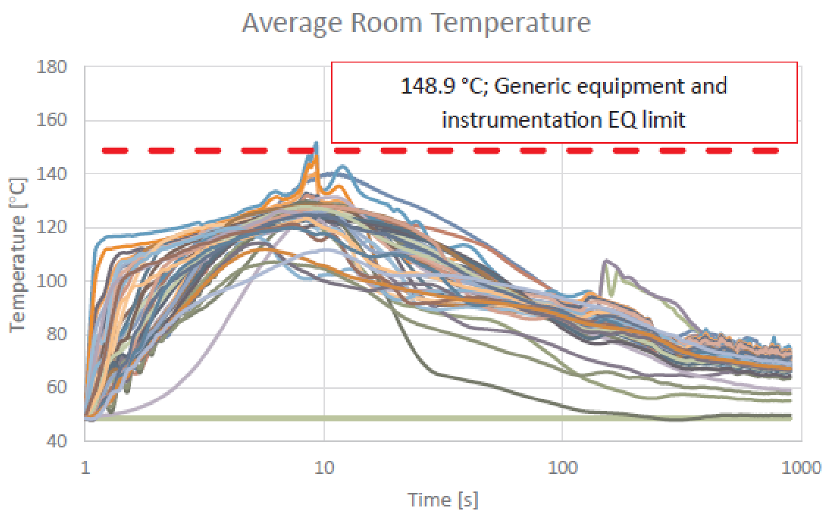


Figure 54: Room average temperature evolution in a GOTHIC based analysis and comparison with standardized EQ temperature limit. Results come from the nodalization also referenced in (Jimenez et al., 2017)

2.5.2.1. CFD codes in EQ analysis

In the last years, industry trends on CFD use for DBA/SA service conditions equipment analyses and containment response simulations have multiplicated, although the excessive computational time that these models require is nowadays still a limiting issue for the implementation of fluid dynamics 3D modelling codes. The capabilities of CFD codes exceed by far the level on which thermal hydraulic containment phenomena are accurately reproduced, involving for example non condensable gases releases, comparing to other 3D model codes as the ones mentioned earlier (OECD/NEA, 2014b).

2.6. Experiments and Industry tests on EQ

Experimental data to validate codes on the performance of many components are derived from ad hoc experimental facilities created to perform combined tests and examine the specifications of multiple specimen types together, for different NPPs, different zones within them and several accident scenarios. Combined testing saves resources and envelope all component harsh service conditions, such as peak maximum temperature and pressure and their durations or shocking evolutions, the effects of chemical sprays and worst case pre/post-accident aging development.

To assess the latter point, sequential tests are to be made to age the component to an end-of-life condition prior to exposure to postulated DBE conditions. From inspection and baseline testing, components must be sequentially subjected to accelerated aging (thermal, radiation and operational cycling aging), vibration and seismic simulations, radiation/T/P/steam accident simulations, post-accident (long-term) simulations and finally to post simulation testing and inspection.

Performing those experiments raises another issue, the qualification of installations used for testing. Shake-tables, LOCA-chambers, irradiation installations, autoclaves, and other related installations need to be accurately calibrated to give birth to reasonable enveloping profiles that can be used as references for industrial EQ. It is relevant to point out that in general, many NPP fleets rely on local sets of those installations to develop the revisions of their EQ programmes and cover their needs. Moreover, those installations are crucial to develop nuclear qualified equipment and boost nuclear industries around the world. Figure 13 displays some images of the aforementioned installations.

Industrial technical services play a vital role helping upcoming and operating NPPs in taking appropriate decisions in areas such as (TECNATOM, 2010):

- Standardization of new engineering hardware and their procurement
- Estimation of residual life and qualified life extension of installed equipment
- Failure analysis and reliability improvement
- Import substitution
- Generation of alternative spare parts
- Equipment and instrumentation redesign or refurbishment of obsolescent items

On the other hand, some testing installations enable a sound comparison between analytical results and real phenomena, e.g., the study of synergistic effects of combined environments prevailing simultaneously in NPP containments. These facilities are comprised of temperature humidity chambers and gamma radiation sources along with provisions for applying electrical stresses. An example of a synergism simulator implementation can be found in (BARC HIGHLIGHTS, 2007).

An example of an schedule of accreditation for an installation with a chamber to perform LOCA, MSLB and HELB tests can be found in (ENAC, 2014; TECNATOM, 2010), where typical test variables and configurations are enumerated. Temperature and pressure in these chambers shall be controlled to meet the requirements of plant specific HELB profiles and it is generally important to keep the values above plant ones (Kim, 2013).

Figure 14 shows a comparison between typical planned temperature and pressure enveloping profiles during a testing EQ program for all type test sample configurations, and the actual profiles measured during the environmental exposures during the various sequential tests performed (TYCO, 2004).

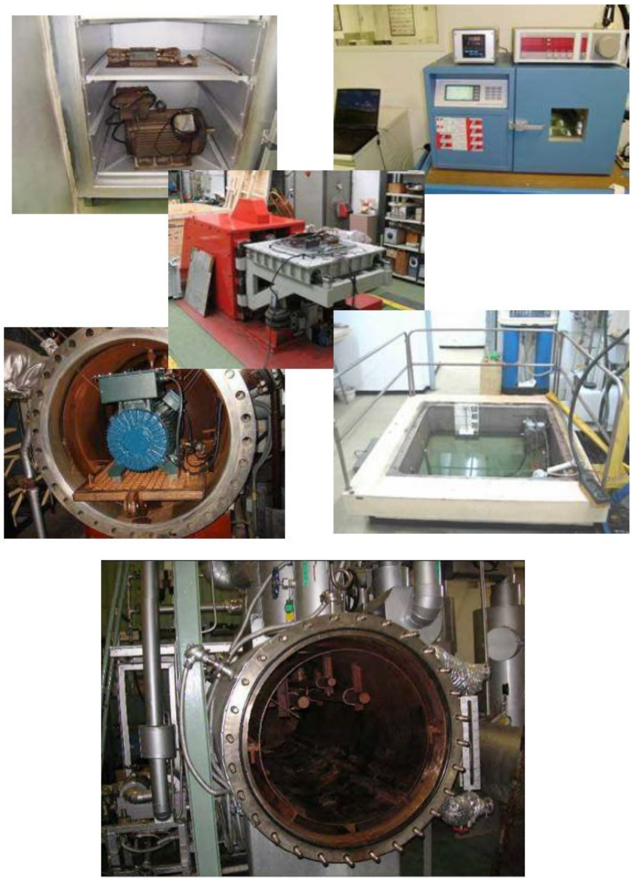


Figure 55: Examples of testing installations to perform combined and type testing experiments and test sequences. Up: thermal and aging chambers, seismic shake-table, LOCA chamber and irradiation facility (taken from (TECNATOM, 2010)). Down: DBA accident simulation test chamber (taken from (Gonzalez, 2012))

Since TMI-2 accident, U.S. regulation and international standards began to address much deeper the issue of EQ of safety-related electrical and mechanical equipment, although regulatory interest was already present in NRC and other organisations. The main issue that was raised is that the operators shall need to be assured that the safety related equipment would perform its intended function in the unlikely event of a DBA, allowing for the prompt mitigation of the event.

The numerous programmes and the industry development on EQ have enabled professionals of the nuclear sector to learn some important lessons on the matter, regarding various vital items of electrical and mechanical safety-related equipment and components (Castleberry, 2012; SCHULZ & Dean, 2019).

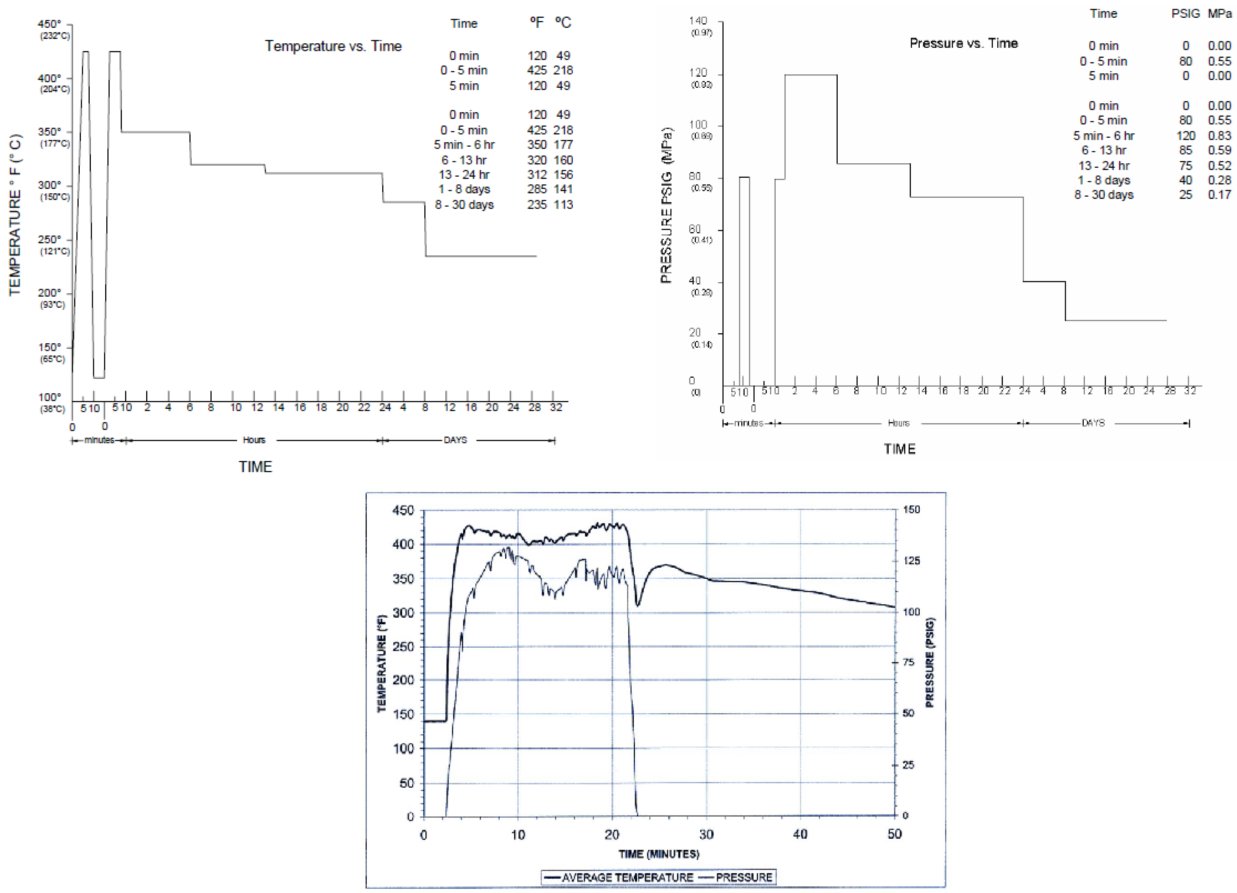


Figure 56: Comparison between planned and real outcome enveloping profiles of T and P during LOCA camber testing for requalification of electrical components (TYCO, 2004)

2.6.1.1. Seismic testing principles

All safety-related components must be able to withstand the effects of postulated earthquakes without losing their capability to perform safety functions. For equipment to be qualified to that scenario, a seismic categorization of every sensitive component has to be made, demonstrating their seismic and dynamic capability by analyses (usually limited to structural capability), operating experience methods (to qualify basing on historical data records on a case-by-case basis) or tests like those performed on devices such as seismic shake-tables (see Figure 15). To create envelopes like the one showed on section 1.1.6., it is necessary to perform single- and multi-frequency tests, preferably in 3D vibratory schemes, to account for complex equipment operability during OBEs and SSEs.

Figure 57: AREVA´s seismic shake table with three orthogonal vibratory motion, (from us.areva.com)

2.6.1.2. EMC testing principles

To evaluate the impact of EMI/RFI interference on equipment, many regulations address the range of test and analyses that have to be performed on sensitive equipment. Some of these tests are the following:

- Susceptibility tests of low/high conducted and radiated magnetic and electrical fields
- Surge tests to verify equipment ability to withstand high-energy overvoltage conditions on power lines due to switching and lightning transients
- Electrically-Fast Transient or Burst Tests on repetitive burst on signal and control cables due to switching transients created by inductive loads and relay contact bounces
- Electrostatic Discharge (ESD tests)
- Emissions tests to limit harmonics emissions on power cables

2.6.1.Examples of nuclear class qualified components

In this subsection, a few examples of electrical and mechanical equipment components (motor operated valves, differential pressure transmitters, etc.), qualified under the standard regulations already reviewed, are shown, as technical instances of nuclear qualified items that have followed environmental and seismic qualification programmes to meet the requirements of normal and accidental conditions in current and future NPPs. Detailed information is displayed in Annex C.

2.7. New Qualification approaches

Since the first industry EQ tests performed in the late 60´s, with programs focused only on in-containment qualification in response to LOCA´s, not including aging simulations prior to accident test and therefore not focusing on LTO related scenarios, many efforts on refinement of EQ approaches have been undertaken, although the fundamental principles of EQ have largely remained unchanged. Nevertheless, during the last decades, the previous needs of qualification have shifted (Gonzalez, 2012).

Some of the originally installed equipment in many NPPs had a qualified life of less than 40 years, for what **extension of qualified life** approaches have had to be developed, establishing a new qualification target. The process would be that of evaluating components and equipment with the lapsed qualification to assess if life extension is feasible and then for example apply accelerated thermal aging to those naturally aged components in plant, to validate a new qualification life aim. The new EQ undertaken for these items would be a process equal to the DBE and seismic processes previously reviewed in this document.

On the other hand, some items may had been originally qualified under criteria nowadays out-of-date. For that issue, NPPs and engineering associates contemplate reviewing current qualification and refurbishing the equipment to meet the possible new most severe regulations. Then, to **update original qualification**, it is necessary to set out the new service conditions and qualification requirements and with that, renew an EQ testing program to evaluate equipment with the goal of verifying the adequacy of revamping the components. It will be also necessary to implement possible new redesigns in the new test subjects to completely validate the re-qualification and to further implement the updates in the already installed equipment.

Other issue raised is the scarcity of original spare parts for safety-related equipment and its impact in EQ maintenance programmes. The solution can go through the **generation of alternative spare parts** qualified to maintain the current status of the concerned components. Going further, in many cases the problem is to find whole new qualified equipment, either for EQ inconsistencies or for costs issues. Newly, the solution of a specific plant or enterprise can be to **generate new qualified equipment**, considering material studies and limits to manufacture a redesigned equipment that can be easily subjected to the current standards.

Many safety-related sets of equipment are obsolete, or their qualification status can no longer be considered as of nuclear class grade. To face this, an approach is to simply **implement alternative commercial grade equipment** by technically evaluating and verifying the ability to meet safety functions and the pass the equipment through a standard EQ program for its acceptance.

Lastly, facing the aging of critical components like cables inside the NPP fleets, regulatory bodies and enterprises viewed the necessity of developing some sort of indicators to measure the actual capacity of these components to withstand a DBE. This last approach is known as **Condition-based Qualification** and indicates the level of degradation (QLD) that a sample can withstand while maintaining the ability to overcome abnormal and accident scenarios. Those indicators would measure several representative values such as strain or elongation stresses, in the case of cables, during the qualification period over additional samples extracted in equivalent stages of aging of 5-10-15-20 years, and so on. Thus, an evolutionary profile of each indicator or parameter during aging history is obtained and with that the final levels of QLD as a reference of DBE degradation.

After compiling degradation envelopes of selected parameters, the next step takes place within the plant by means of a test/experimental program using monitoring techniques over naturally aged samples, out of service or in-service. Some of the tests performed to observe the degradation evolution of a property are: visual and tactile inspections, elongation at break tests, induced oxidation time/temperature measurements or thermogravimetry analyses (TGA). Figure 16 graphically extends the concept of condition-based qualification for DBE scenarios.

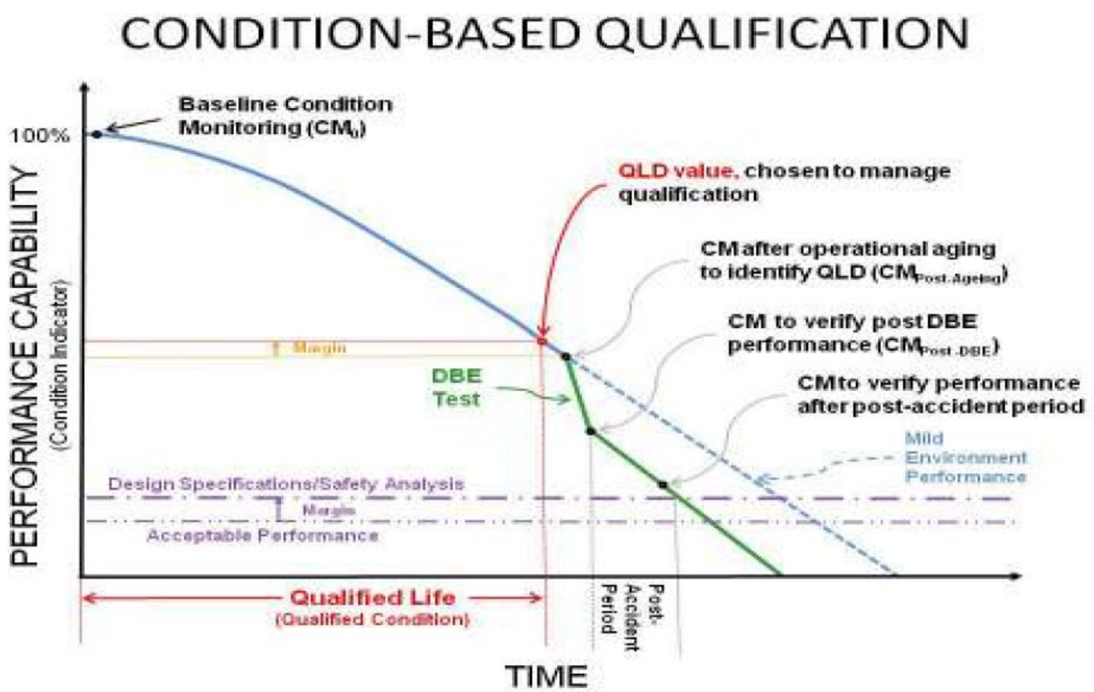


Figure 58: Condition-based EQ criteria (Gonzalez, 2012)

3. Containment equipment and instrumentation Survivability Assessment on Severe Accident scenarios

This chapter deals with the basis for survivability assessment of equipment and instrumentation during the Design Extension Conditions (DEC) and their phases, namely early and late phases of Severe Accident scenarios. The bulk of this state-of-the-art review will be devoted to exploring the criteria developed during SA environmental conditions, which can exceed the environmental parameters presented in DBE-EQ. The analytical tools and experimental tests applied to this field of nuclear safety, are also to be expounded in the next subsections. Many of the concepts and principles reviewed in the first section of this report will be revisited and will act as thoughtful comparisons between DBE and SA qualification fields.

The purpose of the technical data compiled within this section is to be also a repository of equipment and instrumentation qualification principles as well as a SOAR guide concerning the wide range of analyses and technical approaches to the problem of safety-related items availability assessment. The limiting values that play a role in this enterprise will be reviewed primarily for the sake of PWRs (Western type, KWU and VVER fleets) containment qualification programmes, and will stand as a reference for the comparison of real plant-specific values versus analytical or theoretically derived variables. Moreover, simulations conducted in future WPs of the AMHYCO project, will benefit from the information contained herein, which can be regarded as a general survey of damage and survivability criteria for a variety of important items under a rather significant range of accident scenarios.

3.1. Principles of Survivability Assessment under DEC/SA criteria

During a Beyond Design Basis Accident or Event, scenarios recently renamed by institutions like IAEA and WENRA as Design Extension Conditions (IAEA, 2017b) (IAEA-TECDOC-1982, 2021), and specifically during SA scenarios, the environmental conditions may affect the equipment and instrumentation performance. Some of those items are used to mitigate the consequences of the accidents and its correct functioning or interpretation can make a substantial difference in the accident development.

A SA, normally evolves under profiles of temperature, pressure and other variables that can be considerably harsher than those from the enveloping profiles used in DBE-EQ. An useful reference that comprises the experience on assessing those harsher conditions and the relation with the capabilities required on electrical and I&C equipment to perform reliably during severe accidents can be found in (IAEA, 2017a). The DEC/SA conditions and impact are assessed under the equipment and instrumentation survivability area, on which all items prone to be used in a severe scenario are identified and their availability is analysed. Thus, equipment survivability surveillance may be defined as the obtention of a reasonable level of confidence on the equipment mitigative function in an SA during the time span required (SNPTC, 2012).

Several methodologies are available today to study survivability during a SA and many of them categorize the accidental events into different time frames where each instrument is evaluated in terms of failure and damage level (Arcieri & Hanson, 1991; Fernández-Cosials et al., 2020; Hanson et al., 1994), for a better interpretation of the information needed during accident sequence phases and a clearer depiction of the relationships with the safety objective trees and also with SA Management Guidelines (plant instrumentation provides a vital link between SA conditions inside the plant and the decision making process in SAM activities) (Queral, 2020). In this procedural way, it is easier to identify and study Candidate High Level Actions (CHLA) to arise during a SA and whether they might be fully covered by the instrumentation required over the whole accident, after the transient development of the incident.

On the other hand, to obtain in-containment parameters and to analytically study survivability under extreme conditions, many plant codes have been historically used. These SA codes are capable of simulating relevant phenomena related to the Primary and Secondary Coolant Systems and the containment atmosphere behaviour. Also, they provide accurate information about the environment surrounding the different elements and instruments subjected to conditions such uncertain as for example a Molten Core Concrete Interaction (MCCI) scenario. Nevertheless, instrument failure will not be explicitly provided by the simulations, as instruments are tested to just satisfy the enveloping profiles that apply in each case. Nowadays, the most commonly used plant codes that can obtain SA conditions are MELCOR, ASTEC or MAAP (OECD/NEA, 2014b).

An example of the implementation of various theoretical approaches to the field of equipment and instrument survivability assessment can be instanced on the studies developed after the Fukushima accident (OECD/NEA, 2015). During the Station Black-Out and external flooding that occurred at Fukushima-Daiichi NPPs, a harsh environment was created and the availability of most of the safety-related elements and I&C was challenged, hampering the adequate interpretation of critical instrumentation, which although malfunctioning still was a vital source of information (Clayton & Poore, 2014). The role of available instrumentation performing their safety-related functions at those conditions would have been vital to reconduct the accident and mitigate the latter consequences (TEPCO, 2017).

That outstanding demonstration of the importance of a proper qualification of equipment and instrumentation used for SA mitigation is still nowadays a challenge for the nuclear power community, who has identified that the assessment of equipment, instrumentation and penetrations performance during DEC conditions is one of the key gaps in nuclear safety knowledge to be filled (Farmer, 2015).

As a reminder of the current view on Plant Design Envelopes within DEC/SA approach concepts, Figure 17 shows the evolution of the BDBA to DEC concept:

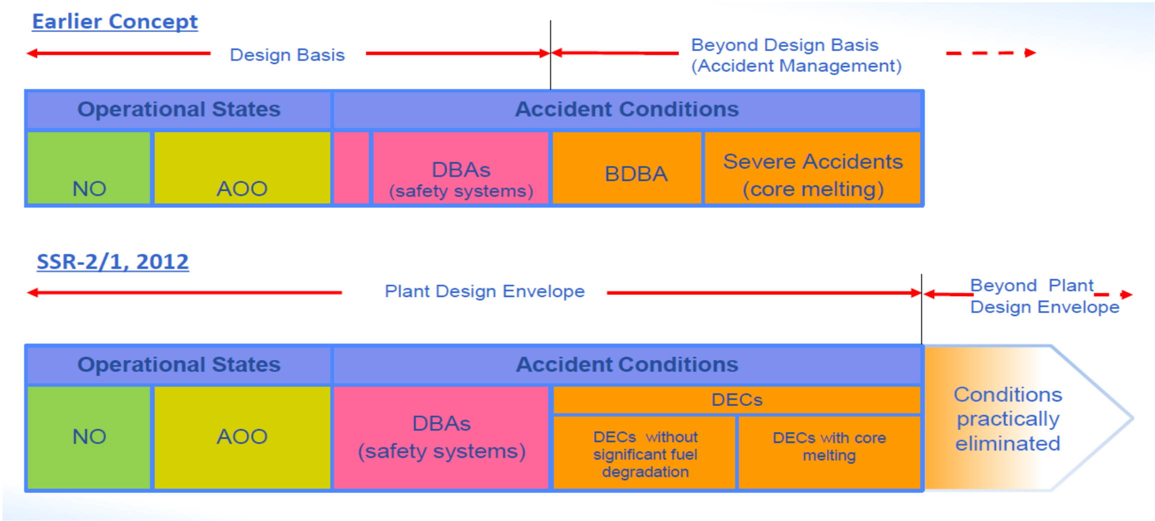


Figure 59: Evolution of SA and DEC concept (taken from (Kral, 2018))

3.1.1. Functional requirements and performance criteria

General recommendations for electrical and I&C equipment, for instance monitoring equipment, regarding their functionality during and after severe accidents can be found in Safety Guides like (IAEA, 2016), where it is stated that equipment might be protected against the effects of severe environmental conditions resulting from a DEC and that that level of protection may be achieved by physically separating the items, installing them at safer locations or shield them against the negative phenomena.

Nevertheless, adequate protection may not be feasible, thus being necessary to subject equipment to capability assessments to assure reliable performance under severe conditions. Those assessments need to consider availability, accessibility, functionality and location of the safety-related items, the uncertainties surrounding loading parameters and also the degree of acceptability towards degraded performance after exposure to the harsh conditions. Instrument accuracy or cable insulation resistance are examples of the output variables that comprise the functional requirements list.

With a sufficiently robust assessment, prediction of performance in advance is made easier in terms of interpretation of measured values and actuations, also enabling trustworthy protocols on the possibilities to repair or replace items or on the lecture of alternative sources of signals, in a severe accident scenario. For example, entire instrument loops may be affected, and the design limits can be exceeded with higher probability the higher the duration of the event, giving birth to signal oscillations, over or underestimations, but also to complete failure.

This fact gave rise to preplanning the identification of alternative signals in the accident mitigation procedures and guidelines, for the operators to be able to identify degraded equipment and relate the strange readings or malfunctions to the environmental conditions presumably present in the location of interest. Then, it is vital to provide methodologies for addressing the usability of existing plant equipment and I&C during severe scenarios. EPRI´s technical report TR-103412 gives interesting conclusions on the development of such methodologies (EPRI, 1993).

The main functional requirements for mitigating equipment in these kind of assessments can be summarized in the next points (IAEA, 2017a):

- **Confidence in instrumentation readings and equipment functions**: as performance criteria that takes into account the validation of measurement values by crosschecking with measurements of available alternatives and with modelling estimates.
- **Reliable performance criteria:** including functionality, accuracy and response time, which can be derived from the intended safety functions and may be treated with several degrees of relevance.
- **Long-term functionality**: more relevant than the accuracy attained because replacement during and after a DEC might not be feasible, although a minimum degree of accuracy will always be needed for proper decision making in the frame of the mitigation strategies.

For instrumentation, specific criteria are to be met in order to achieve reliable performance (IAEA, 2017a):

- **Instrumentation measurement range**: determined to cover all accident conditions including expected stages of each scenario. Severe accident conditions may extend DBA qualification ranges to account for uncertainties and to cover margin boundaries.
- **Instrumentation accuracy:** its degree of importance has to be determined against other criteria such as trend indication, although accuracy requirements have always to be specified towards each SAM strategy. Accuracy needs to be sufficient for measurements uncertainties not to cause trending information to be ambiguous.
- **Update frequency**: adequate frequency to avoid misleading operators.

- **Instrumentation response time**: since equipment and I&C will provide information in different stages of the accident, response time have to be commensurate with the most demanding mitigation strategy. Early stages of an accident demand shortest response times.
- **Instrumentation mission time**: established based on the intended functionality within the framework of the appropriate mitigation strategies. Mission times vary for each item and their active and passive phases can be derived from the analyses of the different stages of an accident. This is fundamental to divide SAM strategies into several stages of response and to reassess design and qualification requirements imposed on dedicated equipment.

Finally, it is possible to develop specific qualitative acceptance criteria although it is more important to demonstrate that equipment and instrumentation remains available and is providing the required functionality. As stated in (IAEA, 2017a), an example might be that of a reduction in measurement accuracy at an acceptable level over the demonstration that the instrument is able to retain its functions under SA conditions, giving information on the trends of important parameters for days.

3.1.2.Severe Accident environmental profile parameters

As was the case of environmental qualification for Design Basis conditions, in a Design Extension scenario it is of the utmost relevance to identify the conditions affecting instrument and equipment availability. For severe accidents, the parameters of interest are hereditary from those arising in the previous transient stages, being nevertheless, generally harsher in the early phases and milder in the long term. Thus, environmental profiles depicting those variables versus time have to be derived, either from real severe accidents or from severe accident condition simulations, taking into account the installation location of each item.

These profiles should show that parameters during a DEC/SA vary during the different stages, due to ongoing physical and chemical processes inside the reactor and the containment and may indicate higher values than those anticipated in a DBA assessment. To fulfil their mission, some points have to be regarded during their development, such as estimation of durations to develop mission time dependent profiles, potential recurrence of specific phenomena like MCCI, flooding or H2 combustion, combination of materials and compounds that can have degradation effects and radiation profiles that could be anticipated.

The variables and conditions that characterize the onset of a SA can be categorized as follows (I. Basic, 2015; IAEA, 2017a):

- **Harsh pressure, temperature and humidity**: resulting from mass and energy releases during the accident or due to lack of appropriate actuations. These are the most common parameters that cause instrument performance to degrade. To give a figure, Slovakian PWR VVER-440 of Mochovce NPP is expected to bare conditions of 215 ºC, 5.2 bar and 100% humidity (Tengler, 2012).
- **High radiation fields**: the loss of capability to cool the core can eventually lead to a fission product release into the containment atmosphere, not only elevating the previously mentioned parameters, but also impeding access to instruments, equipment or sampling stations located in the different buildings. The main contributors of the field are beta and gamma radiation, which cause additional heat up on the equipment surfaces and influence their degradation.
- **Flooding and submergence**: consequence of an interfacing system event such as a LOCA or of a mitigation strategy, it may very well have an impact on the functionality of electrical items. The effects of the hydrostatic pressure and the contact with radiologically contaminated coolant can be fatal, but on the other hand, temperature spikes and gradients would be significantly avoided.
- **Electrical power failure**: it can result from an SBO, the loss of a DC bus or other interruptions, causing active safety-related countermeasures to be unavailable.
- **Explosive atmospheres**: H2 & CO generation and release are crucial phenomena to be considered in the profiles and SA assessments, as if an uncontrolled combustion occurs, equipment and containment structures may be exposed to extreme peaks of temperature and pressure which will challenge their function and integrity. PARs and igniters are dedicated equipment aimed at reducing those risks.
- **Chemical processes**: derived from the significant chemical composition changes developed in the containment atmosphere and sumps during a SA, as a consequence of the release of gases, aerosols, chemical compounds and degraded materials. These processes can be challenging in terms of chemical degradation of equipment and instrumentation insulating, or sealant, materials.

These parameters will comprise the output of the different calculations performed to estimate representative environmental characteristics for equipment performance and will be the basis of the test profiles defined based on the results of the modelling of severe accidents.

3.1.3. Process for the demonstration of reliable performance in DEC/SA conditions

As in the case of DBE EQ, a general process for assessing equipment capability to perform reliably under severe accident conditions must be defined by the professionals responsible for the evaluation of equipment and I&C survivability in an NPP. As stated in the latest IAEA´s SOAR on Equipment Capability (IAEA, 2017a), a general process for equipment capability or survivability assessment should include the next considerations to increase the robustness of the plant electrical and I&C equipment for mitigating a SA and enhance the overall plant safety:

- Surveying and evaluating available information on assessment of reliable performance of equipment as described in international technical reports, codes and standards.
- Describing the assessment process that demonstrates the capability of the equipment to perform reliably.
- Evaluating the impact of specific environmental effects typical for severe accidents, such as temperature spikes as a consequence of H2 combustion, high radiation levels caused by the release of active material from the melted core, atmospheric conditions in the containment after the possible quenching of the melted core, and corium concrete interaction.
- Evaluating the impact of specific environmental effects at individual equipment installation locations.
- Extract the SA environmental conditions of the plant based on the specific plant design.
- Developing the general approach for assessing the reliable performance of the equipment. This approach may include equipment type testing, assessment of equipment survivability comparison with previously tested equipment and evaluation of existing margins that may be available from previous qualification testing.
- Identifying alternative measures if the equipment performance is not sufficiently reliable.

To achieve an effective approach of evaluation of equipment and I&C availability, each NPP or regulatory body may develop a specific process for the demonstration of performance at each stage of the DEC/SA conditions subjected to evaluation. To give an example of that approach, the next five-step program for instrument availability, extracted from (I. Basic, 2015), is presented in Figure 18. Furthermore, Figure 19 depicts an example of sources of information that are needed for defining the scope of equipment subject to assessment for severe accidents (IAEA, 2017a).

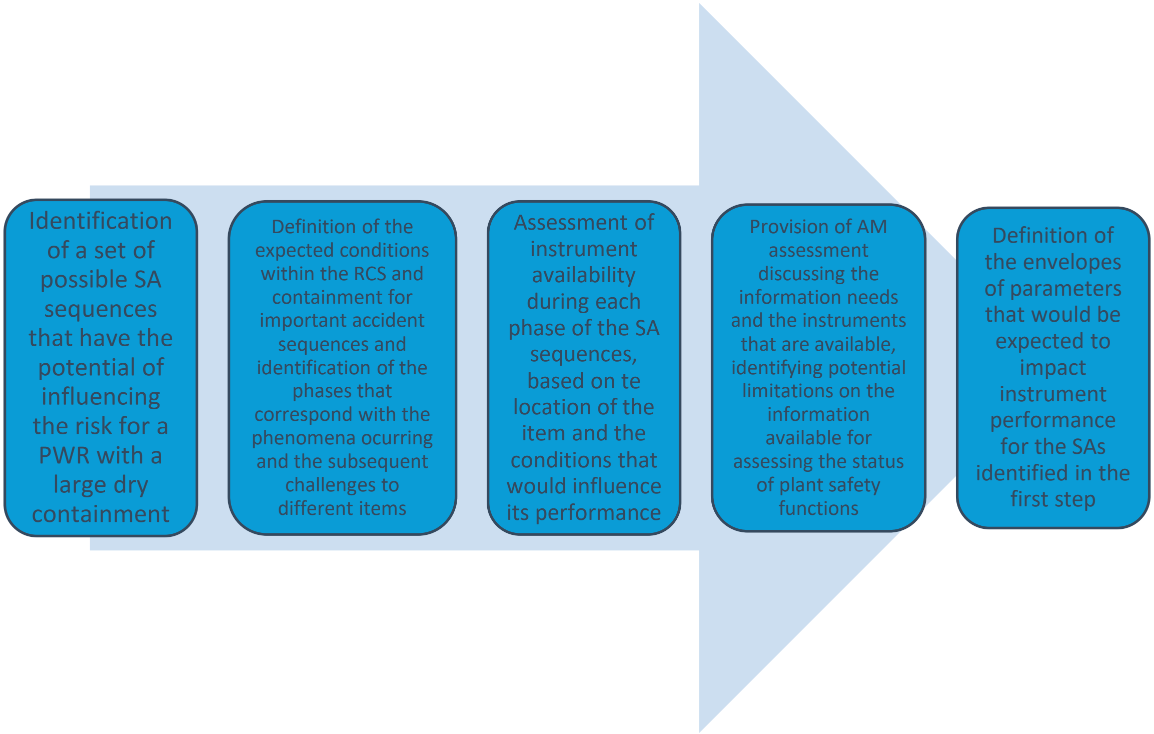


Figure 60: 5-step program for instrument survivability assessment (Basic, 2015)

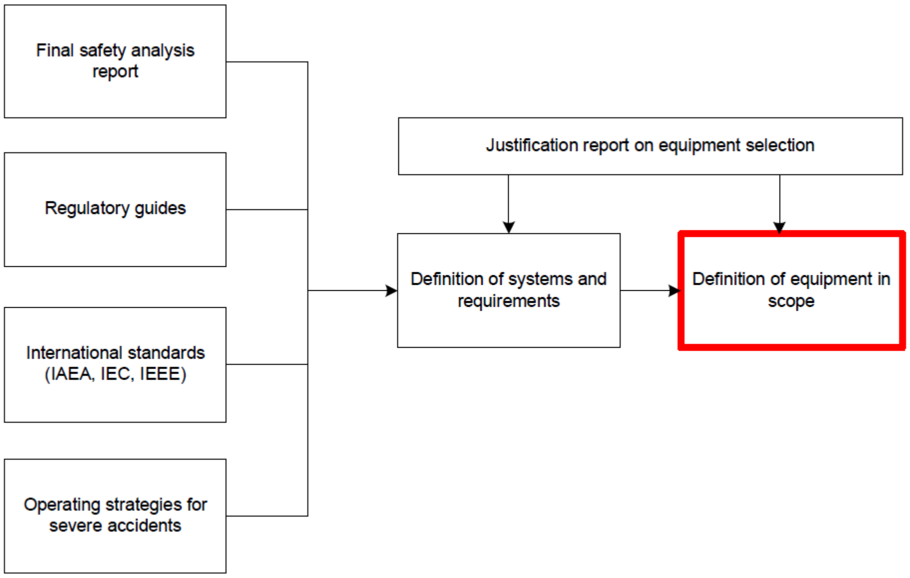


Figure 61: Sources of information needed for defining the scope of equipment subject to assessment for SAs (IAEA, 2017a)

3.1.4. Methodologies for Equipment Survivability Assessment

The methodologies presented in this section do not form part of any regulation and are just technical approaches to the field of survivability assessment.

An important issue when assessing all of these parameters and conditions is to understand the progression of a BDBA/SA or DEC scenario and the order of response activities within the framework of mitigation strategies. Each stage of the accident progression is associated with its own SAM strategies and set of environmental parameters, as shown in Figure 20, where a typical example of accident stages and associated environmental parameters in a PWR SA are depicted. That relationship between stages of the accident and relevant environmental parameters is worth to be dissected. An illustrative example may be the one discussed in (IAEA, 2017a):

- In the **First Stage**, parameters in the same range of those expected in a DBA, are associated with unsuccessful implementation of measures to mitigate an initiating event.
- In the **Second Stage**, parameters that can exceed limits anticipated for a DBA, are associated with SAM measures for preventing high pressure gradients and loss of containment integrity.
- In the **Third Stage,** the initial stages of core melt are developing, and temperature, pressure, humidity, radiation and concentration of combustible gases reach their maximums.
- In the **Fourth Stage**, stabilization of the melted core and preservation of containment integrity for a long-term period are as expected as a decrease in the leading parameter values, except for radiation levels which may be longer lasting.

On the other hand, in order to assess the equipment and I&C survivability under the enveloping parameters typical in a DEC/SA scenario, several methodologies have been established in different countries and for different NPP fleets to set the scope of the beyond basis eventualities and parameters. Most of these methods followed the rather trend setting works of (Arcieri & Hanson, 1991), where the accident is separated into different time zones on which damage conditions would be evaluated. This staged approach was based in a similar fashion as to the four stages dissection reviewed in the previous subsection and was looked over by the same authors several years later, defining a five step approach for large dry PWR containments (Hanson et al., 1994). The steps went through an examination of the credible accidents and their relationships to plant safety functions and safety objective trees, determining the necessary information for SAM measures, following a determination of instrument capability and conditions expected, and ending with an availability evaluation.

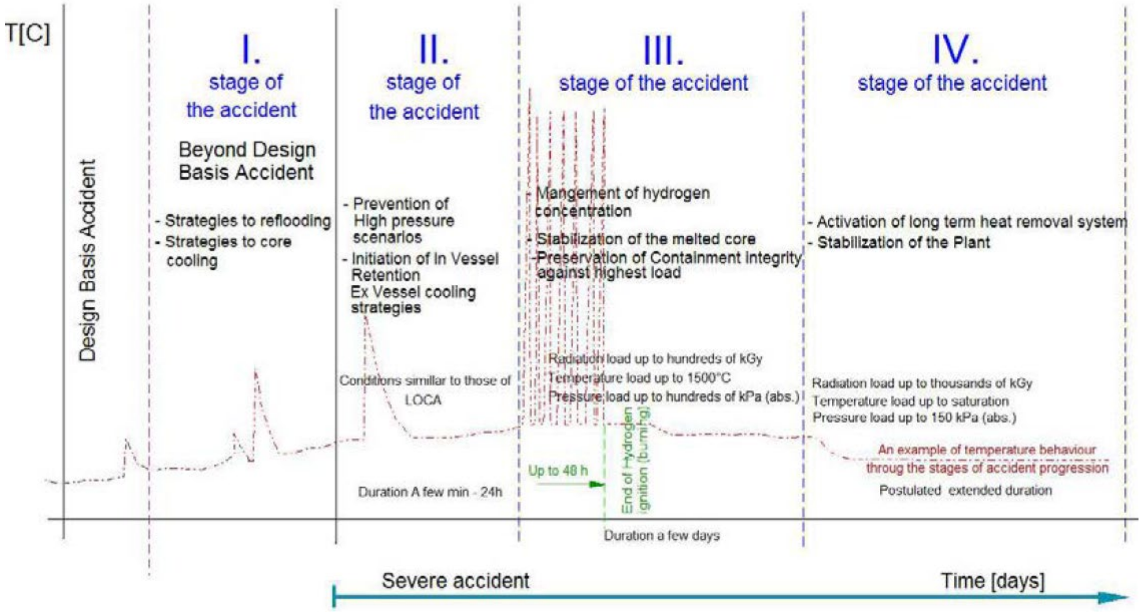


Figure 62: PWR SA typical accident stages and associated environmental parameters (IAEA, 2017a)

Table 21: PWR SA typical accident stages and associated environmental parameters (IAEA, 2017a)

Plant condition (SA) / Environmental conditions within CV	SA1 Fuel damage ↓ Melt RV integrity is sound CV integrity is sound	SA2 Fuel melting RV is damaged CV integrity is sound	SA3a Fuel melting RV is damaged CV is damaged	SA3b Fuel melting RV is damaged CV is damaged
– Max-temperature	– 190 ^{0}C	200 ^{0}C	– 200 ^{0}C	– 300 ^{0}C
– Pressure	– 0.414 MPa	1.6 MPa	– 1.6 MPa	– Atmospheric pressure
– Humidity	– 100%	100%	– 100%	– 100%
– Radiation	– Below the conventional PAM's environmental conditions	– 2MGy/year (an annular space is 5MGy/year)	– 2MGy/year (an annular space is 5MGy/year)	– 2MGy/year (an annular space is 5MGy/year)
Environmental conditions outside CV				
– Max-temperature	– Ambient temperature	– Depends on the installed location	– Depends on the installed location	– Depends on the installed location
– Pressure	– Atmospheric pressure	– Atmospheric pressure	– Atmospheric pressure	– Atmospheric pressure
– Humidity	––	––	––	––
– Radiation	––	– Depends on the installed location	– Depends on the installed location	– Depends on the installed location
A required functional duration	More than 80 hours			N/A

Other studies, such as (B. C. Lee & Jeong, 2003; Murata et al., 2016), subdivide the SA in four and five timeframes respectively, following the accident progression based on the core state and then identifying the environmental role parameters for equipment survivability. Westinghouse also performed an important study for the licensing of the AP1000® (Scobel & Powell, 2017), where equipment types and locations were identified, the survival times required were assessed and then the calculations of the SA environmental conditions to justify survivability were made, comparing the modelled thermal hydraulic conditions for the representative severe cases with the acceptance criteria developed from EQ testing and large scale hydrogen burn equipment testing (Achenbach, 1985). An example of a H2 source term envelope used in the equipment survivability analysis of the AP1000® is shown in Figure 21.

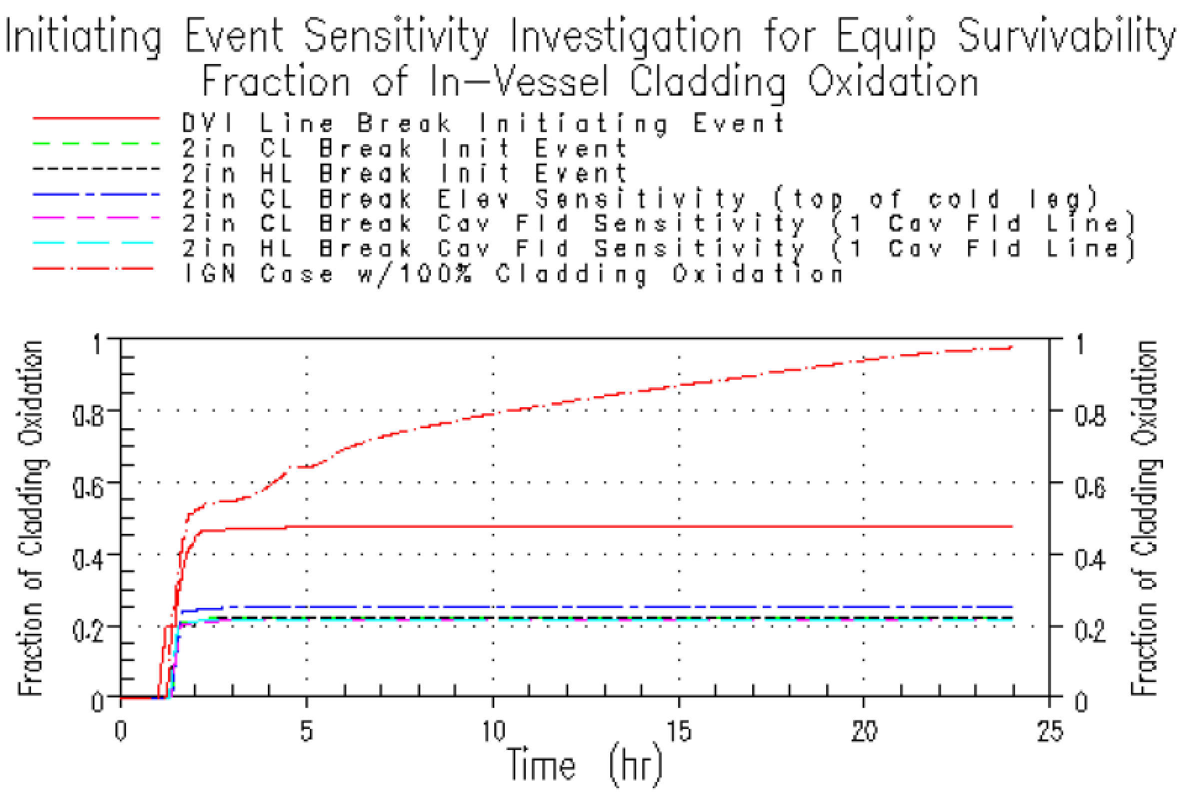


Figure 63: H2 source term envelope for 100% cladding oxidation used in equipment survivability analysis of AP1000 and comparison with source terms from multiple scenarios (Scobel & Powell, 2017)

Another interesting approach, similar to the Westinghouse one, is the development of an assessment more focused in the control room point of view, walking through the accident stages while comparing the requirements in the SAMGs relative to equipment and I&C and their degradation level. That methodology, found in (Fernández-Cosials et al., 2020), is based on the identification of Candidate High Level Actions and monitoring parameters referenced in the Severe Accident Guidelines and Severe Challenge Guidelines and their temporal zones of application, listing also the items needed to perform those actions. Then, five different states of degradation, ranging from normal operation to destruction condition, are defined and related to the reliability of measurements, which influence the use of a safety-related instrument over another. Finally, evolution of survivability across the accident is assessed, simulating severe accidents by code and then checking each CHLA and parameter profile against the degradation levels defined.

This last approach will serve here as a final example of an application of survivability assessment methodology to a SA, specifically a LBLOCA with recirculation failure, as an introduction to the issues discussed in sections 2.3 and 2.4 regarding Survivability Assessment technical data for different NPPs and the analytical assessment with computer codes in this field. Annex III of IAEA TecDoc 1818 (IAEA, 2017a) is also referenced, where a general example of the mapping of environmental parameters inside and outside the containment during a severe accident, for a French PWR 1000 type reactor, is depicted (see Figure 24)

Figure 22 show the temperature enveloping SA profiles for different plant locations derived from a MELCOR model applied in (Fernández-Cosials et al., 2020) and adapted from a previous work (Martin-Fuertes & Fernández, 1994). The proposed range of damage level conditions for equipment and instrumentation is shown in Figure 23. That range draw from several useful references regarding damage conditions on generic PWR-W instrumentation, which give an important insight on margins of conservatism historically set on temperature, pressure and radiation values (EPRI, 1993; Giot et al., 2017; Rempe et al., 2015; Rempe & Knudson, 2013).

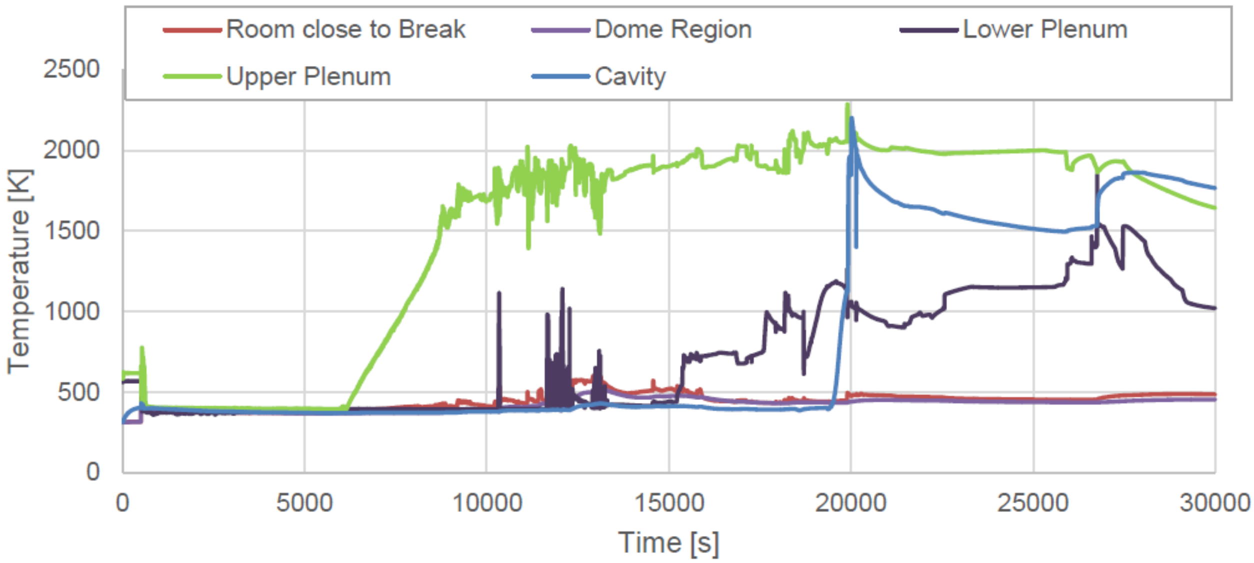
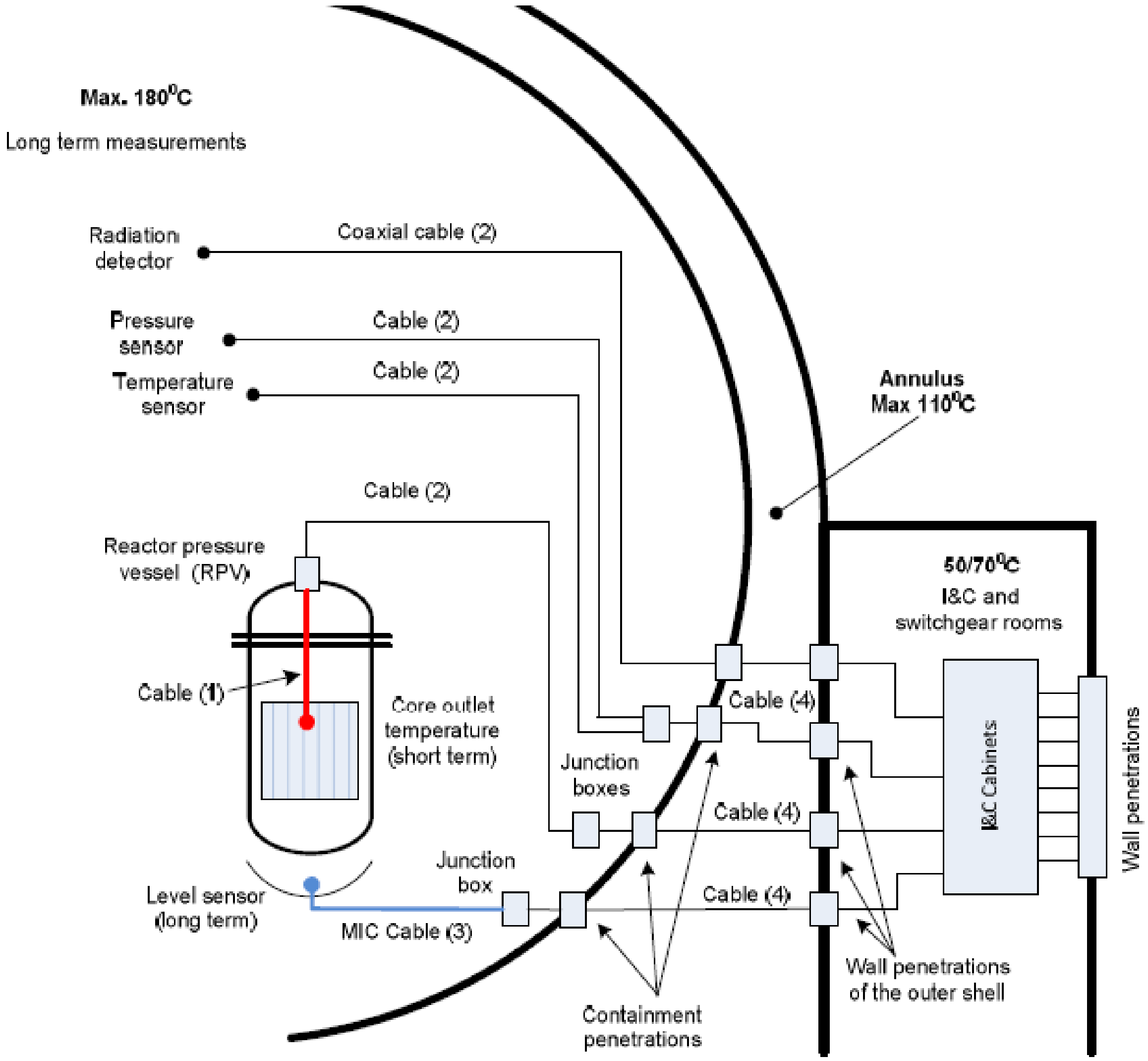


Figure 64: Example of PWR MELCOR simulation output of environmental profile of temperatures for a LBLOCA with recirculation SA, for survivability assessment methodology analysis purposes (Fernández-Cosials et al., 2020)

Damage Condition 0	Normal Operating Conditions
Damage Condition 1	**Anomalous operating conditions I**. The operating conditions are challenging or above the design, but useful measurements in tendency and values are still obtained.
Damage Condition 2	**Anomalous operating conditions II**. The limit is greatly surpassed, and measurements on value are no longer valid. The information on tendency and order of magnitude is still useful.
Damage Condition 3	**Damage Operating Conditions**. The instrument measurements are only reliable in terms of tendencies, not values or orders of magnitude.
Damage Condition 4	**Destruction Conditions**. The measurements lack of any value and they should not be used at all.

Figure 65: Example of methodological approach to the range of damage level conditions for survivability assessment of equipment and instrumentation (Fernández-Cosials et al., 2020) (Fernandez-Cosials, , January 2022, 11155)



No.	Designation	Temperature (long term)
1	Cable (1) inside RPV	1000^0C
2	Reactor penetration (inside RPV/containment)	1000^0C/180^0C
3	Cable (2) / junction box	180^0C
4	Cable (3) / junction box (MIC)	Greater than 180^0C
5	Junction box inside the containment	180^0C
6	Penetrations – containment /annulus	$180/110^0$C
7	Cable (4) inside annulus	max. 110^0C
8	Penetrations – annulus/reactor building	max. 110^0C
9	Cable (5) inside reactor building	$50/70^0$C
10	Electronics	$50/70^0$C

Figure 66: Mapping of instruments and environmental parameters for a French type PWR 1000 for DEC/SA equipment survivability assessment (courtesy of AREVA and taken from (IAEA, 2017a))

3.1.4.1. Evolution of instrument survivability assessment methodologies

As instrumentation items during an SA are needed to detect the transition from EOPs to SAMGs, to obtain parameter trends to execute the guidelines, to assess the state of fuel and containment and to recognize when a controlled state is reached, several I&C survivability assessment methodologies haven been developed throughout the years after TMI-2 accident (Rempe et al., 2015). These approaches were not legally binding and served as technical recommendations for regulatory bodies and utilities. Some of them are enumerated here (Queral, 2017):

- **NRC Regulatory Guide 1.97 (1983):** it provided a specific list of instrument variables to monitor. This guide completed RG 1.97 Rev.2 of 1980.
- **INL-NRC NUREG/CR-5691 (1990):** five step top-down-approach methodology developed to systematically determine the required information for accident management and to evaluate instrumentation availability. The different steps aimed to identify potential SA sequences to then determine plant information needs, identify SA conditions and instrument capabilities and finally assess their availability.
- **INL-NRC NUREG/CR-5702 (1991):** revision where information needs to manage SAs were developed in a table format, indicating available and potential instruments and indirect information sources.
- **INL NUREG/CR-5444 (1992):** it provided a categorization by the grade of importance to safety of each measurement requirement. The highest category was intended for key variables and that instrumentation would have the requirements of full qualification, redundancy, and continuous real time display.
- **EPRI TR-103412 (1993):** based on a three-phase approach, its main idea was to identify a minimum set of key information needed to support SA mitigation to then identify SA environmental and process conditions to finally evaluate if instruments met information needs. Also, the use of calculation aids was taken into account. NRC acknowledged this methodology as valid for SAM strategies.
- **IAEA NP-T-3.16 (1996-2015):** revised in 2015 in response to the Fukushima event, this study recommended that the methodological approaches needed to ensure instrumentation adequate reliability in a similar way that the one followed by INL and EPRI previously. IAEA emphasized that analyses should be plant-specific and that aspects such as range, accuracy, response time and duration of operation need to be accounted for accident monitoring purposes. The study also recommended instrument maintenance in accordance with nuclear quality assurance programs and instrument isolation from harsh environments.

- **INL INL/EXT-1535940 (2015):** current INL approach stemming from the latest international efforts (see Section 2.7) and the previous industry approaches. In a first step, the methodology examines risk-important SAs. In a second step, it determines critical plant information needs (Drywell H_2/O_2 concentration, FCVS radiation levels, etc.). The third step aims to identify the instrumentation needed to provide the crucial readouts and locate the sensors positions (e.g., for drywell H_2 concentration, containment atmosphere monitors and gas sampling units are identified). The fourth step quantifies instrumentation environmental conditions and instrument location while the last step finally assesses instrument availability.
- **Westinghouse AP1000 equipment survivability assessment (2017)** (Scobel & Powell, 2017)**:** this approach uses the SAMGs to identify essential equipment in each accident stage (different damage conditions). Acceptance criteria and parameters are developed from the EQ test data and instrument performance analyzed in dedicated codes is compared to that criteria to demonstrate reasonable assurance of survivability. The methodology identifies CHLAs from the SAMGs used to achieve a controlled stable state, then it defines time frames for each mitigation action, determines equipment and I&C used to diagnose and verify each SAMG action during each SA environment and ultimately derives an evaluation of survivability and performance. This approach has also been used for the licensing process of the Korean APR1400 (KEPCO & KHNP, 2013).

3.2. Regulations and requirements for equipment survivability assessment

In contrast with the well-established regulations implemented in the field of LDB and DBA equipment qualification, under the name of EQ, the requirements for the demonstration of equipment survivability under SA conditions do not find a specific or detailed approach on how to implement the requirements. Indeed, no official consensus on the approach exists, although the various regulators and international bodies have raised the necessity of such a frame for regulations (Yan et al., 2016).

Under the term equipment and instrument survivability, several approaches have been taunted. Survivability would refer to the ability of equipment to survive conditions beyond their licensing basis, a different situation from qualification for design basis which requires rigorous adherence to codes, procedures and standards comprised in the guides and licensing basis. The assessments on survivability are rather engineering ones, based on realistic assessments of failure to stresses which may or may not have been anticipated by the design. Moreover, the historic approach has claimed that it was neither required to provide the same level of reliability for equipment identified as useful for severe accident mitigation as for safety-DBE-related equipment, nor it was necessary.

Therefore, equipment used in SAM actions have not had to comply with the qualification basis for expected environments, in accordance with 10CFR50.49 guides, and it is not required to show redundancy, diversity and quality assurance in accordance with 10CFR50 Appendixes A & B. Thus, safety related equipment used in SAM scenarios would be only required to be qualified for LDB conditions and provided with QA consistent with LDB requirements.

That being said, there are several codes and regulations that address, quantitatively or qualitatively, regulatory requirements regarding equipment survivability, which are explained hereafter:

- **10CFR50.34** American code states that the equipment necessary for achieving and maintaining safe shutdown should perform their functions during and after exposure to the environment conditions created by the burning of H2 clouds (NRC, 2011b).
- **10CFR50.44** is the primary American based criteria for equipment survivability, for both mechanical and electrical equipment, required for recovery from SAs in PWRs large dry containments (NRC, 2011a). Part 50.44(c) states that *"systems necessary to ensure containment integrity shall be demonstrated to perform their function under conditions associated with an accident that releases hydrogen generated from 100 percent fuel-clad metal-water reaction. […]. Equipment must be provided for monitoring hydrogen in the containment that is functional, reliable, and capable of continuously*

measuring the concentration of hydrogen in the containment atmosphere following a significant beyond design-basis accident for accident management, including emergency planning".

- **10CFR Part 52** (Licenses, Certifications, and Approvals for Nuclear Power Plants) contains requirements for new reactor design certification and combined license applications to complete severe accident performance analyses that provide assessments of severe accident equipment needs, predicted environments, and equipment survivability (Farmer, 2015).

- **Regulatory Guide 1.97 Rev. 4** states that licensees of new NPPs should provide instrumentation with expanded ranges capable of surviving the accident environment (with a source term that considers a damaged core) in which it is located for the length of time its function is required (NRC, 2006).

- **SECY-12-0025, SECY-90-016** and the enveloping **SECY-93-087**, were developed after Fukushima accident and are related to SA mitigation features and state that equipment provided only for SA protection is not subject to 10CFR50.49/50 A&B. It is however stated that mitigation features should provide reasonable assurance and operate in the SA environment over the time span for which they would be needed (EPRI, 2014a; NRC, 1993).

- **IEC/IEEE 6078-323** joint logo standard fills the gap of their IEC and IEEE relatives regarding specific qualification methods and strategies for demonstrating reliable performance for SAs, taking DEC conditions into account. The standard states that *"for all items of equipment that are needed to operate under design extension conditions, demonstrable evidence shall be provided that it is able to perform its function(s) under the applicable service conditions including design extension conditions […] for such equipment a plant specific severe accident profile may be used for component specific qualification requirements…"*. Methods included in IEC and IEEE stds., such as type testing and analysis, may also be applied to SA mitigation and monitoring items (International Electrochemical Commission & Institute of Electrical and Electronics Engineers, 2016).

- **RCC-E-2012 Section B6000** (French Design and Conception Rules for Electrical Equipment of Nuclear Island) states *that "the qualification to severe accident conditions is similar in procedure and methodology to qualification for design basis accident conditions that can be described by the test sequences, aging (radiological and thermal), seismic tests and accident simulation tests"*. This code allows omitting seismic tests only if similar or identical equipment has already been tested for DBA EQ.

- **HAF102-2004** code of the Chinese NNSA states that *"it shall be demonstrated with reasonable assurance that the equipment which are to be used to mitigate the severe accident can satisfy the design requirements, such as the systems and equipment to isolate the containment and keep it intact, to remove heat and to control the hydrogen concentration , etc."*. (Department of Environment Protection, 2004)

A thorough review of existing international standards that apply some adaptations to DEC/SA qualification for equipment survivability can be found in (IAEA, 2017a).

In conclusion, there are methods and procedures similar to DBA qualification that are applied or adapted for DEC/SA scenarios, although environmental profiles may substantially differ, as in the case of radiation level profiles. Nevertheless, almost all standards consider qualification for DBA only and requirements are given in a descriptive form providing expectations on the outcomes of the qualification processes.

3.3. Survivability Assessment within NPP containments

Equipment and instrumentation survivability assessments evaluate the availability of the items used during a SA to achieve a controlled and stable state after core damage, under unique containment environments (high temperature and pressure and a significant concentration of combustible gases), where local or global burning of non-condensable gases may occur, challenging even more the SSCs of the plant.

In this section, a review of environmental parameters used in real plant equipment survivability assessments and/or qualification processes for DEC/SA demonstration of reliable performance in such conditions, is developed with the aim to act as a revision of values found in the literature. The bulk of the collection of plant-specific data will focus on referencing peak temperature and pressure values, although other parameters such as humidity or radiation levels might be depicted. The values will mostly come from experimental and code analysis efforts from various European and non-European PWRs.

An important source of information, as in the case for DBE EQ, will be encountered in the numerous code-based analyses performed by the industry, experimental facilities, regulatory bodies and academic centres, whose thermal-hydraulic calculations have generally tried to envelope a wide range of SA scenarios to derive conservative figures regarding the harshness of the environments that are encountered during a DEC. In many cases, nevertheless, values can be very similar as those reviewed for DBA EQ, due to the utilisation of such figures for the late phases of SAs historically.

Table 9 compiles some examples of plant-specific parameters used for survivability and performance assessment of equipment and instrumentation used to mitigate or monitor SA (DEC) scenarios. Margins, in this case, are not provided since they are not included in any of the references in this review nor are endorsed by any official standard.

Table 22: Different PWR containment maximum temperatures, pressures and other variables in the profiles for performance/survivability assessment used in a variety of countries and NPPs regarding DEC/SA service conditions

Country	Max. Temperature (ºC)	Max. Pressure (bar)	Observations	Reference
China	190	9	CAP1400 equipment survivability in containment with PCS systems	(Yan et al., 2016)
China	150	5.8	HPR1000 SA instrument survivability assessment	(Xu et al., 2019)
Czech Republic	185	9	Dukovany NPP (VVER-440/213) & Temelin NPP (VVER-1000/320) LBLOCA+SBO SA with ongoing MCCI and PARs actuation	(Kotouc, 2019)
Korea	187/627	7.6	APR1400 Equip. Surv. Analyses with MAAP code. 627ºC corresponds to 10 sec peak after H2 burn. Most limiting sequence for radiation: 4.4E7 rad (LOFW)	(KEPCO & KHNP, 2013)
Romania	140	3.1	Cernavoda NPP (CANDU-6) SSC EQ extension for SA conditions in SBO and Stagnation Feeder Break accidents	(Dinca & Vasile, 2019)
Slovakia	139-215	3.5-5.2	Mochovce NPP (VVER 440 V-213) for 1 year post-SA duration under postulated DEC conditions. H2 burn Tp = 1600 ºC Rad. = 0. MGy; Hum. = 100%	(Tengler, 2012)
Sweden	185	7.5-8.3	Forsmark Unit 3 NPP penetrations and PEEK insulated cables SA	(VATTENFALL, 2014)

			performance verification for > 30 days	
UK	156	6.5	EPR design safety overview. SA bounding conditions for qualification	(AREVA, 2007)
USA	187	4.9	Sequoyah NPP (PWR-W): Equipment survivability under degraded core environments. Several sequences simulated by MAAP code. Dry cavity and MCCI phenomena leading to containment failure	(IDCOR, 1983)
USA	1015	10.5	Zion NPP (PWR-W): Equipment survivability under degraded core environments. Several sequences simulated by MAAP code	(IDCOR, 1983)
USA	205-1640	0.8	Surry NPP MELCOR results for unmitigated STSBO sequence for SOARCA project	(Rempe et al., 2015)
USA	550-677 / 200-1025	2.8-4.9	AP1000 Equip. Surv. range of cases for Direct Vessel Injection Breaks with igniters on/off	(Westinghouse, 2007)

3.4. Analytical assessment of survivability with computer codes

Nowadays, severe accident codes are considered one of the main technical sources to identify containment thermal-hydraulic bounding conditions and performance or instrument ranges and margins, since there is a lack of data from experiments and plant operations, even greater compared to the DBA case of study. Analytical containment safety studies have been also performed by different approaches and the reasons to follow each path are intrinsically equal to the particularities exposed in the homologous section of this review, devoted to analytical approaches for EQ (see Sec. 1.5.).

However, to characterize containment thermodynamic profiles under DEC scenarios is not as straightforward as in the case for DBE transients. Environmental parameters in SAs are dependent on a large number of accident phenomena and phases, therefore it is necessary to simulate a great range of scenarios to fully determine the scope of the assessments performed over safety-related equipment or SSCs used in the course of SAs. Another issue at the time of defining a program for simulating those conditions is whether the accident will be considered unmitigated or SAM actions will be implemented. This extends the complexity and variety of the simulations and the outcoming values (as can be seen in Table 9, T & P values are sometimes given in a range, to account for different types of SA simulations and their bounding profiles for survivability assessments).

To fulfil this aim, codes which follow SA progression and which calculate parameters such as burning gases generation and distribution, were developed and used to sort out the main output variables interesting for survivability assessment. Codes like MELCOR, ASTEC, or MAAP5 calculate the temporal evolution of temperature and pressure in the containment, as well as the gas composition, humidity, fission product´s distribution or the occurrence of deflagrations due to combustible gases accumulation. Then, by retrieving data from those codes, other containment codes like GOTHIC, COCOSYS or GASFLOW calculate the variables of interest, namely P&T, during the course of the accidents under simulation. Also, other codes like RADTRAD can be used to calculate dose distributions (source term analyses) using data provided by those previous codes, as shown in (Ivica Basic, 2018).

Code capabilities and validations of the main integral codes used for SA and H2 generation and mitigation analytical studies where vastly compiled in NEA/CSNI/R(2014)8 report (OECD/NEA, 2014b), regarding the strengths, limitations, improvements and application methods of each code. The envelopes of plant conditions given by these codes, act as upper limits that cover the expected parameters for each SA phase for any sequence, but uncertainties are still present on the analytical predictions, such as the occurrence of severe events like lower head failures or hydrogen burns or the margins on local conditions and in the timing of the phases.

To demonstrate code capability in the frame of SA system codes, how to assess model uncertainties and gaps in phenomena modelling is a challenging aspect. To compensate for the uncertainty introduced by the hypotheses and code biases, Best Estimate Plus Uncertainty (BEPU) methodologies (Fernández-Cosials, 2017), can be applied in the calculations that are necessary to estimate environmental characteristics for equipment performance during SA conditions. Those calculations focus on selected parameters for locations directly subjected to SA conditions inside the containment but also for outside containment locations, subjected to milder conditions but affected by the accident itself.

Examples of the implications on the use of one code against a previously used one, by determining code capabilities and analysis limitations under SA scenarios to perform updated survivability assessments, can be found in NRC regulatory audits on the use of GOTHIC code to calculate SA environmental parameters (Fessier & NRC, 2015; NRC, 2013).

Scoping efforts that used analytical simulations have been developed to identify the environmental conditions that instrument monitoring SA parameters would have to survive and the gaps where predicted environments exceed instrumentation qualification levels. A relevant example is the MELCOR modelling of a PWR SA by Rempe et. al. (Rempe et al., 2015), where the harsh conditions of temperature, pressure and dose surrounding the different instruments were compared against EQ limits under a SBO scenario for the Surry NPP (see Figure 25). Studies that extend that methodology, comparing damage and reliability levels with typical SAMG actions, can be found in simulations like the one referenced in (Fernández-Cosials et al., 2020).

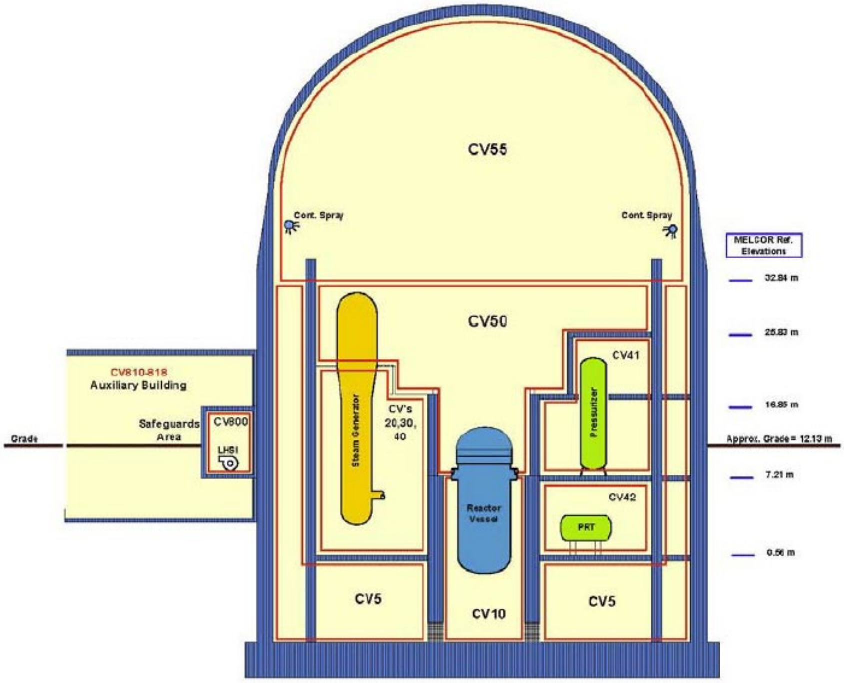


Figure 67: MELCOR model for Surry (Rempe et al., 2015)

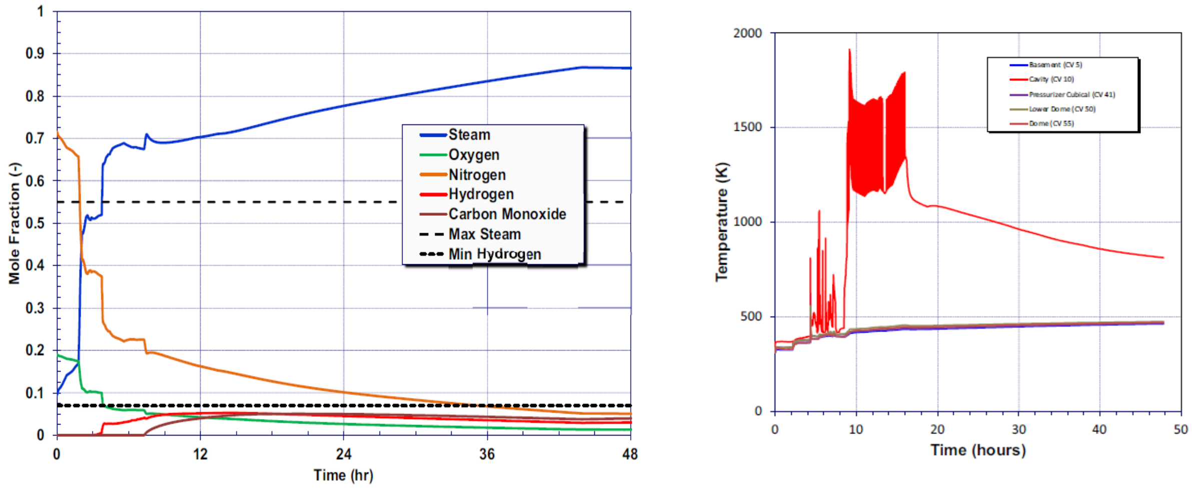


Figure 68: STSBO containment gas concentrations and containment control volume temperatures in the MELCOR simulations of Surry NPP within the SOARCA program (Rempe et. al., 2015)

3.5. Experimental tests for equipment survivability

As in a DBE EQ program, survivability assessments focused on equipment performance in the stages of a SA, need the backup and insights coming from experimental tests developed to verify some of the conditions and envelopes that could arise in a DEC scenario. Testing is based on the same qualification processes and approaches used for DBE qualification, but SA survivability tests have intrinsic limitations, as not every step of an accident may be replicable, due to time limitations or to uncertainty-related issues. Thus, it is important to define a proper sequence of steps to assess reliable performance within the tests, defining temporal and parametrical limits. A general sequence to perform experiments on equipment and I&C items to test survivability under SA conditions can consist on the following points (IAEA, 2017a):

1. To perform reference functional tests to confirm the safety function under normal operating conditions. Then, conditionate the items using applicable methods in order to simulate the consequences of thermal, radiological and mechanical aging under normal operation conditions.
2. To apply SA-type radiation dose (which may be higher than the dose under a DBA scenario) and to assess if seismic tests are necessary (if there are gaps in the previous qualification).

3. To apply the p-T profiles including humidity and chemical exposure simulating the SA phases of interest.

4. To apply conditions of post-accident phases, that may be last up to a year or longer.

5. To perform reference functional tests in order to assess the survivability of the equipment during the accident.

On this basis, it is important to specify that equipment performance acceptance criteria do not necessarily have to be established for the assessment of reliable performance. Rather, the objective of SA type-testing is to document the expected equipment behaviour under simulated SA loads and to compare their performance to the expected conditions in individual plant zones.

Nevertheless, unlike DBE plant safety analyses, where anticipated environmental conditions are well defined, the case for DEC/SA test procedures, profiles and environmental loading conditions is different. There are not widespread agreements nor standards on how to test equipment and instrumentation for SA conditions and knowledge of the parameters and conditions to be simulated has gaps that hamper the development of significant and replicable procedures. Moreover, uncertainties affecting SA phenomena modelling are large, usually bringing technical complications.

On the other hand, mission times required for the equipment and instrumentation may be quite long and experiments need to be accelerated to achieve reasonable testing times (as in the case of submergence tests, where the Arrhenius approach is used at elevated temperatures to accelerate long periods of testing). That arises questions on which is the minimum testing time needed, which irradiation conditions are reasonable to test, what differences in acceptance criteria from the criteria for DBA should have to be accounted or which qualification margins need to be defined in the case of SAs (Plaček, 2019).

Qualitative data on the degradation on equipment function suffered in the accident, would also have to be derived from the tests. If uncertainties are big enough, approximated environmental profiles for test purposes should be developed and used. For example, using the method of energy deposition calculated for bounding cases, accident profiles can be adapted to tests and a simplified bounding profile can be created to account for the proportional relationship between degradation of equipment and energy deposition.

An important early reference post-TMI-2 accident on the testing of safety-related equipment and cabling in NPPs facing a SA phenomenon, can be found in the large-scale H2 burning experiments on equipment developed by Achenbach et. al. and King et. al. (Achenbach, 1985; King et al., 1988), where it is stated that utilities can and should use test data for the assessment of survivability under bounding phenomena (as the case of a H2 combustion during a SA). The results of those tests showed that LOCA (DBA) qualified equipment should be able to operate during and after the high-temperature spikes produced by the burns, but uncertainties were properly accounted to give benchmark data that could be well compared with computer code predictions of different plant environments, in a plant-specific basis.

Lastly, it is also important to consider which commercial equipment to test, as many items will have a variety of designs and homologous equipment, and all of them may not be tested. This issue is addressed on Sandia National Laboratory Containment Integrity Research (Hessheimer & Dameron, 2006), for instance in the tests performed to CPAs (Cable Penetration Assemblies), where three different commercial electrical penetrations were tested and the results were extrapolated to the most common used CPAs in the American NPP fleet. The same identification of CPAs to evaluate is done in (Hrdý, 2014), where design and qualification of significant manufactured assemblies were key to choose which commercial items to test.

3.6. Implemented approaches and practices

The need of robust equipment and instrumentation capable to withstand severe accident conditions has led to the development of new qualified equipment and instrumentation which can be implemented as part of the accident monitoring systems at new NPP designs or as backfits of existing plants. Some examples of this recently implemented practices and items will be reviewed in this sub-section.

3.6.1. Implementation of robust equipment and I&C

One example is the development of accident level measurement (ALM) equipment in the framework of AREVA´s EPR™ design for monitoring the level of pools and vessels under SA conditions, in positions where total integrated accident doses could reach up to 5 MGy over one year mission time and temperatures up to 156ºC in steam saturated atmospheres for at least 12 hours. The idea is to rely on a sufficiently robust electrical circuit for signalling the extreme conditions and transmit them outside the reactor building with acceptable accuracy, which is achieved by a measurement principle based on resistor/reed-relay chains with magnetic floats. To demonstrate the reliable performance of these ALM equipment, experimental tests, consisting in accident temperature and pressure loads, accident radiation and chemical exposure, were performed in accordance with the KTA3505 standard, used for DBE EQ in the same test campaign (IAEA, 2017a).Other example is the creation of new hydrogen monitoring systems to measure the presence and combustion risk of hydrogen gas formed within the containment during and after DBAs and SAs. The development of these new robust monitoring systems is part of the Japanese SA-Keisou monitoring project and the idea is to provide plant operators with reliable measurements and signals to know hydrogen risk at each critical location, where the devices are to be installed, and in each accident stage. Simultaneous hydrogen and carbon monoxide concentration, risk of detonation, oxygen concentration, ambient temperature and pressure, and steam/humidity levels, can all be provided with an expected accuracy of 2% in these systems, enabling an enhanced control over those critical parameters. The systems consist of a gas monitoring unit of sensors located in the area of interest and qualified for harsh SA conditions (5 MGy, 700 ºC, 1.07 bar) and of a gas monitoring controller located outside containment and qualified for milder environmental conditions (Wada et al., 2014).

Figure 27 shows a picture of a gas monitoring unit for in-containment SA monitoring of H2/CO concentration and explosive risk, accompanied by an extract of the qualification analyses performed. These units are stable over a wide range of ambient conditions, which make them suitable for LTO operation following SA scenarios both in containment and outside, where leakage through piping and electrical penetrations can occur following pressure spikes and other phenomena.

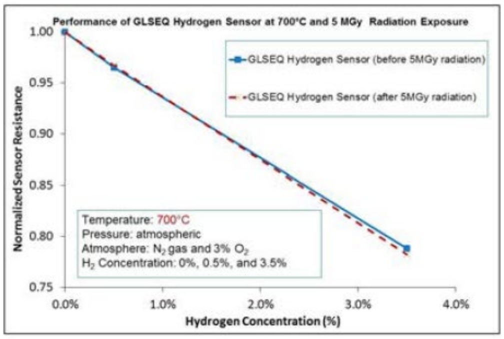


Figure 69: GMU for In-containment SA monitoring of H2/CO levels and explosion risk, tested for 700ºC before and after radiation exposure of 5 MGy gamma radiation (IAEA, 2017a)

3.6.2. Requalification of electric cable penetrations

Another approach consists in demonstrating reliable performance of already installed equipment at NPPs for the case of SA scenarios, as can be the issue with electric and cable assembly penetrations (CPAs). The main safety function of CPAs during SAs is to maintain leak tightness and only the CPAs that transfer signals from sensors needed for monitoring accident conditions or to operating mitigation components, need to retain their electrical functionality. To demonstrate that degradation on the worst-case effects of the SA, occurring in the in-containment side of the CPA, the items would be subjected to tests probing functionality, gas leak rates and electrical properties. Oher sequential tests performed on these equipment are the following (see (Hrdý, 2014) for more insight on this approach):

- Pre-aging tests to simulate LTO normal operation: thermal cycles, vibration, thermal and radiation aging.
- Tests to prove the functionality of pre-aged CPA specimens.
- Irradiation of CPA specimens on containment side with SA integrated total doses and simulation of the thermodynamic T-p profiles to demonstrate continued functionality.
- Analysis of results to prove the reliable performance of the connected measurement and actuator chains.

3.6.3. Protection of the equipment and reduction of mission time

If reliable performance of an equipment or an instrument cannot be demonstrated, protecting the equipment from the effects of SA phenomenology can be an acceptable approach to ensure equipment survivability in a variety of scenarios. For example, to protect instrumentation from hydrogen burning P&T spikes, the heat transfer between the atmosphere and the surface of the item can be limited, or the thermal capacity of the equipment enclosure materials can be optimized. Figure 28 shows the heat exchange processes in a protected radiation probe that penetrates in the containment, when subjected to a H2 burning and subsequent T spike.

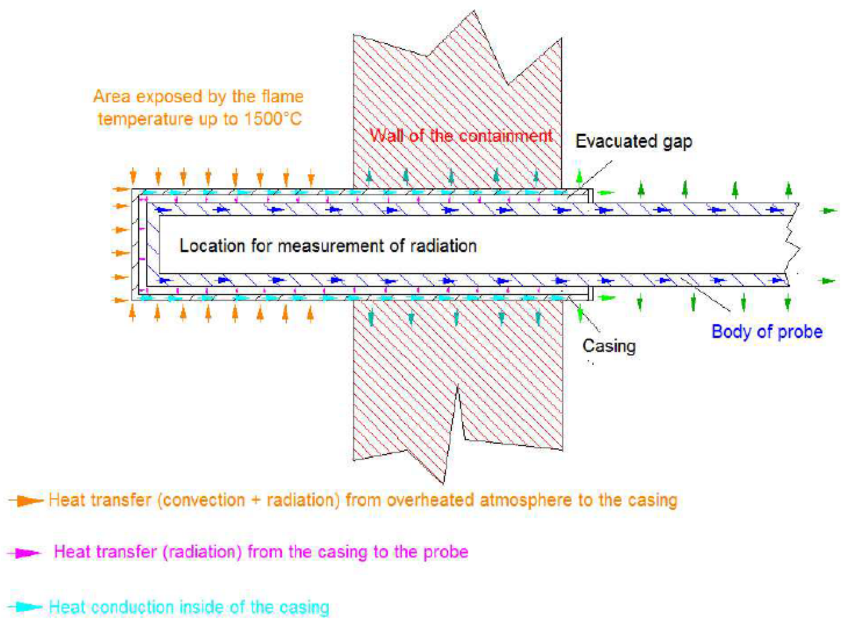


Figure 70: Heat exchange processes in a protected radiation probe facing a hydrogen burn (taken from (IAEA, 2017a))

3.6.4. Separate testing for the most severe environmental parameters

Peak values in environmental profiles used for SA survivability assessments might make necessary to separate profiles, and therefore the tests in which they are used, into segments. Thus, functional tests for peak values can be performed separately while tests for the entire profile can be performed integrally and with the appropriate durations (simulated mission times). Also, another approach can be to test the equipment into ultimate failure conditions with the aim to determine the actual safety margin available and to identify the needs for supplemental measures for the related SAM strategies.

3.7. International efforts on equipment survivability assessment approaches

The need for better and reliable post-accident equipment and instrumentation was recognized after the events of TMI-2 and Fukushima-Daiichi, as instrumentation data provide critical information for the operators to diagnose the condition of the plant and assess the evolution and impact of the stages and mitigation actions occurring during the accident progression. This equipment and I&C survivability require knowledge of the environmental conditions faced during a wide range of risk-important events and that raised the issue of developing better standards and approaches that addressed the problem. Moreover, although some generally accepted regulatory requirements were placed on instrumentation survivability for new NPP designs prior to certification, gaps are to be filled to ensure the reliable assessment of the performance and ability of equipment to inform of plant conditions during a DEC scenario and aid in the SAM strategies.

In this section, a review of the most important programs and international efforts undertaken on the field of equipment and instrument survivability assessment during SA conditions is presented. The following bullet points expound some information on the programs referenced:

- **US NRC´s Accident Management Research Program** (Arcieri & Hanson, 1991; Farmer, 2015): funded in the 1990´s to evaluate instrumentation survivability during SA´s. NRC developed a methodology to identify information needed to understand the status of the plant during a broad range of SA conditions including corrective actions, the existing plant measurements to supply these information needs, the limitations on the capability of these measurements to properly function under a wide range of postulated SA scenarios and the potential information misguidances received by plant operators. The method was applied to representative PWR´s and BWR´s transducers, cabling, electronics, and other components for five different phases of an accident, namely initiation, core uncover, fuel melting and relocation, vessel failure and ex-vessel interactions in the containment.

- **EPRI survivability assessment** (EPRI, 1993): completed for a pilot 4-loop Westinghouse PWR, a Combustion Engineering PWR, a Babcock & Wilcox PWR and a Mark II BWR, it focused on identifying the crucial set of key information to support SAMG implementation, by comparing the instrumentation and equipment operating envelope with predicted risk-important conditions.
- **DOE updated LWR instrumentation survivability evaluation** (Rempe & Knudson, 2014): focused on determining key information for SAM and mitigation, on quantifying the environment that instrumentation monitoring this data would have to survive, and on identifying the gaps in existing instrumentation that would require further research and development. Pilot plants for the evaluation were BWR Peach Bottom NPP and PWR Surry NPP, where critical instrumentation needs were identified based on plant-specific accident management procedures and discussions with plant operators. MELCOR models were used to quantify SA environmental parameters to which critical instrumentation would be subjected, and operating envelopes were compared to assess instrumentation availability.
- **EPRI´s Technical Advisory Group on I&C for BDBA and SA´s** (EPRI, 2014c): formed to facilitate exchange of information and research results between EPRI, NRC, DOE, INPO, PWROG and BWROG on addressing post-Fukushima lessons about the required durability and capabilities of I&C systems during severe accident events, identifying the required parameters and ability of reactor and containment I&C systems and performing research to determine if the availability of I&C can be improved so that plant data are not lost during BDBA´s.
- **PWROG & BWROG Technical Support Guidelines on Instrumentation behaviour for SA´s** (EPRI, 2014c; Lutz, 2015): developed to complement their post-Fukushima enhanced SAMG programs and to provide SAMG users with a basis to determine the validity of information displayed by existing plant instrumentation during a SA.
- **IAEA´s Action Plan on Nuclear Safety – Post-accident and severe accident monitoring systems** (International Atomic Energy Commission, 2015): developed as guidance to IAEA´s Member States, reflecting current knowledge, experience and best practices in the field of equipment and instrumentation performance in DEC scenarios. It provides a common international technical basis to consider when establishing new criteria for accident monitoring instrumentation to support operation under design basis and design extension conditions in new and existing NPP designs. This Guide also recommends that a plant-specific process should be implemented to ensure

instrument availability and reliability following aspects such as operating range of conditions, accuracy over the anticipated range, response time, and operating duration.

- **Japanese SA- Keisou (Severe-Accident – Instrumentation & Monitoring Systems) program** (IAEA, 2017a; International Atomic Energy Commission, 2015; SA Keisou R&D Working Team, 2015): established to develop systems that could prevent the escalation of a Fukushima-type event, it emphasized the need to monitor vital variables like H2 concentration during a SA, values that operators can use to mitigate the consequences of the accident and early achieve a safe state for the plant. The program included representative equipment and instrumentation from various electric power companies, vendors and instrumentation manufacturers. An objective was also to define parameters that SA monitoring equipment will need to be capable of withstanding, and to develop qualification specifications to determine test conditions under which each equipment need to be tested. Survivability qualification tests on SA monitoring instrumentation were carried out in the framework of the program, by establishing environmental conditions, determining SA basic specifications, verifying the test methods for the instrumentation, and extrapolating acceptance criteria ranges whenever test conditions could not be accomplished due to testing facilities limitations.

4. Conclusions

This document serves as a review of the different approaches and main principles of the qualification of safety-related equipment and instrumentation under conditions of DBA and SA. The objective of this state-of-the-art report is to give sufficient insight in the fields of DBA-EQ and SA survivability assessment, and to provide parameters, namely stressors as temperature and pressure. The values have been extracted from different studies performed in various PWR NPPs worldwide. These parameters will be valuable to assess future simulations and discuss improvements to SAM measures. To fulfil that aim, this WP1-IDL4 compares the principles, stressors, regulations, code analysis studies, industrial tests, experiments, methodologies, and approaches surrounding first the EQ of subjected SSC´s, equipment, and I&C in the harsh/mild conditions of an in-containment DBA and then, in a homologous fashion, the basis of survivability assessments in the BDBA/SA (DEC) field, where regulation and methodological particularities arise.

On one hand, items subjected to DBA qualification follow well established processes with regulations and practices in constant revision, sheltered by international and national regulatory bodies. For that reason, a thorough review of DBA-EQ criteria and enveloping profiles has been undertaken using the extensive documentation publicly available. EQ programmes are implemented to verify that items do not see their performance impaired under the plant conditions of a HELB, a significative earthquake or an EMC incident. The main stressors addressed in analytical and experimental reports are P&T values and their margins, ranging from 120 to 260 ºC and 2 to 6 bar, depending on the NPP.

On the other hand, components and instruments subjected to SA conditions pass through a process denominated survivability assessment, a surveillance approach developed under several methodologies that is still not consolidated in any official standard. These assessments generally consider several accident stages where functionality and damage issues are assessed, under P&T profiles normally harsher than those of a DBE. Nevertheless, survivability assessments generally rely on EQ criteria, making necessary a comparison between data and procedures between DBA and SA approaches, although survivability regulatory requirements are not yet fully developed nor implemented.

Finally, this document should be used as a reference technical document for further AMHYCO WPs, namely WP4 where equipment and instrumentation surveillance under SA scenarios will be compared with the data gathered in this report. Also, WP5 where proposals for SAMG long-term-operation improvements and guidelines for equipment and instrumentation survivability assessment will be given, considering typical containment qualification requirements as the ones described herein.

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Annex A: List of typical PWR systems containing class 1E electrical equipment

As an example of common encountered systems in a typical PWR plant, the list of systems containing class 1E electrical equipment, and subjected to the related environmental qualification, of units 2 & 3 of San Onofre NPP (2-loop PWRs, supplied by *Combustion Engineering*) is provided hereafter. The reader would be able to find here components and systems that are located in the containment or have close relation with that zone of the plant.

Items accompanied by (*) indicate exposure to harsh environment.

- Containment heat removal systems
  - Containment spray systems (CSS) *
  - Containment atmosphere emergency cooling system (CAECS) *
- Containment isolation system (isolation devices) (CIS) *
- Combustible gas control system (CGCS) *
- Safety injection system (SIS) *
- Fission product removal and control systems
  - Containment spray systems (CSS) *
  - Emergency operation control room ventilation system
  - Fuel handling building post-accident cleanup system (not required for LOCA/HELBA/MSLB mitigation)
- Fuel Handling Building Isolation Systems (not required for LOCA/HELBA/MSLB mitigation)
- Onsite electrical power systems (AC/DC power systems (electrical penetrations and cable)) *
- Salt water cooling system (SWCS)
- Component cooling water system (CCW) *
- Chemical and volume control system (CVCS) *
- Emergency operation containment building ventilation systems (HVAC)
  - Containment atmosphere emergency cooling system (CAECS) *
- Emergency operation HVAC systems
  - Control room habitability system
  - ESF switchgear system
  - Charging pump room system *
  - Battery room system
  - Chiller room system

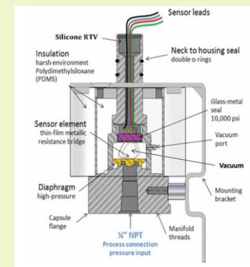
	o Emergency chilled water system
	o Fuel handling building post-accident cleanup system
	o Safety equipment pump room emergency cooling system *
	o Diesel generator building emergency ventilation system
	o Intake structure emergency ventilation system
• Emergency evacuation alarm system (not classified as Class IE equipment)	
• Diesel generator systems (DGS)	
	o DG fuel oil storage and transfer system
	o DG cooling water system
	o DG starting system
	o DG lubrication system
	o DG combustion air intake and exhaust system
• Auxiliary feedwater system (AFWS) *	
• Fuel pool cooling system (not required for LOCA/HELBA/MSLB mitigation)	
• Reactor protection system (RPS) * (electronic equipment in control building not exposed to harsh environment)	
• Engineered safety features actuation system (ESFAS) * (electronic equipment in control building not exposed to harsh environment)	
• Radiation monitors (airborne) (RAMS) *	
• Shutdown cooling system (SDCS) *	
• Post accident monitoring (PAMS) *	
• Reactor coolant gas vent (RCGVS) *	

Annex B: Glossary of most common regulations on EQ

- ASME QME-1 (2007), Qualification of Active Mechanical Equipment used in Nuclear Power Plants
- IEEE 100 (2000), The Authoritative Dictionary of IEEE Standards Terms
- IEEE 317 (1983), Standard for Qualifying Continuous Duty Class 1E Motors for Nuclear Power Generating Stations
- IEEE 323 (1971/1974/1983/2003), Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations
- IEEE 334 (2006), Standard for Qualifying Continuous Duty Class 1E Motors for Nuclear Power Generating Stations
- IEEE 344 (2004), Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations
- IEEE 381 (1977), Standard Criteria for Type Test of Class 1E Modules used in Nuclear Power Generating Stations
- IEEE 382 (2006), Standard for Qualification of Actuators for Power Operated Valve Assemblies with Safety-Related Functions for Nuclear Power Plants
- IEEE 383 (2003), Standard for Type Test of Class 1E Electric Cables, Field Splices and Connections for Nuclear Power Generating Stations
- IEEE 420 (2001), Standard for the Design and Qualification of Class 1E control Boards, Panels and Racks used in Nuclear Power Generating Stations
- IEEE 535 (2006), Standard for Qualification of Class 1E lead Storage Batteries for Nuclear Power Generating Stations
- IEEE 572 (2006), Standard for Qualification of Class 1E Connection Assemblies for Nuclear Power Generating Stations
- IEEE 603 (1998), Standard Criteria for Safety Systems for Nuclear Power Generating Stations
- IEEE 627 (2010), Standard for Design Qualification of Safety Systems Equipment used in Nuclear Power Generating Stations
- IEEE 638 (1992), Standards for Qualification of Class 1E Transformers for Nuclear Power Generating Stations

- IEEE 649 (2006), Standard for Qualifying Class 1E Motor Control Centres for Nuclear Power Generating Stations
- IEEE 650 (2006), Standard for Qualification of Class 1E Static Battery Chargers and Inverters for Nuclear Power Generating Stations
- IEEE 7-4.3.2 (2003), Standard Criteria for Digital Computers in Safety Systems of Nuclear Power Generating Stations
- IEEE C37.98 (1987), Standard Seismic Testing of Relays
- IEEE C37.105 (1987), Standard for Qualifying Class 1E Protective Relays and Auxiliaries for Nuclear Power Generating Stations
- NRC 10 CFR 50, Appendix B-1980, Quality assurance criteria for nuclear power plants ad fuel processing plants.
- NRC 10 CFR 50.49-1983, Environmental Qualification of Electric Equipment important to Safety for Nuclear Power Plants
- NUREG 0588-1980, Interim staff position on environmental qualification of safety related electrical equipment
- NRC Regulatory Guide 1.63 (1987), Electric Penetration Assemblies in Containment Structures for Nuclear Power Plants
- NRC Regulatory Guide 1.73 (1974), Qualification Tests of electric Valve Operators Installed Inside the containment of Nuclear Power Plants
- NRC Regulatory Guide 1.89 (1984), Environmental Qualification of Certain electric Equipment Important to Safety for Nuclear Power Plants
- NRC Regulatory Guide 1.156 (1987), Environmental Qualification of Connection Assemblies for Nuclear Power Plants
- NRC Regulatory Guide 1.158 (1989), Qualification of Safety-Related Lead Storage Batteries for Nuclear Power Plants
- NRC Regulatory Guide 1.180 (2003), Guidelines for Evaluating Electromagnetic and Radio Frequency Interference in Safety-Related Instrumentation and Control Systems
- NRC Regulatory Guide 1.211(2009), Qualification of Safety-Related cables and Field Splices for Nuclear Power Plants

Annex C: EQ of some containment NPP components on DBE conditions

Component	Supplier	EQ regulation	Test Temperature	Test pressure	Test Radiation	Seismic Conditions	Observations	Component Photography
Weed Model DTN2070 Differential Pressure Transmitter	Ultra Electronics	IEEE 323-1974 IEEE 344-1987	129.4 ºC	4.68 bar	36.5 Mrad TID	15 g @ 2 Hz (SSE)	Abnormal event, seismic, LOCA, submergence and post accident monitoring. EQ reqs. For GEN III+ NPPs (ULTRA Electronics, 2013)	
3150 Pressure Transmitter Series	ROSEMOUNT	IEEE 323/344 RCC-E KTA 3505 RG 1.180	224 ºC (LOCA/HELB peak) 55 ºC (submergence)	N/A	112 Mrad	8.5g ZPA (HRHF)	3159 Seal component values 20 yrs qualified life at 49 ºC and 1 yr for post accident	

							(ROSEMOUNT, 2014)	
MOV LWR motor	Schulz Electric	IEEE 323/344 IEEE 334/382/383	202 ºC (LOCA/HELB peak	4.82 bar	65 Mrad TID	10g SSE, 6.67g OBE	20 yrs qualified life at 50 ºC and 1 yr for post accident 100% HR (SCHULZ & Dean, 2019)	
NT8316 Nuclear Solenoid Air Operated Valve	ASCO Neumatics	IEEE 323/344	232 ºC LOCA 260 ºC HELB	7.79 bar	40 Mrad	4.4 g 2-64-2 Hz OBE	AP1000 1E class valve (ASCO NEUMATICS, 2014)	

Annex D: Glossary

- **Abnormal conditions**: loss of power supply (station blackout), failure of heating, ventilation, and air conditioning (HVAC) systems, steam or fluid leaks from small process piping or components such as valves, maintenance actions.
- **Acceptance criterion**: specified limit of a functional or condition indicator used to assess the ability of an SSC to perform its design function.
- **Aging**: general process in which characteristics of an SSC gradually change with time or use.
- **Class 1E equipment:** A classification of electrical equipment and systems that are essential for the safe shutdown of the reactor, isolation of the containment structure, maintaining safe shutdown conditions (decay heat removal), and preventing significant radiation release to the environment.
- **Common-cause failure**: failure of equipment or systems as a consequence of the same cause. The term is usually used with reference to redundant equipment or systems. Common-cause failures can occur due to design, operational, environmental, or human factor initiators.
- **Design Basis Event**: any event that produces a harsh environment, different from the normal or abnormal conditions and are addressed in the Final Safety Analysis Report of an NPP.
- **EMC Testing**: evaluation of the impact of electromagnetic interference / radiofrequency interference (EMI/RFI).
- **Environmental conditions**: conditions external to the equipment or I&C, such as ambient temperature, radiation, pressure and externally induced vibration.
- **Environmental Qualification**: the generation and maintenance of evidence to assure that equipment will operate on demand, to meet system performance requirements within specified environmental conditions - a more limited term than equipment qualification.
- **Environmental Qualification Master List**: list of all directly or indirectly safety-related equipment that require harsh environmental qualification. EQML-component´s performance requirements are tested regarding their location, qualification criteria or harsh DBA, among others.

- **Equipment Qualification**: verification of equipment design by demonstrating functional capability under significant operational and environmental stresses, including those resulting from design basis events (accidents).
- **Equipment capability to perform reliably**: capability of the SSC to perform reliably under SA conditions to be achieved by an appropriate choice of measures including the use of proven components (proven by experience under similar conditions or adequately tested and qualified), redundancy, diversity (the potential for common cause failure, including common mode failure), physical and functional separation and isolation.
- **General Design Criteria**: design requirements in the Code of Federal Regulations that apply to all NPPs.
- **High Energy Line Break**: rupture of a pipe which contains fluid containing high thermal energy in the form of temperature, pressure or both.
- **Margins:** differences between test conditions and expected accident conditions for which the device is being qualified.
- **Mission time:** time for which the equipment is able to perform or maintain its intended function, considering the actual environmental conditions.
- **On-going Qualification:** environmental qualification that uses installed test samples which will be tested or analyzed at a future date.
- **Qualified Life**: the interval for which a component can be shown to have satisfactory performance for a given set of environmental conditions.
- **Service conditions**: environmental, loading, power, and signal conditions expected as a result of normal operating requirements, expected extremes (abnormal) in operating requirements, and postulated conditions, appropriate for the design basis events of the station; or the actual physical states or influences during the service life of an SSC, including operating conditions (normal and error-induced), design basis event conditions, and post-design basis event conditions (The second definition is more general than the first and clarifies that service conditions are actual conditions in contrast with design service conditions, which may include margins of conservatism and be viewed as "expected").
- **Surveillance**: observation or measurement of condition or functional indicators to verify that an SSC can function within acceptance criteria.

- **Survivability assessment**: provision of a reasonable level of confidence that equipment will carry out their intended function under severe accident conditions for expected mission time.
- **Type Testing:** testing of actual equipment using simulated accident conditions, first exposing components to radiation doses equivalent of the expected lifetime dose and thermally aging them to finally exposing them to DBE value conditions.