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Mitigation of Hydrogen Hazards in Severe Accidents in Nuclear Power Plants

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MITIGATION OF HYDROGEN HAZARDS IN SEVERE ACCIDENTS IN NUCLEAR POWER PLANTS

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FOREWORD

Consideration of severe accidents in nuclear power plants is an essential component of the defence in depth approach in nuclear safety. Severe accidents have very low probabilities of occurring, but may have significant consequences resulting from the degradation of nuclear fuel.

The generation of hydrogen and the risk of hydrogen combustion, as well as other phenomena leading to overpressurization of the reactor containment in case of severe accidents, represent complex safety issues in relation to accident management. The combustion of hydrogen, produced primarily as a result of heated zirconium metal reacting with steam, can create short term overpressure or detonation forces that may exceed the strength of the containment structure. An understanding of these phenomena is crucial for planning and implementing effective accident management measures. Analysis of all the issues relating to hydrogen risk is an important step for any measure that is aimed at the prevention or mitigation of hydrogen combustion in reactor containments.

The main objective of this publication is to contribute to the implementation of IAEA Safety Standards, in particular, two IAEA Safety Requirements: Safety of Nuclear Power Plants: Design and Safety of Nuclear Power Plants: Operation. These Requirements publications discuss computational analysis of severe accidents and accident management programmes in nuclear power plants. Specifically with regard to the risk posed by hydrogen in nuclear power reactors, computational analysis of severe accidents considers hydrogen sources, hydrogen distribution, hydrogen combustion and control and mitigation measures for hydrogen, while accident management programmes are aimed at mitigating hydrogen hazards in reactor containments.

The IAEA staff member responsible for this publication was C.O. Park of the Division of Nuclear Installation Safety.

CONTENTS

1. INTRODUCTION

1.1. Background

The basic goal of severe accident management in nuclear power plants (NPPs) is the protection of the containment integrity and the containment becomes the ultimate barrier against the release of fission products to the environment. There are various potential challenges to the containment integrity during a severe accident in a light water reactor (LWR). The combustion of hydrogen, produced primarily as a result of heated zirconium metal reacting with steam, can create short term pressure or detonation forces that may exceed the strength of the containment structure and lead to early containment failure. For most NPPs, severe accidents lead to hydrogen release rates that exceed the capacity of hydrogen control measures at conventional design basis accident (DBA). Local high hydrogen concentrations can be reached in a short time, leading to combustible gas mixtures in the containment. Moreover, a long term pressure build-up may occur due to steam generation through decay heat and/or through the generation of non-condensable gas from the interaction of the molten core with the containment basemat concrete.

Hydrogen production, distribution and combustion in post-accident containment are very complex and highly plant- and scenario-specific phenomena. Hydrogen combustion can take place in a variety of forms: mild deflagration, fast or accelerated flames, deflagration to-detonation transition (DDT) and detonation. In order to study the influence and mitigate the consequences of hydrogen combustion, detailed studies are needed to determine the hydrogen generation rates and overall amount released to the containment. The distribution of the hydrogen released within the containment determines local and global hydrogen concentrations, which are decisive for the evaluation of the various combustion modes, such as diffusion flames, deflagration and detonation, depending on geometrical effects and concentrations. An understanding of all these phenomena is crucial for planning and implementing effective hydrogen management measures. These measures include enhancement of mixing, deliberate combustion through igniters, use of recombiners, and post-accident inerting.

In most countries, there are no strict regulatory requirements on the implementation of hydrogen mitigation measures for existing plants, while for reactors that are planned or under construction, these measures have to be incorporated into the design. Therefore, mitigation measures for hydrogen already exist in some countries. Nonetheless, these measures have been implemented in many NPPs on a voluntary basis. The need for such measures was derived both from deterministic consideration of plant vulnerabilities and from risk investigations, but sometimes also owing to non-technical reasons. The implementation level varies significantly from country to country and even from plant to plant in an individual country. In some plants, no decision has been taken yet on the implementation of measures. In other plants, measures have been implemented to cope with hydrogen produced during DBAs. In many plants, the measures are already capable to cope with hydrogen produced during severe accidents. In some cases, a final decision on this partial issue has been postponed after specification of an overall approach to severe accident management. The issue of mitigation measures for hydrogen is in progress in a number of countries. It is therefore appropriate to share views and experiences among the countries.

Since combustion of hydrogen represents a severe challenge to the containment integrity, mitigation measures for hydrogen are one of the essential parts of any accident management programme and all the IAEA publications developed for accident management are also applicable to the hydrogen issues.

According to the IAEA INSAG-10 [1], consideration of highly improbable severe plant conditions is an important component of defence in depth and measures aimed at controlling the course of severe accidents and mitigation of their consequences need to be available. The most important objective of accident management is the protection of the containment. According to this publication, management of severe accidents has to be flexible enough to take into account many uncertainties about the actual course of a severe accident. The importance of adequate instrumentation qualified for accident conditions is also stated.

Among basic safety principles specified in IAEA INSAG-12 [2] there are three principles specifically devoted to management of accidents beyond the design basis: the need for development of strategies for accident management, training and procedures for accident management and engineered features for accident management.

The IAEA has developed a number of publications that provide guidance and support in severe accident analysis and accident management at NPPs [3–10]. Various strategies are discussed in Ref. [11], which provides a comprehensive overview and comparison of mitigation measures for hydrogen in severe accidents. However, this publication is limited in scope and requires updating, as the information it contains represents the level of knowledge of the early 1990s.

Several comprehensive publications dealing with the hydrogen issue have been also developed within the framework of OECD/NEA activities [12–14]. All these publications represent a valuable source of information for any further work on hydrogen issues.

Consideration of severe accidents and accident management in plant design and operation is stipulated by the IAEA Safety Requirements publications Safety of Nuclear Power Plants: Design [3] and Safety of Nuclear Power Plants: Operation [4], respectively. According to these requirements, control of severe accidents is an important part of defence in depth. Among other plant design requirements it is also stated in Ref. [3] that:

> “5.31. Certain very low probability plant states that are beyond design basis accident conditions and which may arise owing to multiple failures of safety systems leading to significant core degradation may jeopardize the integrity of many or all of the barriers to the release of radioactive material. These event sequences are called severe accidents. Consideration shall be given to these severe accident sequences, using a combination of engineering judgement and probabilistic methods, to determine those sequences for which reasonably practicable preventive or mitigatory measures can be identified.
>
> Acceptable measures need not involve the application of conservative engineering practices used in setting and evaluating design basis accidents, but rather should be based upon realistic or best estimate assumptions, methods and analytical criteria. On the basis of operational experience, relevant safety analysis and results from safety research, design activities for addressing severe accidents shall take into account the following (Ref. [3] paras 531, 531 (1, 3, 6):
>
> (1) Important event sequences that may lead to a severe accident shall be identified using a combination of probabilistic methods, deterministic methods and sound engineering judgement.

(3) Potential design changes or procedural changes that could either reduce the likelihood of these selected events, or mitigate their consequences if these selected events were to occur, shall be evaluated and shall be implemented if reasonably practicable.

(6) Accident management procedures shall be established, taking into account representative and dominant severe accident scenarios."

Ref. [4] establishes the following requirements on severe accidents and accident management in the operation of nuclear power plants:

"3.12 Plant staff shall receive instructions in the management of accidents beyond the design basis. The training of operating personnel shall ensure their familiarity with the symptoms of accidents beyond the design basis and with the procedures for accident management.

5.12 (…) Emergency operating procedures or guidance for managing severe accidents (beyond the design basis) shall be developed."

Further details on design considerations for severe accidents can be found in the IAEA Safety Guide on Design of Reactor Containment Systems for Nuclear Power Plants [15] which makes distinction between existing and new plants in accident management. For existing plants, severe accidents are carefully analysed in order to identify safety margins and accident management measures. For new plants, consideration of severe accidents are aimed at practically eliminating the damage to the containment in both the early and the late phase, severe accident conditions with an open containment or with containment by-pass. In addition, the publication provides more specific guidance related to capability of containment systems under severe accident conditions, including:

- Making available proper instrumentation and procedures to initiate preventive or mitigatory measures;
- Verifying the necessary survivability of equipment and instrumentation under severe accident conditions;
- Ensuring integrity and leaktightness of the containment; for existing plants "as far as this can be achieved by reasonable means";
- Preventing combustion or deflagration of hydrogen potentially damaging the containment systems;
- Providing for hydrogen and other combustible gases monitoring as well as for monitoring of other parameters important for performing of severe accident management guidelines.

In addition to the aforementioned Standards established from a design perspective, there are four IAEA Safety Standards [5, 98, 99, 100] that deal with in part how to perform safety analysis including severe accident analysis. Reference [5] specifies the generally applicable requirements to be fulfilled in safety analysis for all facilities and activities relevant to radiation risks. It is stated in the Ref. [5] that the consequences associated with beyond design basis accidents (BDBAs) have to be addressed in the safety analysis. Also stated is that both deterministic and probabilistic approache have to be included in the safety analysis. Reference

[98] provides detailed guidance on deterministic safety analysis whereas Ref. [99] and Ref. [100] describe guidance on level 1 and level 2 probabilistic safety assessments for nuclear power plants, respectively.

There are also three Safety Reports [7–9] and several other IAEA safety related publications dealing with severe accidents. The IAEA Safety Report on Accident Analysis of Nuclear Power Plants [8] gives a practical general guidance for performing accident analysis based on present good practice worldwide. The report concentrates on analysis of accidents within the design basis, but includes also some suggestions for analysis of severe accidents. It describes basic approaches used for severe accident analysis, characterization of initiating events and scenarios to be analysed, designators for categorization of accident sequences, overview of recovery strategies for prevention and mitigation of severe core damage, basic characteristics of computer codes and acceptance criteria used in severe accidents domain, applicability of results of analysis. More specific information on methodology for severe accident analysis can be found in the IAEA Safety Report on Approaches and Tools for Severe Accident Analysis for Nuclear Power Plants [9]. The publications include description and status in modelling of severe accident phenomena, examples of acceptance criteria for severe accident domain, overview of applicable computer codes, their characteristics and status of validation, approaches recommended for various applications of analysis and advice on selection of codes, advice on selection of scenarios, consideration of essential design characteristics, basic steps in developing data and calculations, main suggestions for best estimate calculations, presentation of results, and consideration of uncertainties. Issues related to the hydrogen are also addressed, but due to the broad scope of the publications, hydrogen specific information is very limited.

Detailed information on approaches applicable for development of accident management programmes has been published in the IAEA Safety Report on Implementation of Accident Management Programmes in Nuclear Power Plants [10], which is based on developments that have been made in the field of accident management worldwide. The Safety Report provides a description of all elements that need to be addressed by the team responsible for the preparation, development and implementation of a plant specific accident management programme at a NPP. The elements include the establishment of the team, selection of accident management strategies, safety analyses required, evaluation of the plant systems performance, development of accident management procedures and guidelines, staffing and qualification of accident management personnel, and training needs. However, the Safety Report does not contain any technical details regarding mitigation measures for hydrogen in severe accidents.

The publication on the approaches to the safety of future NPPs [16] also specifies that severe accidents have to be considered explicitly in the design, but as a separate category. Systems added to the design to address severe accidents need to be of high quality, but safety grade quality levels are usually not required. Particular attention is devoted to the preservation of the containment integrity and leaktightness. For analysis of severe accident sequences selected and addressed in the design, best estimate assumptions, methods and data are the preferred tools to avoid distortion of the physical picture. Accident management is supported by NPP design features, aimed at providing time for management actions and to contributing to smooth plant response and to simplification of emergency planning.

The need for development of specific guidance to cover major issues relating to hydrogen sources, hydrogen distribution, hydrogen combustion, prevention of hydrogen combustion, control and mitigation measures for hydrogen was extensively discussed at the IAEA Technical Committee Meeting on Implementation of Hydrogen Mitigation Techniques and Filtered Containment Venting [17]. Participants at this meeting felt that an up to date IAEA publication on mitigation measures for hydrogen was needed, provided that the publication would concentrate on the practical aspects of the implementation of the measures for various reactor designs, with reference to already existing publications.

1.2. Objective and scope

The main objective of the present publication is to contribute to the implementation of relevant IAEA Safety Standards, in particular regarding two requirements (Refs [3, 4]):

- Performing computational analysis of severe accidents, and notably all problems related to hydrogen sources, hydrogen distribution, hydrogen combustion, hydrogen control and mitigation measures;

- Development and implementation of accident management programmes in NPPs, notably of those measures which are aimed at mitigation of hydrogen in the reactor containments.

This publication is intended as a self-standing report, it is suggested for the user to read also other relevant guidance publications to learn more comprehensively about accident management. This publication is aimed to be useful for utilities, as well as for regulatory bodies and their technical support organizations.

Although this publication does not explicitly differentiate among various reactor types, it has been written essentially on the basis of available knowledge and databases developed for LWRs. Therefore, its application is mostly oriented towards PWRs (including WWERs) and BWRs. However, it can be also used as a preliminary publication for other types of reactors such as PHWRs and RBMKs. For the reasons stated above, this publication is more appropriate for existing NPPs, although to large extent it contains information which is also applicable to new reactor designs. Since hydrogen mitigation measures are typically plant specific, the practical solutions for different reactor designs in the present publication should be considered as examples that are not intended to be adopted without a critical evaluation.

1.3. Structure

The present publication consists of eight sections. Section 2 discusses potential hydrogen sources during a severe accident. They are described at various stages, such as from in-core degradation to core-concrete interaction. Sections 3 and 4 describe the distribution and combustion of hydrogen, including calculation tools and related experimental facilities. These sections consider the effects of release mode and spraying on hydrogen distribution, containment layout effects and combustion modes such as deflagration, detonation and flame acceleration. Section 5 discusses possible risks from hydrogen combustion and the evaluation of risk due to static and dynamic loads on the containment. Section 6 reviews hydrogen measurement systems, systems qualification and probe position. Section 7 introduces various techniques for the control of hydrogen and mitigation measures such as inertization, post-accident dilution, early venting and hydrogen removal. Section 8 considers analytical aspects for hydrogen behaviour analysis. Also discussed in this Section are calculation methodology, computer codes, scenarios, models and other numerical aspects. Section 9 reviews the remaining issues in mitigation measures for hydrogen. Finally, Annexes I to IV describe detailed experimental facilities to investigate hydrogen sources, to measure hydrogen distribution and combustion and practical examples of techniques for mitigating hydrogen hazards.

2. POTENTIAL HYDROGEN SOURCES DURING THE EVOLUTION OF A SEVERE ACCIDENT

2.1. Introduction

Potential hydrogen sources during the development of a severe accident in a LWR come from:

- In-vessel metal oxidation (Zr clads and grids and other metallic structures) or B_4C absorber material oxidation with steam or with water contained in the reactor pressure vessel lower plenum,

- Ex-vessel oxidation of metallic material (Zr, Cr, Fe…) during direct containment heating (DCH) or into the water eventually contained in the cavity pit (short term event occurring at vessel lower head failure),

- Ex-vessel oxidation of metallic material (Zr, Cr, Fe…) during molten core concrete interaction (MCCI) (complete and rapid energetic oxidation of Zr and Cr during the first hour, then partial and slow oxidation of Fe up to the time of the complete basemat penetration by the corium).

Despite the fact that the water radiolysis (in-vessel or in the sump water of the containment) and the metal corrosion in the containment (mainly with Al and Zr) are taken into account in hydrogen sources during a DBA (e.g. loss of coolant accident), these sources are considered negligible during the development of a severe accident. As a matter of fact, in the event of a severe accident, several days are required before the amount of hydrogen produced by these two processes 'alone' renders the air flammable. For instance, typical figures for water radiolysis are around some hundreds of kg of hydrogen produced after three months and 100 kg of hydrogen produced by metal corrosion after several hours, i.e. far less than from other sources [14].

Boron carbide (B_4C) is used as absorber material for BWRs, WWERs and some western PWRs. For instance, in the French P4 and P'4 type of PWRs, the upper part of the hybrid B_4C/AIC control rods is composed of pellets contained inside a stainless steel cladding, contained in a Zr guide tube. Typical for PWR design, the B_4C is in the form of sintered pellets, which have been sintered at atmospheric pressure. In the WWERs and BWRs, usually, the B_4C is in the form of powder, contained inside a stainless steel cladding, and the control blade is also made of stainless steel. Table 1 gives some orders of magnitude of the B_4C and Zr masses, for specific and typical PWRs, WWERS and BWRs.

Very rough orders of magnitude could be:

- 200 to 300 kg of B_4C for PWRs with B_4C compared to at least 4 times more for BWRs with the same power level,

- 20 to 30 tons of Zr for PWRs compared to at least 2 to 3 times more for BWRs with the same power level

TABLE 1. ORDERS OF MAGNITUDE OF THE B4C AND ZR MASSES, FOR SPECIFIC AND TYPICAL PWRS, WWERS AND BWRS

	Typical PWR, kg (3600 MW·th)	French P4-P'4 PWR, kg (3800 MW·th)	French N4 PWR, kg (4270 MW·th)	WWER-1000 Russian fuel, kg [18]	WWER-1000 Westinghouse Fuel Temelin, Czech Rep., kg [18]	Typical BWR, kg (3800 MW·th) [18]
B_4C	No B_4C	~320	~340	~270	~200	~1200
Zr	~26000	~28000	~30000	~22630 (l% Nb cladding)	~24765 (with ~1090 kg spacer grids)	~76000
UO_2	~10^5	~1.15×10^5	~1.24×10^5	~80100	~91750	~1.55×10^5

2.2. In-vessel hydrogen source

2.2.1. Short description of core degradation during a severe accident

Early core degradation

After the core is uncovered, the heat transfer from the fuel to the steam is small compared with decay heat produced and, hence, the fuel temperature increases. The high temperature leads to oxidation of the Zr fuel cladding and hydrogen generation and can also lead to clad ballooning and rupture. Clad rupture is the cause of the first fission product release. The heat-up rate can increase to well above 1 K/s as the local temperature increases above ~1300 K, due to rapid oxidation of Zr and the strongly exothermic nature of the reaction. This part of the core degradation with no loss of fuel rod-like geometry, and only metallic melt and blockage of some channels, is often considered as the ‘early phase of core degradation’.

During the core heat-up of this early degradation phase, hydrogen is mainly produced by steam oxidation of Zr cladding. For BWRs, B_4C oxidation may also have some contribution.

For intact geometry, fresh metallic surfaces exposed at extreme temperatures oxidize, where the oxygen transport through the material is by gas diffusion. Otherwise, the solid state transport of oxygen determines the reaction and the growth rate of the oxidized layer.

From [14], it is commonly agreed that prediction of the hydrogen average source rate, without core reflooding, is typically about 0.2 kg/s for a typical 1000 MW(e) PWR, and this value is sufficiently accurate as long as the core geometry remains intact.

The Zr oxidation kinetics in a steam environment – for intact core geometry – is often described by diffusion models and parabolic correlations, based on experimental investigation, under the laws detailed in Table 2. For other fuel clad materials, such laws are defined in Table 2. Here δ is a kinetic constant under Arrhenius law.

TABLE 2. MAIN ZR OXIDATION CORRELATIONS WITH STEAM IN CLAD GEOMETRY

Correlation	Details
Baker-Just [19]	$\delta = 4.059 \exp(-190200/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1273<T<2123$) *This correlation retains its importance for comparison and licensing purposes. However, from a common understanding of EC 5th PCRD COLOSS project experts, it is advisable not to consider it in best-estimate calculations. It is commonly agreed to use the Baker-Just correlation for 'envelope calculation' type.*
Urbanic-Heidrick [20]	$\delta = 0.036 \exp(-139841/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1323<T<1853$) $\delta = 0.108 \exp(-138095/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1853<T<2123$) *From EC 5th PCRD COLOSS project experts, doubts in the given specimen temperatures and their homogeneity, both related to the method of inductive heating, are fostered by strong discrepancies in comparison to data gained in test programmes using furnace heating. The low-temperature correlation over-estimates the oxidation towards lower temperature. The high-temperature branch under-estimates oxidation with increasing temperature.*
Prater-Courtright [21]	$\delta = 0.3622 \exp(-167200/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1783<T<2673$), relative error ± 35%. $\delta = 32.94 \exp(-220000/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1573<T<1783$), relative error ± 42%. *From EC 5th PCRD COLOSS project experts, in the temperature range above 1800 K, the Prater-Courtright correlations are the unrivalled only choice. Their precision is judged to be considerably inferior due to experimental procedures and evaluation methods, necessary for measuring fast reactions.*
Erbacker-Leistikow [22]	$\delta = 0.524 \exp(-174284/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1073<T<1783$), relative error ± 42%.
Cathcart-Pawel [23]	$\delta = 0.362 \exp(-167117/RT)$, δ in $g^2m^{-4}s^{-1}$, T in K ($1273<T<1573$) *The Cathcart-Pawel and the Leistikow correlations are judged to be of equal and high reliability by EC 5th PCRD COLOSS project experts. This standard is understood to result from strong efforts towards precise temperature measurement and control, the volume of the data bases and adequate and consistent evaluation procedures. Similar results from other programmes confirm this judgment. For support of a choice between both sets of correlations, only comparably weak arguments might be mentioned, the more standardized procedures and the special temperature calibration efforts in favour of the Cathcart-Pawel correlations, the larger data base, the availability of experimentally determined mass gain (oxygen uptake) for all tests and the better fit for lower temperatures in favour of the Leistikow correlations.*

Loss of core geometry

UO_2 fuel can be liquefied at temperatures well below its melting point (3100 K) by dissolution in molten Zr or other metallic material such as iron. At higher temperatures, fuel liquefaction can occur due to the interaction between UO_2 and ZrO_2.

Because of their higher freezing temperature compared to metallic melts, the (U-Zr-O) melts created can lead to a channel blockage at a higher elevation in the core than the metallic blockage. As a result of the diversion of steam around the blockage and of the low thermal conductivity of this (U-Zr-O) crust, heat transfer inside the ceramic blockage is slow, and a molten pool can form inside the core within a ceramic crust.

During the loss of geometry of the core, experts presently consider that the main source of released H_2 comes from (U-Zr-O) melt oxidation. Correct modelling of the (U-Zr-O) melt oxidation is still under investigation, based on newly dedicated experimental programmes.

Presently, in the severe accident core degradation codes, the Zr oxidation correlations established for intact clad geometry are often extrapolated well beyond their domain of validity, being also used to calculate the hydrogen production during the (U-Zr-O) melt oxidation and the reflooding of the damaged core during this phase of the degradation.

Consequently, a large uncertainty stills exists regarding the hydrogen production during this phase of the core degradation. Nevertheless, due to the decrease of metal surface in contact with steam during this phase, experts estimate that the H_2 production can be lower than in the previous phase. But only the use of experimentally validated correlations in the code will confirm this assessment.

Late core phase degradation

Crust failure and melt relocation to the lower plenum are 'late-phase' core damage progression phenomena for which the uncertainties are greater than for the early phase phenomena. The general understanding of the late-phase phenomena is based on examination of the damaged TMI-2 core, because large scale experiments have not been run at high enough temperatures and for long enough time periods for the phenomena to occur fully.

In the late core degradation phase, hot melt can drop into the lower plenum of the vessel, which may be filled with water. Such injection of the melt into the water, for instance in the form of a jet, and fragmentation of the melt, would lead to an increase of the oxidation reaction surface (fragmented particles) and to a strong production of steam, which can oxidize the available metal. Experiments ZREX performed in the USA [24] with Zr/ZrO_2 and Zr/stainless steel, with oxidation degrees of up to 40%, have indicated that typically 5 to 25% of the metals are oxidized.

Presently, as mentioned above, in the severe accident core degradation codes, the Zr oxidation correlations established for intact clad geometry are often extrapolated well beyond their domain of validity, being also used to calculate the hydrogen production during the late reflooding of the damaged core and also during the oxidation of fragmented particles falling into water during this late core degradation phase.

Consequently, a large uncertainty stills exists regarding the hydrogen production during this phase of the core degradation.

2.2.2. In-vessel hydrogen source from Zr oxidation

Orders of magnitude of the H_2 mass assuming a complete oxidation of 100% of the Zr mass with steam

Table 3 gives orders of magnitude of the H_2 mass assuming a complete oxidation of 100% of the Zr mass with steam following the complete chemical reaction:

$Zr + 2H_2O \rightarrow ZrO_2 + 2\ H_2 + \Delta H$ $\quad\quad\quad\quad$ $\Delta H = -\ 586.6$ kJ/mole Zr

Where ΔH is an energy released during the chemical reaction and 0.0442 kg H_2 per Kg Zr was oxidized.

A very rough order of magnitude of hydrogen created by full Zr oxidation could be up to 1000 kg of H_2 for a typical PWR compared to at least 3 to 4 time more for a BWR with the same power (around 1000 MW(e)), and around 1100 kg of H_2 for a 1000 MW(e) WWER.

TABLE 3. ORDERS OF MAGNITUDE OF THE H_2 MASS ASSUMING OXIDATION OF 100% ZR WITH STEAM FOR SPECIFIC AND TYPICAL PWRS, WWERS AND BWRS

	Typical PWR, kg (3600 MW·th)	WWER-1000 Russian fuel, kg	WWER-1000 Westinghouse fuel, kg	Typical BWR, kg (3800 MW·th)
Zr	~26000	~22630 (l% Nb cladding)	~24765 (including 1090 kg spacer grids	~76000
H_2	~ 1150	~1000	~1095	~3360

Main phenomena involved in the H_2 release during a core degradation

The main physical phenomena controlling the in-vessel Zr oxidation are listed in the following sub-sections. For each phenomenon, the level of present knowledge or uncertainty is stated. From all these phenomena, the thermohydraulic effect is considered by experts to be the most influential.

1) Thermohydraulics

The Zr oxidation kinetics is strongly connected to the steam kinetics in the core. In a calculation, the behaviour of steam in the core depends on the thermohydraulic models of the code, which could be 1D (as in integrated severe accident codes, such as MELCOR, MAAP or ASTEC or 2D (in mechanistic core degradation codes, such as ICARE/CATHARE). But whatever the codes are, there exist two main events of the core thermohydrauylics which control the hydrogen release:

- The duration time of the core uncovery:

  As long as steam starvation does not happen, the longer the uncovery time, the greater the amount of hydrogen produced by Zr oxidation, because the core has enough time to heat up and steam is always available.

  Small break loss of coolant accident (LOCA) has a long core uncovery time and, as a consequence, its scenario must be included in the list of calculated scenarios.

- The redistribution of steam flow around a channel blockage:

  During the early phase of the degradation, ballooning and deformation of the cladding leads to a redistribution of the steam in the core. Later on, the molten material relocation can plug some channels. These events prevent locally the arrival of steam on some available Zr surfaces and redistribute the steam in the surrounding core channels, leading to an increase of temperature in the core periphery, for instance.

The 1D or 2D thermohydraulic modelling approach of this event will give very different results in terms of hydrogen release, because of the very different flow redistribution scheme and associated heat transfer in the core. For example, very preliminary calculations using a

2D thermohydraulic model versus a 1D thermohydraulic model in the same code have been performed by IRSN with the ICARE/CATHARE code. Results show a large discrepancy between the calculated hydrogen releases, the 2D production giving the greater one. Nevertheless, validation of such 2D flow redistribution models is difficult because of a lack of dedicated tests.

When using a 1D code and running calculations to check if no possible ‘cliff edge effect’ could exist in the plant regarding the hydrogen risk mitigation, the potential consequences of this lack of 2D modelling of the code need to be kept in mind.

2) Zr oxidation kinetic of the fuel rod clads (intact geometry)

The Zr oxidation kinetics is very often described by consistent diffusion models and parabolic correlations, based on experimental investigations, under the law:

$$k^2 = \delta\ t$$

where k = mass of oxidized Zr/m^2, t = time in second, δ = kinetic constant under Arrhenius law as a function of temperature = Aexp(-Q/RT), Q= activation energy, R = 8.314 kJ/mol/K, T in Kelvin.

The codes using the Zr oxidation correlations for reactor calculations rely on the extrapolation of Zr oxidation correlations coming from specific tests, with given physical conditions.

Limits of the Zr oxidation correlations

Experiments used to obtain the Zr oxidation kinetics have some limits:

- All correlations have been obtained from tests using intact clad tube geometry:

  They are used only during the so-called ‘early phase degradation’ phase of the core.

- Zr used in the tests was non-irradiated:

  Presently, there exist no tests of Zr oxidation using irradiated Zr.

- The parabolic law used in the correlations has been established under isothermal tests:

  The temperature gradient is less than 5 K/s to use the correlation for transient calculations post test calculations of temperature-transient experiments calculated have confirmed the use of these Zr correlations under those conditions; the reaction rate, however, can differ with time/temperature during the transient;..

- All tests have been done under atmospheric pressure (Annex I):

  There exists presently only 2 tests done under elevated pressure, around 60 bar: the PBF-SFD-1.1 and the PBF-SFD-scoping test. These tests were in-pile core degradation tests. Some French calculations of these 2 tests have been performed using the ICARE-2 code (version V3 mod0.4) and the calculated H_2 production was not under-estimated. But it would be hazardous to conclude anything from only 2 tests, because these tests had substantial uncertainties.

- These correlations require a correct modelling of the oxygen diffusivity around the clad.

Presently, there is no international consensus on the best Zr oxidation correlation to be used and the severe accident core degradation codes often offer the choice between several correlations.

- In addition to diffusion, there is oxygen transport through cracks and oxidation by spalling, as discussed above

For instance, the MAAP 4.04 uses the Cathcart-Pawel correlation for temperatures less than 1850 K and the Baker-Just correlation for higher temperatures and the ICARE-CATHARE (version V1Mod1.2) uses the Urbanic-Heidrick correlation.

Nevertheless, the use of some oxidation correlations, even those perfectly matching the experimental Zr oxidation results, can lead to largely overestimate the H_2 production if e.g. not a proper interface model is used to calculate the right amount of steam arriving at the Zr surface, such as the H_2O diffusion in the (H_2+H_2O) mixture at the clad interface. Consequently, most of the international severe accident codes presently use the Urbanic-Heidrick correlation because it tends to give better results when compared to integral tests such as PHEBUS, despite the present lack of correct modelling of the core thermal hydraulic in these codes (the diffusivity models of oxygen around the clad overestimate the oxygen diffusion).

When running calculations for a scenario, this effect needs to be kept in mind. If interface models are present in the code allowing to calculate the amount of steam arriving on the Zr surface, such as the H_2O diffusion in the (H_2+H_2O) mixture at the clad interface, the Baker-Just correlation can e.g. be used for an 'enveloping' calculation, or the Cathcart-Pawel with Baker-Just (or Leistikow) correlation as in MAAP 4.04 for 'best-estimate' calculations. If no such models are present, the Urbanic-Heidrick correlation still remains the usual choice.

3) Onset of ceramic melt relocation

Concerning the loss of core geometry, the onset of melt relocation and fuel rod collapse changes from one experimental result to another. This is partly caused by especially the chemical parameters, which are still not well understood today. The start of the loss of core geometry is relevant for the hydrogen production, because the loss of core geometry is linked to the decrease of the oxidation surface.

Any criterion used in a code linked to the onset of melt relocation plays a role in the calculated H_2 release. E.g., in the French ICARE codes, the 'clad failure criteria' depend on temperature criteria and the thickness of ZrO_2 created on the external surface of the clad. In the MAAP code, the approach is similar but there is in addition a simplified mechanistic failure criterion (creep failure criterion). Both codes have also chemical dissolution models of Zr with surrounding materials.

When running calculations for a scenario, this effect has to be kept in mind and run sensitivity cases, choosing the time of the onset of the ceramic melt relocation 'later' than the reference case choice. Help to find a proper value for this parameter needs to come either from the validation report of the used code or from the advised values list given in the code manual.

Choosing a parameter value allowing a 'later core relocation' increases the time of intact geometry rod for rod oxidation, which gives usually a higher hydrogen release, because hydrogen releases of relocated core are judged to be lower than with an intact geometry, assuming the same parabolic oxidation correlation. This is due to the fact that that the metallic surface is decreased in a relocated core compared to an intact geometry. Note that the use of the oxidation correlation depends also on the possibility of the 'break away' effect, discussed before – this item is further treated in Item 4) below.

4) Oxidation of (U-O-Zr) melts

Some experimental work oxidation of (U-Zr-O) mixtures are in the frame of the COLOSS project of the EC-FWP-5, such as the SKODA-UJP experiments, using solid U-Zr-O alloys ingots (Annex I). Preliminary experimental results tend to show that Zr oxidation kinetics is linear, i.e. faster than the parabolic kinetic of the intact geometry Zr oxidation kinetics. This means that when melt relocation starts, the oxidation of U-Zr-O mixtures could contribute to a significantly larger hydrogen production, with a high kinetics. Consequently, the use of parabolic Zr oxidation correlation (such as ones used for intact geometry) is not advised.

As parabolic correlations are presently used in codes and calculations have to be run to check if no possible 'cliff edge effect' exists in the plant regarding the hydrogen risk mitigation, the potential underestimation of the hydrogen source due to this lack of modelling of the (U-Zr-O) mixtures oxidation needs to be kept in mind.

5) In-vessel reflooding

Large uncertainties remain to exist concerning the hydrogen production in case of reflood of a degraded core. High hydrogen production rates associated with reflood have been estimated from the TMI accident and recorded in some integral experiments (CORA, LOFT, etc.). The current FZK QUENCH experiments have extended the knowledge base (see Annex I). But since this programme does not use prototypic materials and investigates mainly rod-like geometries, there will still be some remaining uncertainties.

Nevertheless, some quantitative and qualitative useful information can be presently extracted from all related experiments. IRSN conducted recently a synthesis of knowledge regarding in-vessel core-reflooding, based on analysis of international synthesis documents and re-analysis of some main experimental outcome [19]. The main conclusions of this work are:

- For a mostly intact core, it is rather unlikely to get a hydrogen peak during reflooding. In the QUENCH international workshops, consensus was achieved on a weak contribution of ZrO_2 cracking and shattering (leading to oxidation of underlying Zr), and of clad hydriding on hydrogen release during reflooding. If 'break away' occurs, however, a large hydrogen source will occur due to the cracking and spallation, as was seen in the QUENCH-12 test for WWER-fuel [18].

- For a slightly degraded core, it is likely that the hydrogen peaks observed during reflooding in the tests come from the oxidation of metal rich (Zr-O, U-Zr-O) mixtures during their candling flow or after freezing. The H_2 kinetics during reflooding in this core configuration is rather rapid (~ linear kinetic), compared to the parabolic kinetics of the oxidation of an intact Zr bundle. B_4C seems to contribute to the H_2 peak (QUENCH-07 and CORA tests).

- For a ‘particulate bed’ core, the oxidation of metal is responsible for significant additional H_2 release, due to the increase of the exchange surface.

- Concerning the status of models and codes in 2002 to calculate the H_2 peak during in-vessel reflooding (models for ZrO_2 cracking and shattering, and clad hydriding, no reliable model for U-Zr-O mixture oxidation), the thermochemical and mechanical models in the codes underestimate the heat-up and the H_2 production.

One of the main conclusions of the EU COLOSS project [20] is that oxidation of U-Zr-O and Zr-O mixtures could explain the high peak of hydrogen observed in CORA and QUENCH experiments, due to the high oxidation kinetics of these mixtures.

IRSN experts have made an extrapolation of oxidation kinetics observed in the QUENCH experiments to the 4500 MW·th EPR. This extrapolation, which is only a rough estimate, leads to reactor kinetics between 0.2 kg/s (extrapolation from QUENCH-01 results) and 7.5 kg/s (extrapolation from QUENCH-03 results). Extrapolation by IRSN for the H_2 peak release during in-core reflooding of a degraded core for a French 2800 MW·th PWR is around 1 kg/s.

These extrapolations, to be used only with care for the purpose of comparison, show that the variation of hydrogen production rates during in-vessel reflood can be very large, and kinetics very different from one transient scenario to another. This effect has to be taken into account in calculations of scenarios with reflooding when checking if no possible ‘cliff edge effect’ could exist in the plant regarding the hydrogen risk.

The research on in-vessel reflooding is still ongoing. Future tests are planned in the QUENCH facility for the years to 2010.

2.2 3. In-vessel hydrogen production coming from steel oxidation

Steel oxidation may contribute about 10% to 15% of the total in-vessel hydrogen production [14]. Similar to Zr, sufficiently accurate oxidation correlations are available for an intact geometry, but no molten steel oxidation correlation exists at the present time.

2.2.4. In-vessel hydrogen production coming from B_4C absorber material oxidation

During the melting of the core, when steam comes into contact with the remaining B_4C inside the control rods, it is likely that any exposed B_4C will react rapidly with the steam atmosphere. The B_4C–steam reactions are summarized in Table 4 [25]. The energies released at 1500 K and 2200 K according to Ref. [21] are also included in this table.

The gas phase produced involves H_2, CO, CO_2 and CH_4. In addition, vapours of B_2O_3 and various acids of boron are produced. It is important to add to these reactions those possible between the gases produced and the gaseous atmosphere (H_2/steam ratio) of the primary circuit under severe accident conditions. If the gaseous fission products contained in the primary circuit and in the containment are neglected, these reactions are the following ones:

TABLE 4. POSSIBLE CHEMICAL REACTIONS DURING B_4C OXIDATION

Existing reactions	Energy released at 1500 K (kJ/mol B_4C)	Energy released at 2200 K (kJ/mol B_4C)
$B_4C + 7\ H_2O \leftrightarrow 2\ B_20_3 + CO + 7\ H_2$	–740	–712
$B_4C + 8\ H_2O \leftrightarrow 2\ B_20_3 + CO_2 + 8\ H_2$	–770	–738
$B_4C + 6\ H_2O \leftrightarrow B_2O_3 + CH_4 + 4\ H_2$	–965	–930
$B_2O_3 + H_2O \leftrightarrow 2\ HBO_2$	661	624
$B_20_3 + 3H_2O \leftrightarrow 2\ H_3B0_3$	–79	–72
$3B_2O_3 + 3\ H_20 \leftrightarrow 2\ (HBO_2)_3$	–85	–122

(a) $CH_4 + H_2O \leftrightarrow CO + 3\ H_2$

(b) $CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$

(c) $CO + H_2O \leftrightarrow CO_2 + H_2$

Consequently, B_4C/H_2O reactions contribute to the hydrogen source term and these oxidation reactions under steam are more exothermic than the Zr ones and produce more hydrogen per gram material than Zr oxidation. The consequence of this effect depends on the mass of B_4C in each reactor type.

To illustrate the effects of B_4C oxidation, Table 5 summarizes the orders of magnitude of H_2 resulting from B_4C oxidation versus H_2 resulting from Zr oxidation. A rough order of magnitude of the H_2 production is 0.15 to 0.30 Kg H_2 per kg of B_4C oxidized by steam.

Consequently, the quantity of H_2 generated by the oxidation of B_4C remains low for PWRs and WWERs compared to the H_2 produced by the oxidation of the fuel rod cladding. Nevertheless, the strong linear kinetics of the oxidation of B_4C could contribute to local effects in the containment, such as hydrogen pockets.

TABLE 5. POSSIBLE CHEMICAL REACTIONS DURING B_4C OXIDATION

Reactor type	H_2 generated by B_4C oxidation with steam	H_2 resulting from B_4C oxidation versus H_2 resulting from Zr oxidation, with steam
French P4-P'4 PWR	between 45 kg and 95 kg	less than 10%
French N4 PWR	between 50 kg and 100 kg	less than 10%
Russian WWER-1000	between 40 kg and 80 kg	at most ~ 8%

As BWRs use 2 to 3 times more B_4C mass than PWRs or WWERs, H_2 contribution arising from B_4C oxidation to the total H_2 release may not be anymore negligible.

An experimental programme on B_4C oxidation has been performed in Europe (EC 5^{tlh} FWP COLOSS project [20]). Also the PHEBUS FP programme has performed a test with a B_4C absorber rod (Test FPT3).

2.2.5. Consequences to be drawn regarding calculations

In-vessel hydrogen source and release are already large enough, and appear early in the accident, to warrant a separate hydrogen risk analysis.

In order to deal with the great amount of uncertainty in the calculation of the in-vessel hydrogen source by the core degradation codes, a set of representative accident scenarios, depending on the purpose of the calculations, has to be chosen first.

- In order to detect the hydrogen risk on a NPP, a common way is to run a core degradation code (or even several codes) on representative scenarios of severe accidents (a small break LOCA with different break locations and one loss of secondary feed water scenario should be enough), using a certain assumed quantity of Zr mass (or metal mass) oxidized at the time of the vessel lower head failure. This assumed quantity of oxidized Zr (or metal) is often derived from national regulations. This method is often used by safety authorities, but there is no international consensus on this quantity. For instance, to identify the H_2 risk in France, containment calculations with 100% Zr ACL (active cladding length) have to be performed. Calculations in the USA use often a maximum of 75% Zr ACL reacted.

- To implement mitigation measures for hydrogen, often a core degradation code (or even several codes) is run on scenarios and direct use is made of the hydrogen output given by the calculations. Section 8.5 of this report describes the selection process of relevant scenarios and corresponding boundary conditions (mass and energy release), using deterministic and probabilistic approaches.

In order to deal with the large uncertainty presently associated with the calculation of the in-vessel hydrogen source, selected sensitivity studies are executed on the code parameters which play an important role in the hydrogen release, such as the loss of core geometry (onset of melt relocation and the collapse fuel rod), the oxidation of relocated and relocating U-Zr-O mixtures, and late core reflooding, because these uncertainties can have a great influence on the hydrogen production. The different values (code specific) given to the parameters for the sensitivity studies on the relevant phenomena have to be set in a way to check possible cliff-edges effects.

2.3. Ex-vessel hydrogen production

2.3.1. Short term H_2 release during vessel lower head failure

H_2 production during release of corium from RPV into a flooded cavity

Uranium may come into contact with steam, for example in the case of the release of corium from the reactor pressure vessel into a flooded cavity. Uranium dioxide reacts with steam to produce UO_2 and hydrogen. The extent of the reaction is dependent on the partial pressures of steam and hydrogen. It was reported in earlier works that the fraction of uranium dioxide that reacts is limited in the presence of a large excess of steam over hydrogen and that it becomes very small when hydrogen is present.

However, experimental results produced during the course of the FARO FCI experimental programme, have shown that hydrogen can be produced in significant amounts during the quenching of corium by water, even though the melt is already oxidized. The interpretation of measurements gave figures of about 0.2 kg of hydrogen produced for 100 kg of melt.

From Ref. [14], a simple extrapolation from the FARO test to the large scale reactor situation would give a H_2 source of 200 kg. Because of limitations of the mixing process of melt and water, it is recognized that the large melt masses would certainly not undergo the same degree of chemical reaction as in a small experiment. Therefore, realistic H_2 rates are expected to be significantly smaller.

In conclusion, it must be stated that the associated phenomena are not understood to date and require further investigations. Nevertheless, the hydrogen produced needs to be only a small fraction of the total in-vessel production.

H_2 production during direct containment heating (or high pressure melt enjection)

In case of a reactor vessel bottom breach when the reactor coolant system is pressurized (accident scenarios as loss of offsite power, small break LOCA), a DCH can happen. As observed in DCH experiments done in the Sandia National Laboratory in USA, the Zr still present in the corium at the time of the vessel breach undergoes a very fast oxidation with the available oxygen and steam. This availability depends on the design of the cavity pit and surrounding compartments. If the corium is directed into an intermediate compartment before reaching the dome, as in some reactors like Zion NPP in USA, it is correct, based on the USA tests, to consider that all remaining Zr contained in the corium at the time of the vessel breach is oxidized in the intermediate compartment during the time duration of the DCH. If the corium is directed into the dome without going through an intermediate compartment, the Zr oxidation process may not be 100% complete. Nevertheless, experts generally assume that 100% of the remaining Zr is oxidized during the DCH event (or very shortly after) in the containment or the cavity pit.

Assuming H_2 combustion in the containment at the same time as the arrival of the dispersed corium into the containment during a DCH adds to the pressure in the containment. The H_2 available for combustion comes from the H_2 present at the time of the vessel lower head failure and from the H_2 released from Zr oxidation during the DCH.

Consequently, the mass of non-oxidized Zr and Cr at time of vessel lower head failure is the main parameter to investigate the effect of this short term H_2 release during a DCH.

2.3.2. H_2 production during molten core-concrete interaction

In case of a reactor vessel bottom breach when the reactor coolant system is depressurized, a gravitational corium drop occurs and in case of a dry cavity pit, a MCCI starts.

The Zr and Cr masses contained in the corium, coming from the remaining Zr and Cr masses in the corium at the time of the vessel lower head failure, undergo a fast oxidation in the steam and CO_2 environment, where the CO_2 is coming from the thermal decomposition of the basemat concrete. Due to the violent gas release from the concrete into the corium at the beginning of MCCI, the masses of H_2O and CO_2 are well in excess of those of Zr and Cr and are in close contact with these. Experts generally assume that 100% of these remaining Zr and Cr masses will be oxidized by steam to give H_2 and CO within the first hour (even less) following the beginning of MCCI. Then, the remaining metal (Fe) is oxidized for days, leading to typical hydrogen release rates of 2 mol/s (4 g/s) [14] until the complete basemat penetration, depending on the reactor basemat thickness.

Consequently, the thermohydraulic characteristics of the corium and the heat transfer mechanism during MCCI, as well as the chemistry treatment, are only of secondary importance at the beginning of MCCI. Later in the MCCI process, the amount of hydrogen generated can be substantial. E.g. a WWER-1000 study reports a total of around 2000 kg hydrogen generated in the MCCI process.

The main parameters controlling the amount of released H_2 during MCCI are the masses of Zr and Cr at the beginning of MCCI (at the beginning of MCCI, Fe mass is not a key parameter because of its very low oxidation potential compared to Zr and Cr).

When the gas mixture emerges from the melt, it undergoes chemical equilibrium at temperatures as low as 1000 K. This experimental observation is consistent with expectations based on the known kinetics of gas-phase reactions. The predominant reactions affecting the gas composition at the exit of the corium are:

$$H_2O + CO \rightarrow H_2 + CO_2$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O$$

With decreasing temperatures, both these reactions are shifted increasingly to the right hand side. Below about 1000 K, these reactions are slow enough that equilibrium compositions cannot be maintained.

If a water pool overlies the core debris, the gases may be quenched rapidly, so that their compositions upon emerging from the core debris will be preserved.

Besides, the real impact of the hydrogen produced in the course of MCCI remains uncertain. Due to the high gas temperature and the simultaneous release of hot particles associated to that phase, it seems reasonable to assume that hydrogen produced ex-vessel will burn immediately, provided oxygen is available. Nevertheless, this assumption is not currently demonstrated (neither the availability of oxygen within the reactor cavity after reactor pressure vessel failure). Therefore, it is not possible to exclude that hydrogen produced ex-vessel could be accumulated with the in-vessel production.

CO effect

During core concrete interaction, also CO can be released, depending on the basemat concrete composition. Hence, the results are highly plant specific. The study of the flammability in the containment must take into account the sum (H_2 + CO) in the risk evaluation due to the combined combustion of hydrogen and CO [22] (see Section 4.3.8 of this report for a detailed description of the safety implications of CO in containment).

The concrete in the reactor basemat may be siliceous or of the limestone type. For a siliceous concrete, the gas production is low and does not have any significant consequences on the pressure rise in the containment. In general, the CO concentration in the containment is less than 1% by volume, regardless of reactor compartment volume. The ratio between the composition per unit volume of hydrogen and carbon monoxide could reach values exceeding 10. As a consequence, for a silicate concrete with a very low $CaCO_3$ concentration, one can neglect the contribution of the CO to the risk from hydrogen.

For a limestone type concrete, there is a higher gas release rate than with a siliceous concrete. On average, during the high-temperature phase of corium concrete interaction (less than one hour), the atmosphere in the reactor pit could contain up to 40% of combustible gas by volume, mostly carbon monoxide. This depends, of course, on the concrete composition. After several hours of MCCI, the ratio between the concentrations per unit volume of hydrogen and carbon monoxide in the containment could vary from 2 to almost 1.

2.3.3. Other possible ex-vessel H_2 production

Radiolysis of water

Radiolysis of water occurs both during normal operation and under accident conditions. It may take place in the core and in the sump. It involves the decomposition of water molecules by radiation, which produces various radicals. The net result is the production of hydrogen and oxygen molecules in essentially a stoichiometric ratio. The phenomena are reasonably understood for pure water at room temperature. More uncertainties exist for elevated temperatures and the presence of solved matter and impurities. However, evaluations have shown that under accident conditions the rate of hydrogen production is low. Typical figures are in the order of some hundreds of kilograms after three months. This low production rate can easily be accommodated with existing mitigation means, such as hydrogen recombiners. Provisions are usually already taken with respect to water radiolysis for post design basis accidents (e.g. LOCA).

Corrosion reactions

In a containment, the only significant sources of hydrogen from corrosion are reactions of zinc and aluminium. Zinc is present in some types of paint and in galvanized steel. These reactions are of importance for high and low pH values. Evaluations have shown that the amount of hydrogen that could be produced by corrosion reactions is in the order of 100 kg in some hours, i.e. far less than from other sources. As for radiolysis, this production can easily be accommodated by existing mitigation means.

WWER chemical reaction between borium and aluminium

In a WWER, there could be a concern about hydrogen production coming from chemical reactions between boric acid and some aluminium components of the containment structures, when the spray is activated.

3. HYDROGEN DISTRIBUTION

The layout of the containment as well as the location and the mass flow rate of the hydrogen source and its mixing with other gases influence the hydrogen distribution significantly. The characteristic of the hydrogen release depends strongly on the accident sequence. For the design of a system for the mitigation of hydrogen risk, different and enveloping sequences had to be chosen. The choice of the scenarios concerning hydrogen sources is described in detail in Section 3. Section 8.5 gives proposals to the choice of representative accident scenarios.

3.1. Description of containment

Containments for NPPs can have different shapes. The most common types are described here shortly concerning the effect on hydrogen distribution.

3.1.1. Full pressure containment

PWRs are mostly equipped with a containment which is able to withstand the pressurization following a double ended break of the main coolant line. A PWR normally needed space for its steam generators (especially for vertical steam generators) in the containment and due to this the free volume of the containment is normally significant larger than for a BWR.

Cylindrical PWR concrete containment

One type of ‘full pressure’ containment is the concrete containment which can be reinforced or prestressed. It is either a single containment or a double containment, and it can be more or less open or compartmentalized. Some of the concrete containments are equipped with an inner steel liner.

Containments where a part is accessible during normal operation are divided into inaccessible equipment compartments (in which the primary circuit is enclosed) and into accessible operating compartments. The two parts are vented separately and under normal operation the inaccessible compartments have a lower pressure than the accessible ones forcing any airborne activity into the inaccessible compartments. In the case of a large break LOCA burst facilities (Flaps or rupture disks) open and connect the accessible and the inaccessible part of the containment to limit pressure differences. These connections are also important for global mixing. If the pressure built up in the equipment compartments during an accident sequence is not sufficient to open a sufficient number of these pressure equalization devices the convection may be disturbed and dead end rooms may exist.

In Fig. 1 the cylindrical containment, as an example for a compartmentalized double containment, and an open single containment (e.g. Westinghouse or French PWR containment as well as the containment for the MHI APWR) is shown schematically.

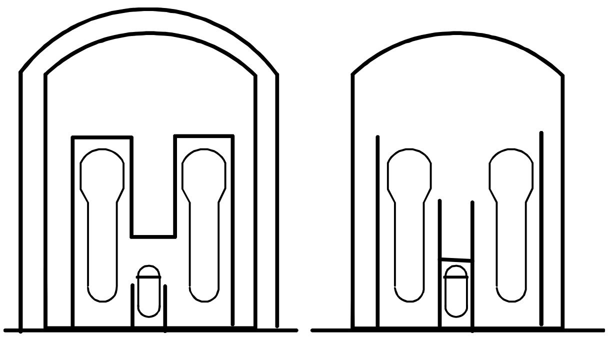


FIG. 1. Cylindrical concrete containment (compartmentalized double containment(left) and open single containment(right)).

Spherical PWR steel containment

An often used type of containment for PWR is the spherical steel containment surrounded by a secondary concrete shell (Fig. 2). In the space between the steel shell and the concrete outer wall, in the annulus, a small sub atmospheric pressure is obtained to prevent radioactivity releases into environment even by small leakages from the steel.

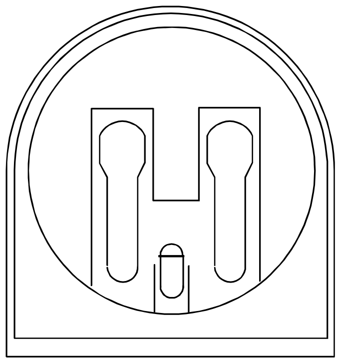


FIG. 2. Spherical steel containment with secondary shield.

3.1.2. Containments with pressure suppression system

PWR containment with pressure suppression system

The WWER-440 has square concrete reactor building with so called hermetic zones (confinement). They can only withstand a relatively small pressurization. The newer types are therefore equipped with a pressure suppression system, the so called bubbler condenser system.

The steam air mixture after a loss of coolant accident flows through a channel into the gap – cap – system of the bubbler condenser tower. The trays of the tower are filled with water in which the steam condenses. Flaps to the air traps open to limit the pressure, when the pressure in the condenser chambers exceeds a certain value,

The hermetic zones are relatively small and low, the steam generators are horizontally arranged. Fig. 3 shows this concept schematically.

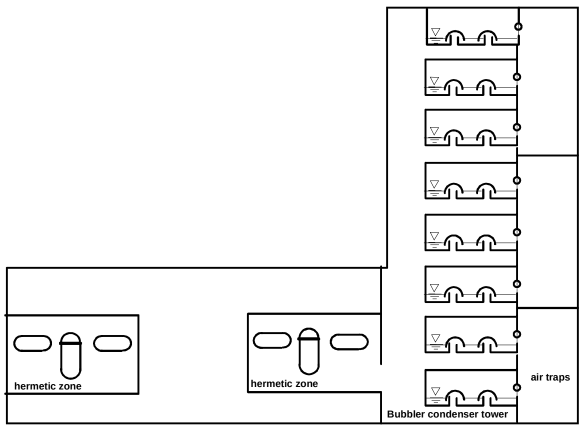


FIG. 3. PWR containment with bubbler condenser tower (WWER-440).

BWR with steel shell

BWRs with a steel containment often have a spherical shell with a bump for the control rod drive compartment (see Fig. 4). The wetwell is arranged in the middle of the shell around the equator. Their free volume is relatively small.

This type of containment is used for the KWU BWR BL69 and similar in respect to hydrogen with the Mark I containment from GE.

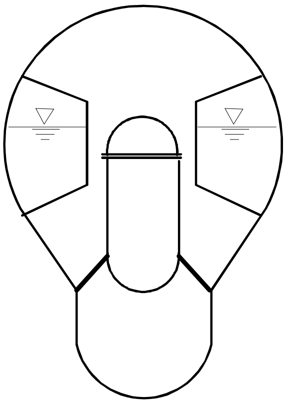


FIG. 4. BWR containment with steel shell.

Concrete containment for BWR

Concrete containments are often cylindrical, prestressed or reinforced and with or without an inner steel liner. A more or less common concrete containment for a BWR is those for the KWU BWR BL72 (Fig. 5). It is more or less similar to the GE Mark 2 containment and the Swedish ABB containment. The wetwell is arranged annular. Above the containment in the same cylindrical building the spent fuel pool is arranged. The free volume is also relatively small and the design pressure is low.

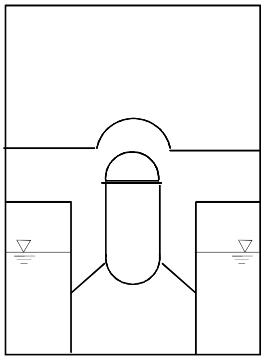


FIG. 5. BWR with cylindrical concrete containment.

Containments with ice condenser

A total other type of pressure suppression system is the ice condenser (Fig. 6). This type is employed by Westinghouse PWRs and also applied in the Loviisa NPP.

The lower vertical inlet doors open into the ice condensers, when the pressure difference across the doors increases due to gas and energy injection into the lower compartment. They have springs attached to them to create a closing torque, when the lower compartment overpressure has been relieved. The lower inlet doors quite efficiently prevent a return flow of cold air to the lower compartment. The horizontal intermediate deck doors are heavy structures that remain in place except during the initial blowdown period of a large break loss-of-coolant accident. The top deck doors are large non-rigid horizontal flaps.

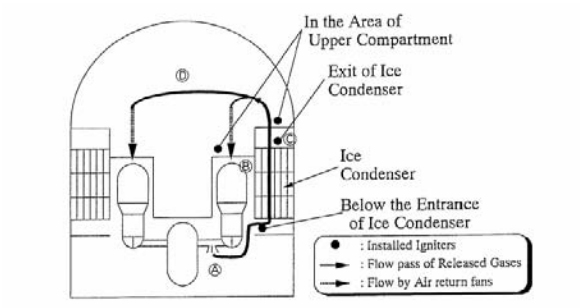


FIG. 6. PWR containment with ice condenser.

3.2. Location of hydrogen sources in the containment

The location of hydrogen release from the primary circuit depends on the accident sequence and the containment layout. It has a strong influence to the hydrogen distribution.

As an example LOCA sequences in a PWR as initial events will lead to steam and hydrogen releases from the main coolant line, the surge line or the pressurizer. In non-LOCA accident sequences the hydrogen release occur in the bleeding phase (pressure relief of the primary circuit) or when the reactor pressure vessel fails.

In plants with vertical steam generators and high containments (PWRs) the main coolant line is in the lower part of the containment, while the burst devices of the pressurizer relief tank are more in the upper part or the middle of the containment. In high spherical or cylindrical containments, especially when they are divided in an outer and an inner part of the containment, due to the missile shield, a mass and energy release in the lower part of the containment will usually lead to good mixing conditions, while a high location for the release will give preference to stratification. This effect was clearly shown in the PHDR experiments E11.2 [27]. In the more or less flat WWER-440 confinements this effect will be minor.

The effect of the location of the hydrogen source has to be taken into account while choosing accident scenarios for designing a system for the mitigation of hydrogen risk. At least a sequence with a high and one with a low location for the release had to be chosen to cover the different mixing conditions.

3.3. Effect of release mode and spraying on hydrogen distribution

The way the hydrogen is released into the containment influences its distribution. A high release rate intensifies the convection but also leads to high hydrogen concentrations.

Besides the location the combined release of hydrogen with other gases (e.g. steam) influences the distribution due to buoyancy effects. When hydrogen is released together with steam (which can be expected in most of the sequences) then there are two effects reducing the risk for deflagration.

- The steam is an inerting dilution of the atmosphere
- The low density of steam and hydrogen support mixing by buoyancy.

Fig. 7 shows examples for a stratification which may occur. On the left side a sequence is shown where the hydrogen is released ‘dry’ without steam due to e.g. a small leak rate. When the hydrogen is mixed with dry air this mixture may have a higher density as the overlaying steam and thus the steam cannot be penetrated. On the right side a high release location (e.g. from the pressurizer relief tank) for a hydrogen steam release is assumed together with relative cold air in the lower part of the containment. The cold air cannot be penetrated by the steam hydrogen mixture with its lower density.

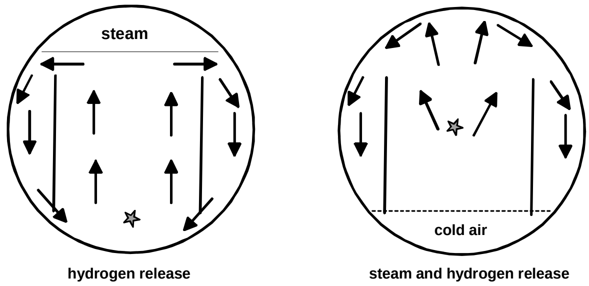


FIG. 7. Examples of mixing and stratification.

Spraying in the containment is used in many NPP to reduce the pressure after an accident. Spraying has two effects concerning hydrogen distribution:

- It intensifies mixing processes and, thereby reduces the risk for hydrogen accumulation in pockets and, hence, the risk of local detonations.
- It condenses steam from the atmosphere (which is the desired effect) and thus enhances the hydrogen concentration and reduces the inerting steam. Initiating the spray system can result in flammable or even in detonable gas mixtures inside containment.

3.4. Containment layout effects

The general layout of the containment affects the hydrogen distribution. The question, if it is possible to build up global convection loops for mixing, the effect of dead end rooms and large water pools, especially pressure suppression pools, depends on the layout.

As mentioned above a high containment with a missile shield will offer good mixing conditions as long as a driving energy source exists and connections are available. A convection flow upward in the inner part and downward in the outer part can be established due to cooling the downward stream on the containment walls. Fig. 8 shows the global convection in principle.

If there are not sufficient connections between the outer and the inner part, a complete other picture will occur (see Fig. 9).

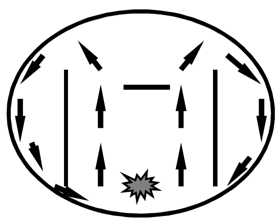


FIG. 8. Global convection in containment with missile shield and an energy source in the lower part (sufficient connections).

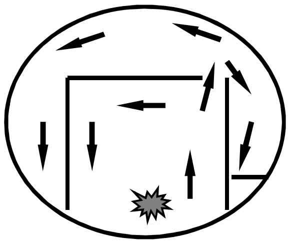


FIG. 9. Effect of dead end rooms.

With no sufficient connection dead end rooms can build. To those dead end rooms steam and hydrogen is released in the first phase of accident progression, when the whole containment is pressurized. In later phases, when the release into the containment decreases, the condensation of steam leads to an increase of hydrogen concentration. In some dead end rooms, without any countermeasures, even explosive mixtures can occur.

In containments with a pressure suppression system (BWRs or WWERs with bubbler condenser towers) the hydrogen will gather in the atmosphere over the pool or in the air traps. In these regions the hydrogen concentration may be high and due to the condensation practically no inerting steam will exist.

3.5. Analytical tools

3.5.1. Integrated codes or system codes

For safety assessments of NPPs, there are computer codes that cover all aspects of in-vessel and ex-vessel severe accident phenomena including thermohydraulic response in the reactor coolant system and containment, core heat up, core degradation and relocation, fission product release and transport, direct containment heating, molten core concrete interaction etc. These codes (e.g. MAAP, MELCOR, ASTEC) are called integrated codes or system codes.

For these codes simpler physics, models and calculation methods were preferred in order to simulate various and complex severe accident phenomena over a long time period and to conduct the calculation within a limited period. For the containment thermohydraulics, and thus the hydrogen distribution analysis, the lumped parameter method with fast running simpler models and with fewer nodes has been applied.

The models of these codes have been validated with experiments and the codes participate in international benchmark exercises. Since they are only used for severe accidents the validation is not as strong as for codes used in the design area.

The general advantage of these types of codes is their ability to calculate even accident sequences with a problem time of some days in an acceptable computation time. This fast computation is due to the simpler physics and models and paid for by less accuracy.

3.5.2. Lumped parameter codes

Up to now the common tools for hydrogen distribution and hydrogen risk mitigation analyses are so called ‘lumped parameter’ codes (e.g. COCOSYS, WAVCO, CONTAIN, GOTHIC). These codes are based on the fundamental assumption that within a chosen volume, called a control volume, spatial differences of thermohydraulic variables – like fluid density, concentration and temperature – are neglected. While only the time-dependent behaviour is represented in conservation equations that describe containment transport processes. In this type of approximation, compartments within containment are built up multidimensional by ‘control volumes and flow paths’. Each flow path connects two control volumes specified by user input data. A control volume is allowed to have an arbitrary number of flow paths. Energy and mass conservation equations are defined in each control volume. The control volumes are linked to each other via a transport of mass and energy. The resulting set of conservation equations, without space dependency, is a set of ordinary differential equations that must be solved for each time step using well-established numerical methods.

The lumped parameter codes are now used for severe accident analysis over years. Since they are also used for safety analysis in the design process they are validated against experiments in these fields. For severe accident analysis the codes have been modified and improved by conducting analyses of relevant experiments and models (e.g. correlations) have been added and modified to handle the installation of the accident management equipment – such as sprays, fan coolers, and recombiners – which mostly induces thermohydraulic mixing processes in the containment.

Advantages of the lumped parameter codes are as follows:

- Modest input set-up requirements using containment data that are readily available;
- Relatively fast-running (economical) on a variety of platforms;
- Structured so that integrated models can be readily incorporated – using simple models to predict complex physical processes, such as global/regional gas mixing behaviour;
- Mature computation technique, with a large validation base, and, extensive user community, representing a considerable resource of experience.

Disadvantages of the lumped parameter codes are as follows:

- Current inability to predict some of the details of local/regional gas mixing (lack of detailed entrained modelling for jets, plumes, and shear layers; lack of momentum convection modelling);
- Molecular/turbulent diffusion modelling is generally lacking;
- Limited capability for predicting compartments flow velocities that could be used in mixed convective heat and mass transfer correlations to improve the containments load prediction;
- Estimation of the efficiency of recombiners may be over or underpredicted depending on the volume of the node.

Some of the disadvantages can be reduced by really experienced users.

3.5.3. Computational fluid dynamics codes

In addition to lumped parameter codes is a class of codes, referred to here as ‘computational fluid dynamics (CFD)’ codes where spatial variation of fluid properties is locally taken into account and a momentum equation is solved at a number of discrete points that represent a finite control volume (e.g. GASFLOW, CFX). Conservation equations for mass, energy, and momentum are developed on the basis of partial differential equations where trends in spatial variations of calculated properties are accounted for inside a control volume.

To avoid extrapolations over too great a distance, these code types require a large number of control volumes to simulate the detailed behaviour of a thermohydraulic system. One noted difference, in relation to the lumped parameter code, is that the momentum equation in the CFD code is derived as a multidimensional equation, considering transfers from the connected control volume and accounting for the advection of momentum between volumes. Moreover CFD codes allow for the calculation of the viscosity divergence term in the Navier-Stokes equation by finite difference methods.

Therefore, CFD codes have, in principle, a method for predicting inhomogeneous gas concentration and gas temperatures within a free volume where shear stresses within the gas flow is important. Such a capability does not exist with lumped parameter codes. However, closure relationships for turbulence modelling are needed to apply these field equations, and these relationships are often only approximately known and must be verified for the flow regime. In addition, these CFD codes, like the lumped parameter codes, do not calculate the boundary layers along structure boundaries; therefore, atmosphere to-structure mass and energy exchange predictions require engineering correlations similar to those used in lumped parameter codes.

The basic equations from these codes are well understood and validated. But the validation of the whole codes, especially the turbulence models and the engineering correlations, is limited.

Advantages of the CFD codes are as follows:

- It predicts local/regional steam gas concentrations that could be important in determining the spatial progression of certain hydrogen combustion events and the details related to an evaluation of hydrogen risk mitigation strategies.

- It provides a prediction capability for determining primary and secondary flow patterns that could improve on models for heat and mass transfer; therefore, they may be used to predict containment loads with a higher degree of local accuracy.

- It enables the prediction of the tight coupling between transport and combustion processes.

- It is adaptable for estimating counter-current flows in large flow paths.

- It is useful for benchmarking lumped parameter thermohydraulic model simplifications.

Disadvantages of the CFD codes are as follows:

- It protracted input set-up times and long computational times that practically require a mainframe computer.

- Ability to perform parametric sensitivity studies is limited because of long running times (these disadvantages will become less significant in the future with increasing performance of computers).

- It has general requirements to demonstrate spatial convergence of the 3D model.
- Potential user and numerical distortions can be amplified.
- Containment configurations are complex (numerous structural/equipment components) and the effect of geometrical simplifications on predicted results could be significant.
- Validation base is limited (turbulence modelling uncertain).
- Mesh size near heat structures is dependent on the empirical heat and mass transfer correlation used (mesh size greater than boundary layer required for consistency).

Despite these disadvantages CFD codes are able to give further inside in physical processes where 'lumped parameter' codes reach their limits. An example is given in Fig. 10.

It can be seen that local as well as short time range effects can be predicted reasonably well by lumped parameter codes.

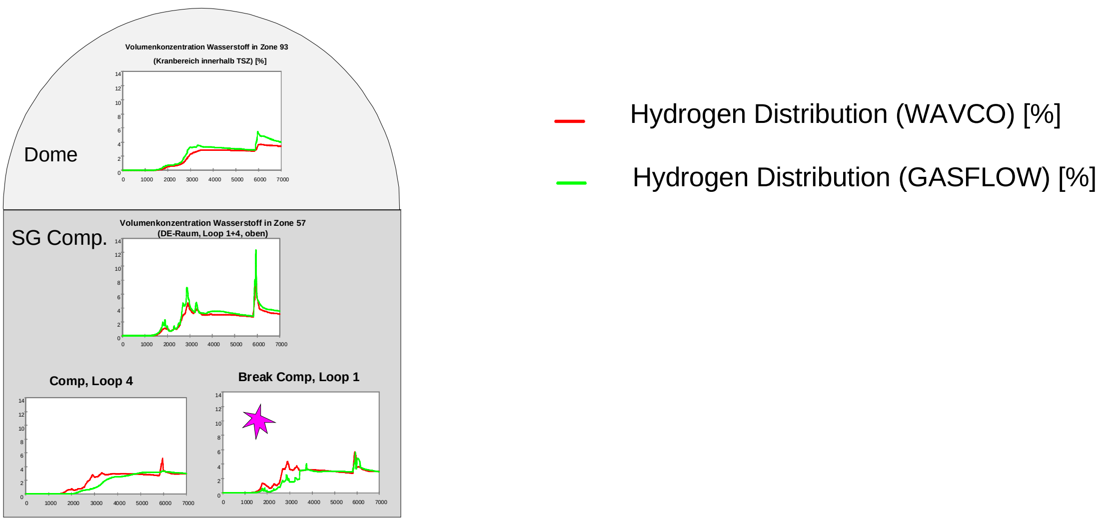


FIG. 10. Example of a comparison of hydrogen concentration results obtained with a CFD code and a 'lumped parameter' code.

3.5.4. Hybrid codes

To combine the advantages of lumped parameter codes and CFD codes some lumped parameter codes have the opportunity to switch to a CFD code in designated control volumes and for a specified time window (e.g. COCOSYS-CFX, COCOSYS-BASSIM, TONUS, GOTHIC). This possibility seems to be very attractive; but further development has to be done to develop this tool for practical application. The transition from the CFD code back to lumped parameter codes can be a critical process.

3.5.5. Comparison of general advantages and disadvantages of the different code types

The comparisons of codes such as integral, lumped parameter and CFD codes for the predictability and ability of the thermohydraulic phenomena during the accidents are summarized in Table 6.

TABLE 6. COMPARATIVE ADVANTAGES AND DISADVANTAGES OF THREE DIFFERENT CODES

Subject	Integral codes	Lumped parameter codes	CFD codes
Computational time	fast-running	relatively fast-running	needs long computational time
Nodalization	limited nodalization (<30 control volumes)	adequate nodalization (≈ 100 control volumes)	Fine nodalization (≈ 100 000 cells, cell size ≈ 1 m^3)
Prediction of regional hydrogen concentration (flammable mixtures)	Rough overview due to simple nodalization	Average concentration for the nodes, local concentrations cannot be predicted	Ability to predict local/regional hydrogen concentrations
Prediction of flow paths	Limited due to nodalization	Adequate if the nodalization is sufficient (user effect)	Ability to predict flow paths in the containment
Prediction of stratification	Very limited	Limited (tendency to overestimate mixing)	Stratification can be predicted
Ability to analyse combustion	no	no	yes
Validation	limited	good	limited

3.6. Experimental Facilities to Measure Hydrogen Distributions

The experimental facilities and the hydrogen distribution experiments are described in more detail in Annex II. Only a broad overview of the facilities and the experiments is given here.

3.6.1. Gas distribution experiments for large dry containments

Figure 11 shows a number of test facilities for dry PWR containment and their scaling compared to a 1300 MW(e) PWR plant.

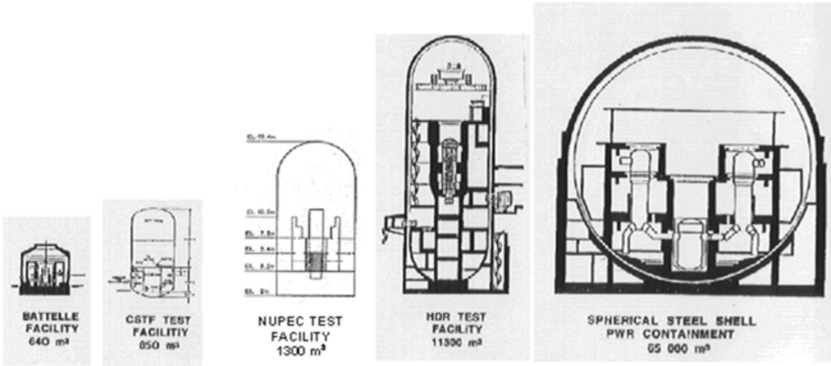


FIG. 11. Scaling of the test facilities for large dry containments.

The main results of the experiments in the HDR and the NUPEC facility are:

- A release of steam and gas (hydrogen) from a break positioned in the lower part of the containment (reactor pressure vessel or reactor coolant line) will result in a good mixing of the containment atmosphere.

- A high position for the release rates (upper end of the pressurizer or pressurizer relief tank) may enhance stratification.

- The spray system (inner spray and outer spray) effectively mixes the atmosphere of an open containment to a uniform helium (hydrogen) concentration.

- The injection position has no effect on the pressure development.

For the mixing experiments performed in the Battelle Model Containment in relevant experimental conclusions are summarized:

- Large scale mixing can be affected by natural convection, provided a suitable geometry of walls and openings and a steam or dry heat source in the lower part of such geometry exists. Even if these conditions are fulfilled, stagnation periods without distinct convection can occur.

- Steam condensation on structures can – in the long term – result in very distinct local accumulation of air and other non-condensables (e.g. hydrogen).

- Depending on the density difference between injected and existing steam–air mixtures, and on the elevations of compartments and vent openings, the following behaviours were observed.

- A dense steam air mixture (i.e. with high air content), injected into a low-elevation compartment ‘fills up’ the injection compartment and the adjacent low-elevation compartments almost completely, whereas the lighter atmosphere (i.e. with high steam and hydrogen content) is displaced upward.

- A low-density mixture injected at the same site tends to immediately escape upward into higher-elevation compartments and to slowly entrain the original atmosphere from the injection compartment.

- Only zones participating in a large scale convection loop show an approximately uniform steam air distribution. In stagnation zones, separated by partitions or stratification phenomena, different compositions can develop, as observed in the annulus compartment, because of (1) the injection and 'fill-up' process, described above, or (2) air and gas accumulation resulting from steam condensation. (Former BMC tests demonstrated that this effect can even produce slight stratification in a single-volume geometry within a period of a few hours without steam injection, after a long homogenization phase.)

The principal findings of the experiments performed in the CSTF vessel are as follows:

- Gas entrainment by the high velocity jet was the dominant mixing process during the release period.

- Helium was an acceptable substitute for hydrogen.

- Mixing characteristics were not strongly dependent on the orientation of the release jet.

3.6.2. Experiments for ice condenser containments

For the Loviisa ice condenser containment gas mixing experiments were performed in the VICTORIA facility. Of particular interest in these mixing experiments were the global convective flow patterns in the containment, as a consequence of forcing open the ice condenser doors during the experiment, and helium transport and mixing under these flow conditions.

Findings from the third phase are discussed in Refs [27, 28]. The experiments indicated that a global convective loop flow developed (with forced-open ice condenser doors), with one ice condenser in up flow and the other one in down flow, even with an initially symmetric ice configuration. This circulation loop tended to be quite effective in mixing the injected helium with volumes participating in the circulation. Mixing above the ice condenser outlet level in the upper compartment was seen to be very effective in all experiments. This well mixed region corresponded to about half of the upper compartment volume.

3.6.3. Recent and future experiments

All these distribution experiments described above and performed in the past were usually integral experiments in compartmentalized containment-like facilities. They were used for validation of the lumped parameter codes and the instrumentation was designed for this purpose. The needs of CFD codes, with their better resolution, cannot be fulfilled with these tests.

The ISP-47 exercise [29], performed from 2002 to 2005, is the first full Containment Thermohydrauylics International Standard Problem exercise. Previous work had led to the conclusion that detailed knowledge of containment thermohydrauylics is necessary for reliable predictions of pressures and temperatures as well as for the prediction of local distributions of hydrogen, steam and air, and for transport and deposition of aerosols.

The objectives of this exercise are the following:

- to bring together users of lumped parameter codes and CFD codes;

- to cover phenomena important for the simulation of containment thermohydrauylics but still uncertain:

- wall condensation;

- atmospheric stratification;

- natural circulation;

- more qualitative insights in turbulent diffusion;

- interactions between these phenomena;

- to contribute to the comprehensive validation of models addressed by the above mentioned phenomena;

- to assess the capability of field codes/CFD codes to take into account the change in scale.

The main objective of the ISP-47 exercise is to demonstrate the actual capability of CFD and lumped parameter codes to handle containment thermohydrauylics in conditions representative of severe accidents, e.g. to predict hydrogen distribution under LOCA conditions.

It had been impossible in practice to identify a single experiment meeting all these objectives summarized above. A systematic approach has been developed using different available facilities, each with sophisticated instrumentation, to validate severe accident containment models/codes to the required levels; this approach follows a strategy progressive in modelling difficulty.

The facilities used are:

- TOSQAN test facility ~ 7 m^3

- MISTRA test facility ~ 100 m^3

- ThAI test facility ~ 60 m^3 and

- PANDA test facility ~ 200 m^3.

The first two facilities are separate effects facilities, with a simple geometry and well controlled boundary and initial conditions. They are used in the first step of the ISP for the validation of refined models (e.g. wall condensation, buoyancy, and the interactions between these phenomena such as condensation/stratification interactions and turbulence buoyancy interactions) in open and blind benchmark calculations.

The TOSQAN and MISTRA tests covered the same phenomena (natural convective flows, heat and mass distributions, condensation heat and mass transfer) but at different scale. They consisted of 3 steady states of air–steam mixtures at 2 pressure levels and 1 steady state of an air–steam helium mixture.

For the second step of the ISP the ThAI and the PANDA test facilities are employed. These test facilities have a compartmented geometry and the objective of the second step is the validation of the codes in a compartmented geometry with a complex and more realistic situation. The stratification in a multi-compartment geometry with asymmetric injection and the coupling of the different effects can be studied. The test facilities are shown and described in Annex II.

4. HYDROGEN COMBUSTION

This section describes first the flammability limits and ignition conditions of a flammable hydrogen air–steam, and discusses basic physical processes of all potential combustion regimes, such as deflagration, detonation, flame acceleration and deflagration to-detonation transition. All combustion modes are potentially possible in a severe accident scenario: (1) for low hydrogen concentration below about 8%, flame speed is expected to be slow and the deflagration produces a quasi-static pressure loads, (2) Above about 8%, combustion is complete and combustion may accelerate leading to higher loads, (3) Above 10%, acceleration up to sound velocity has been found in many experiments and (4) and in an extreme case flame acceleration, supported by turbulence, can reach detonation conditions, called Deflagration to Detonation Transition (DDT). Regarding reactor safety, flame acceleration and DDT can be extremely destructive and have high potential damage for internal containment structures and safety systems required for severe accident management. Direct initiation of a detonation is not possible within containment due to the high energy required.

4.1. Introduction

In 1975, the WASH 1400 report examined the various potential containment failure modes enable, in case of severe accident situation, to involve radioactive releases into the environment. One of the identified containment failure modes (i.e. the so called γ mode) was associated to the explosion of the hydrogen produced in the course of the accident.

In 1979, the TMI accident confirmed, first that accidents leading to core melting were possible, second that the combustion of the hydrogen released in the reactor building is a potential threat for containment integrity. Since this accident, a concerted effort has been devoted to the understanding of the distribution and combustion behaviour of hydrogen air steam mixtures in the containment.

Hydrogen distribution under severe accident conditions has been extensively investigated for different accident sequences in order to quantify the flammable gas composition with respect to the flammability limits in containment with highly complex multi-compartment structures, as has been described in Chapter 3. Combustible gas distributions are affected both by forced convection, when time scales for mixing are short, and natural convection, when time scales are in the range of minutes to hours. Gas distribution strongly depends on the characteristics of the hydrogen and steam release (location, release rate).

This section presents first the flammability limits and ignition conditions of a flammable hydrogen–air- steam. It discusses basic physical processes of all potential combustion regimes, such as deflagration, detonation, flame acceleration and deflagration to-detonation transition. It focuses in particularly on the flame acceleration and DDT involved mechanisms, which have the highest potential damage for internal containment structures and safety systems required for severe accident management.

The prediction of the formation of such flammable mixtures and their combustion processes is essential for safety. As a result of the R&D on hydrogen risk mitigation powerful analytical tools for simulations have been developed in this area. This section discusses certain models to be used in analytical tools available for practical combustion applications. It is not intended as an exhaustive description of all analytical tools used for combustion calculations. The objective is to discuss their capabilities and limitations with respect to hydrogen combustion calculation in highly complex multi-compartment containment.

The state of the art of the analytical description of the premixed turbulence combustion modelling is summarized in this section. With respect to the interaction between turbulence and reacting flames, the most widely used non-reacting turbulent flows models have been listed. On the other hand, for simulation of turbulent premixed combustion, three important model categories are described, covering semi-empirical models such as eddy break-up model, flamelet models, and probability density function approaches. The detailed description of combustion modelling is presented in the section 9 concerning analytical aspects

At the end of this report, the experimental database used to investigate flame acceleration and deflagration to transition and to validate computational tools on large scale facilities is summarized.

4.2. Flammability and ignition conditions

Combustion of hydrogen takes place if the hydrogen–steam–air gaseous mixture is flammable and if an ignition source is present.

4.2.1. Flammability

For a mixture of flammable gases the flammability limit is the experimentally determined minimum concentration of fuel (lean limit) and oxidant (rich limit) required for self-sustaining flame propagation at a given pressure and temperature. With respect to safety assessment the flammability limit is of primary interest. It is considered as a relevant indication of the existence of a combustion hazard and the key point in defining a safety margin for a combustion hazard.

The flammability limits have been experimentally determined by means of standardized small size laboratory facilities (5 to 10 cm in diameter and 1.5 m long). Table 7 presents the hydrogen flammability limits for hydrogen–air mixtures at ambient temperature and pressure conditions (0.1 MPa, 25 °C) [30].

TABLE 7: HYDROGEN FLAMMABILITY FOR HYDROGEN–AIR MIXTURES AT AMBIENT CONDITIONS (0.1 MPa, 25°C) [30]

	Lower limit (vol.%)	Upper limit (vol.%)
Upward propagation	4.1	74
Downward propagation	9.0	74
Horizontal propagation	6.0	74

Experimental results showed that limits for upward propagation of flame are wider than those for downward propagation. In the other hand, limits for horizontal propagation are between those for upward and downward propagation.

Although doubts concerning the applicability of such flammability limits to severe accident conditions and to large containment reactors because of possible associated scales effects, experience suggests that these limits are not significantly affected. So these flammability limits can be used in nuclear safety as guidelines for potential combustion damage assessing.

It has been shown that flammability limits depends on many parameters like turbulence, diluents concentration, temperature of gas mixtures.

- The flammability limits listed in the Table 7 refer to combustion in initially stagnant gas mixtures. Turbulence induced by flows in the gas mixture will wide the flammability domain. It will lower the downward and horizontal propagation limits, so as to approach the upward propagation limit of 4.1%. In reactor building, turbulence may be induced by ventilation or by convective flows under accident conditions.

- The influence of diluent gases is given by the Shapiro diagram (see Fig. 12). If the containment atmosphere contains diluent gases like steam, carbon dioxide, nitrogen the lower flammability limit will generally increase slightly with additional diluent, while the upper limit will drop more rapidly. With continued increase in diluent concentration, the two limits approach one another until they meet and the atmosphere is inerted. Referring to the Shapiro diagram, mixtures containing more than 55% of steam are inerted. Moreover, steam and CO_2 contribute to reduce flame speed.

Flammability limits are weakly depended on pressure of the gas mixtures.

Regarding combustion assessment, the location of this hydrogen–air–steam mixture on the Shapiro diagram determines whether some or all of it will be flammable.

4.2.2. Auto ignition and ignition

Auto ignition temperature is the temperature at which a combustible gas mixture will spontaneously ignite. Because auto ignition is a one of the mechanisms for initiating combustion, it is of interest in safety assessment.

Within the flammability limits, Ignition of dry hydrogen–air mixture can occur with a very small input of energy [31]**.** The minimum energy required for ignition of a stagnant hydrogen–air mixture is of order of tenths of a millijoule for rich mixtures. In that case possible sources of accidental ignition are numerous, such as sparks from electrical equipments and from the discharge of small static electric charges.

For a flammable mixture, the required ignition energy increases as the hydrogen concentration approaches the flammability limits.

Experimental investigations revealed that the addition of diluents, such as steam, will also increase the required energy substantially. Combustible gas mixtures will also auto-ignite if the temperature of the gas mixture becomes sufficiently high [32].

4.3. Modes of combustion

In general combustible gas mixture can support two combustion modes: deflagration and detonation. These two modes of combustion can be easily distinguished from one another, by the velocity, structure and mechanism of propagation of the reaction front.

4.3.1. Deflagration

Deflagrations are flames that travel at subsonic speeds relative to the unburnt gas. They propagate mainly by transfer of heat from the hot burnt gas to into the unburnt gas, raising it to a temperature high enough for a rapid exothermic chemical reaction to take place. The typical velocities are of the order of several metres per second.

It has been showed experimentally that the asymmetrical deflagration for low hydrogen concentrations: In particular, for hydrogen concentrations between 4.1% and 6.0%, there will initially be buoyancy driven, upward propagation from the ignition source. Hydrogen concentrations between 6.0 and 9.0% will produce both upward and horizontal propagation, and hydrogen concentrations above 9.0% will propagate in all directions, although the upward propagation may be faster than the downward propagation. This asymmetry will disappear for mixtures with higher hydrogen concentrations and with enhanced turbulence. In upward propagation of lean hydrogen–air flames, 'separated globules' of flame have been observed [33].

On the other hand it has been found in several and medium scale experiments the hydrogen–air mixture with low hydrogen concentrations in the range of 4 to 8% are ignited with a spark and the hydrogen combustion is incomplete [30, 34].

Experimental results showed that the completeness of combustion in quiescent mixtures increases with increasing hydrogen concentration, and is near 100% at 8 to 10% hydrogen.

The phenomenon of incomplete burning of lean hydrogen–air mixtures is of fundamental importance in reactor safety. Combustion of lean mixtures, below 8% hydrogen, can be a method of consuming hydrogen without a significant increase of containment pressure. Because of the incomplete combustion process igniter devices appears to be as an efficient mitigation system.

4.3.2. Detonation

A detonation is a combustion wave that travels at supersonic speeds relative to the unburnt gas in front of it. For hydrogen–air mixtures near stoichiometric, this speed is about 2000 m/s. The compression of the unburnt gas by shock waves in the detonation raises the gas temperatures high enough to initiate rapid combustion. The detonation wave has a coupled reaction-front/shock-wave structure.

The knowledge of the conditions which hydrogen–air–steam detonation is possible in large scale containment and the likelihood of detonation occurrence are of primary interest in safety assessment.

The first issue can be characterized fairly well with regard to hydrogen–air mixtures. The second addresses the concern of initiation of detonation, either directly or DDT caused by rapid flame acceleration under appropriate conditions.

Detonability of gas mixture

The detonability limits of a reactive mixture are the critical conditions for the propagation of self-sustained detonation. The critical conditions denote both the initial and boundary conditions of the explosive mixture.

Hydrogen–air mixtures near stoichiometric (about 30% hydrogen in–air, two parts H_2 to one part O_2,) are known to be detonable. Mixtures departing from stoichiometric are increasingly more difficult to detonate.

It has been demonstrated, however, that the 'detonation limits' are functions of the tube diameter, and not universal values at a given temperature and pressure [35–37].

In the last 20 years it has been showed that the detonation wave is composed of unsteady oblique shock waves moving in an ever-changing cellular structure. The structure of this cellular pattern (characterized by its transverse dimension), the 'cell size' is found to be a characteristic of the detonation.

The cell size in a detonation can be determined experimentally and appears to be a fundamental measure of the detonability of the mixture. It ties together the chemical reaction rate with the gross macroscopic propagation behaviour of detonations. The further a mixture is from stoichiometric, and hence the less energetic the chemical reaction, the larger is the detonation cell size. It appears that the smallest diameter tube in which a detonation will propagate is one whose diameter is about a third of a cell width [39]. The cell width for hydrogen–air has been measured over an extensive range of hydrogen–air ratios as shown in Fig. 12.

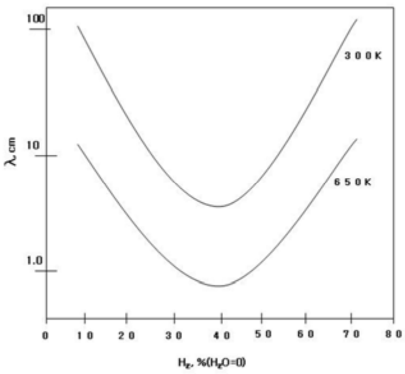


FIG. 12. Detonation cell size for hydrogen–air mixture.

The knowledge of hydrogen–air detonation cell size is valuable for more than tube detonation limits. It is known that if a detonation is to propagate from a tube into an open space, there is a minimum tube diameter for which the detonation will continue to propagate the critical tube diameter [40].

- For smaller tube diameters, the detonation will fail when leaving the tube. Experimental results show that the critical tube diameter is about 13 cell widths.
- For a rectangular duct, the critical duct height varies from about 11 cell widths (for a square duct) to about 3 (for a wide duct).
- For propagation into an open space confined on one side of the duct, there is some evidence that the critical duct height lies between 1.5 and 5.5 cell widths [39].

The developments described above address the issue of the conditions under which a hydrogen–air detonation is possible in containment. The detonation limits are not fixed but depend on the geometry, being wider for larger sizes. The curve of cell size versus hydrogen fraction rises steeply on the hydrogen-lean side. For the large geometrical scales in containments, detonations may propagate in leaner mixtures.

Initiation of detonation

The second issue addresses the problem of detonation initiation. Direct initiation of detonation requires a very high-energy source. The minimum energy to initiate a stable detonation is about (4100 J), which is several orders-of magnitude greater than would be produced from an electrical spark. It is about eight orders-of magnitude greater than the minimum ignition energy required for deflagration flame propagation. In recent shock tube experiments on detonation initiation conditions for stoichiometric mixtures in a long pipe [41]**,** the relationship between minimum initiation energy and pipe cross-sectional area was found to be l0 J/cm^2.

Direct initiation is, therefore, considered unlikely in reactor accidents. However, a deflagration can accelerate to high speeds from different mechanisms and undergo a transition to detonation.

4.3.3. Flame acceleration and deflagration to-detonation transition

Flame acceleration and DDT are important phenomena on containment for severe accidents because they can largely influence the maximum loads from hydrogen combustion sequences and the consequential structural damage.

With regard to reactor safety analysis, the main objective in hydrogen risk mitigation studies is to preserve the containment integrity and design countermeasures that allow operators to avoid flame acceleration and DDT. In current nuclear power plants, the load bearing capacity of the main internal structures can be jeopardized by high flame speeds (e.g. more 100 m/s). New containment designs could, in principle, be constructed to carry higher dynamic loads, however, at the expense of additional costs. To judge the potential for fast flames and DDT, the causes and underlying processes have to be understood.

Various necessary criteria have been proposed for these particular combustion regimes and used in three dimensional numerical containment simulations, testing the effectiveness of hydrogen risk mitigation methods, to decide whether flame acceleration or even DDT is possible.

This section describes in some detail the key mechanisms that are responsible for flame acceleration and transition to detonation and. It also describes the important phenomena of flame quenching regime caused by high intensity turbulence and sensitivity mixture.

Flame acceleration and detonation regimes

A freely expanding flame is intrinsically unstable. Both laboratory scale experiments [42, 43] and large scale experiments [44, 45] indicate that obstacles located along the path of an expanding flame can cause rapid flame acceleration.

Depending on the hydrogen–air–steam mixture, the processes following weak ignition in a combustible mixture can result in generation of a variety of different combustion regimes ranging from slow laminar flames to detonations:

- **Laminar flame:** In this first phase a laminar flame propagates at a velocity determined by the laminar burning velocity and the density ratio across the flame front.

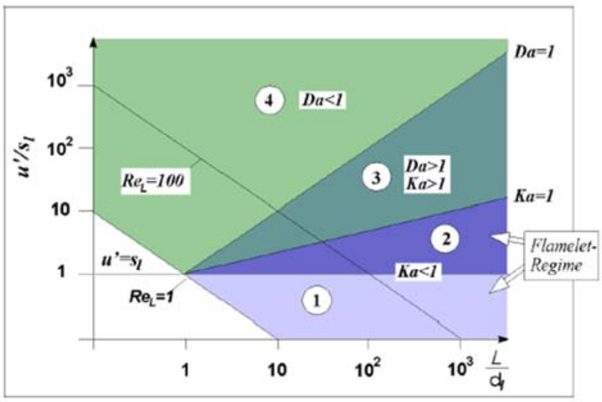
- **Wrinkled flame:** The short-lived laminar flame propagation regime is soon replaced by a 'wrinkled' flame regime, which can persist over relatively large flame propagation distances for most accidental explosions. Because of the increase in flame area, the burning rate and, hence, the flame propagation velocity for the wrinkled flame can be several times higher than for the laminar flame.

- **Turbulent flame:** the effect of obstacles- or boundary-layers-induced turbulence can eventually transform the wrinkled flames into a turbulent flame brush. The flame acceleration is enhanced by increase of the surface area of the laminar flamelets inside the flame brush. For sufficiently high levels of turbulence, the flamelet structure may be destroyed and then replaced by a distributed reaction zone structure

- **Deflagration to detonation transition (DDT):** The flame acceleration process can be sufficient to possibly lead to DDT through shock ignition or the SWACER amplification mechanism (see Section 4.3.4.4.1). In configurations with repeated obstacles experimental results showed that the turbulent flame propagation regime is self-accelerating because of the feedback mechanism between the flame velocity and the level of turbulence ahead of the flame front. The final flame velocity depends on a variety of parameters, such as the mixture composition, the dimensions of the enclosure, and the size, shape, and distribution of the obstacles.

Experimental results have allowed characterizing four turbulent flame regimes that could control the flame propagation in different stages of flame acceleration in a DDT process [46]. These flame regimes are: (1) wrinkled laminar flamelets, (2) corrugated flamelets, (3) distributed reaction zones and (4) a well stirred reactor.

The Borghi diagram [47] provides a useful classification of turbulent combustion regimes based on one dimensional numbers such as the Karlovitz and Damköhler numbers. The validity of combustion models greatly depends on the Borghi diagram and the corresponding flame front structure (see Fig. 13).



1: wrinkled laminar flamelets

2: corrugated flamelets

3: distributed reaction

FIG. 13. Borghi diagram categorizing the flame propagation regime in terms of the turbulence intensity u', the laminar burning velocity s_l, the integral length scale L, the laminar flame thickness d_l, the Damköhler number (Da – indicates whether chemistry is fast (Da>>1) or slow (Da <<1) relative to the integral scale turbulence dynamics), the Karlowitz number (K_a – indicates at which point (Ka≈1) the smallest turbulent eddies penetrate into the laminar flamelet preheat zones) and the turbulent Reynolds number Re_L .

Mechanisms of flame acceleration

Qualitatively, the mechanism for flame acceleration is well understood. Thermal expansion of the hot combustion products produces movement in the unburned gas. Many mechanisms are responsible for flame acceleration. Flame acceleration can result from turbulence and generated by combustion-induced turbulence over structures present ahead of a flame, from flame instabilities caused by flame generated pressure waves when they interact with the flame after reflection at the confining walls, from the confinement of the gas mixture by the enclosure, and from acoustic and shocks interactions:

- **Effect of turbulence:** If obstacles are present in the path of propagating flame, turbulence can be generated in the combustion-induced flow. As the flame front advances into the turbulent flow field, turbulence increases the local burning rate by increasing both the surface area of the flame and the transport of local mass and energy. An overall higher burning rate, in turn, produces a higher flow velocity in the unburned gas. This feedback loop results in a continuous acceleration of the propagating flame. Turbulence can also quench flames. This phenomenon is described in detail in Section 4.3.4.

- **Effect of obstacle-induced turbulence:** The obstacles in the flame path promote velocity gradients in the flow fields and provide a means of turbulent production. Without shear the turbulent eddies decay downstream of an obstacle. Therefore, a series of repeated obstacles in a flame path appears to be the most effective flame acceleration configurations. The flame acceleration rate for transition to detonation for various obstacle sizes and spacings have been examined and have demonstrated the effectiveness of obstacles in causing transition and influencing the combustion pressures [48].

- **Effect of flame instability:** Interface instabilities resulting from the interaction of pressure waves with the deflagration flame front (Taylor's instabilities) [49] generate wrinkled flames. It has been shown that in case of acceleration of an interface towards a fluid having a higher density, perturbations along the interface would grow. The increase of flame speed generates pressures waves, which will be reflected in presence of walls and interacts with the flame front promoting instabilities. These perturbations cause the flame front to grow and increase the flame surface area and, thus, the burning rate.

- **Effect of confinement:** It has been demonstrated that the interaction between the flame propagation and turbulence generation in a flame path is very sensitive to the level of the channel confinement [50]. A decrease of the confinement by venting reduces the flow velocity ahead of the flame and hence reducing the obstacle-induced turbulence. As in the case of flames, detonations are very sensitive to the level of confinement. A sudden venting of confinement at the end of the tube can result in detonation failure.

- **Acoustic and shock interactions:** Flame propagation in an enclosure generates acoustic waves that can interact with the flame front and promote flame acceleration through a variety of instability mechanisms. Such instabilities have been observed for open and closed tubes [51]. These mechanisms can include flame distortion caused by the flame-acoustic wave interaction, and wave amplification caused by the coherence between the acoustic wave and the exothermic energy release (Rayleigh criterion). On the other hand, sufficiently fast flames can produce a shock wave that can reflect off a wall and interact with the flame. As shown by Markstein and Somers [52], this can result in severe flame distortion that can induce flame acceleration and, in extreme cases, cause transition to detonation [53].

4.3.4. Quenching

Turbulence induced by obstacles in the displacement flow does not always enhance the burning rate. Depending on the mixture sensitivity, high-intensity turbulence can lower the overall burning rate by excessive flame stretching and by rapid mixing of the burned products and the cold unburned mixture. If the temperature of the reaction zone is lowered to a level that can no longer sustain continuous propagation of the flame, a flame can be extinguished locally.

The quenching by turbulence becomes more significant as the velocity of the unburned gas increases. For some insensitive mixtures, this can set a limit to the positive feedback mechanism and, in some cases, lead to the total extinction of the flame. Hence both the rate of flame acceleration and the eventual outcome (maximum flame speed attained) depend on the competing effects of turbulence on combustion.

4.3.5. Mechanisms involved in Deflagration to Detonation Transition

The DDT process leading to detonation can be classified into two categories:

- Detonation initiation resulting from shock reflection or shock focusing. This first category essentially involves a direct initiation process where the shock strength is sufficient to auto-ignite the gas and promote detonation.

- Transition to detonation caused by instabilities near the flame front or caused by flame interactions with a shock wave, another flame, obstacles or a wall, or caused by the explosion of a previously quenched pocket of combustible gas. This second category is considerably more complex because it involves a variety of instabilities and mixing processes.

Although the occurrence of a local explosion is a necessary condition for the onset of detonation, it is not sufficient to lead to detonation. This requires the development of a shock wave that can cause auto ignition. The formation of detonation requires the amplification of shock waves from the local explosion.

It has been suggested by Zel'dovich et al. [54, 55] and Lee et al. [56] that induction time gradients associated with temperature and concentration gradients operate to amplify these shocks waves and may be responsible for a wide range of observed detonation initiations. This formation of an induction time gradient process, called shock wave amplification by coherent energy release, can produce a spatial time sequence leading a compression wave through gradual amplification into a strong shock wave that can auto-ignite and produce DDT.

4.3.6. Necessary criteria for flame acceleration and DDT

In case of a weak ignition, all the combustion modes are potentially possible for the same accident scenario, ranging from slow laminar flames to detonations. Following ignition by a weak source, the flame, starting at low speed near the ignition point, can be strongly accelerated by turbulence under particular conditions and can reach a velocity higher than the speed of sound with a complex system of pressure waves. With regard to reactor safety analysis, it is essential to predict the type of combustion regimes that can be developed under certain initial and boundary conditions.

Nevertheless, it is extremely difficult to perform a detailed description of all combustion regimes following ignition in a combustible mixture with presently available tools. It is necessary to describe complex interactions of flow, turbulence and chemical reactions with high spatial and temporal resolution.

In view of this situation, much effort has been focused on the development of macroscopic criteria for flame acceleration and DDT to be used in safety analysis. Two different criteria, derived from many experiments performed in the past, in tubes or tube-like arrangements, have been established:

- the sigma criterion, using the expansion ratio of the gas mixture, in order to determine the possibility of flame acceleration to sonic velocity,

- the lambda criterion, using the detonation cell size and a characteristic length, to determine the possibility of DDT.

These criteria define only necessary conditions for the corresponding phenomena, flame acceleration or DDT, to occur. The satisfaction of the first criterion is, however, necessary for DDT, as flame acceleration is a precondition for DDT.

The database for the assessment of the combustion mode (laminar combustion, flame acceleration to sound velocity in the burned gas (fast deflagration) and DDT) is described in the state-of-the art report [57] and has been completed in the frame of the EC-HYCOM project [58]. The two criteria sigma and lambda are mainly used in order to assess the combustion mode and can be used to facilitate the combustion assessment process in limiting the number of time-consuming combustion calculations and in focusing these calculations to the situations with the higher risk

Both criteria can be calculated using both gas distribution and temperature codes and separate codes applying correlations obtained from the experimental database. Sigma itself can be calculated explicitly as the ratio between the densities before and after combustion.

Nevertheless, there is still an ongoing discussion on whether both criteria can be applied to a non-confined geometry with concentration gradients. With respect to the lambda criterion there are still uncertainties associated with the definition of the cell size value, in particular in case of a complex and a partly confined geometry as in the EPR containment. Furthermore, the validation of the lambda criteria for strong hydrogen concentration gradients is not complete. Further validation efforts are still required.

Despite these and other uncertainties, which are discussed in the following sections, the use of the criteria mentioned and the gas and temperature distribution is relevant to assess the possible combustion mode for severe accidents in nuclear power plants. At the same time, the uncertainties need to be taken into account in practical applications of the criteria for flame acceleration and DDT.

In the following sub-sections both the sigma and lambda criteria are presented, as well as their application.

σ criterion for flame acceleration

The first of these, called the σ criterion, relates to flame acceleration. In particular it states that flame acceleration is only possible in mixtures having a large-enough expansion ratio $\sigma > \sigma^*$, where ratio σ is the ratio of densities of reactants (fresh gas) and products (burnt gas) and σ^* the critical value.

The detailed description of the σ criterion and the experimental data used for its development is presented in the CSNI report [57].

In short, the necessary conditions for development of fast combustion regimes based on experimental correlations presented in the CSNI report are the following.

$\sigma > (3.5 \div 4)$, for mixtures with $\beta(Le - 1) > -2$;

$\sigma > \sigma^*(\beta)$, for mixtures with $\beta(Le - 1) < -2$.

Where the function $\sigma^*(\beta)$ is given by a correlation function of the Lewis number Le ($Le = \alpha/Dv$, is defined as the ratio of the thermal diffusivity α and the diffusivity Dv) and Zel'dovich number β ($\beta = Ea\,(Tb\text{-}Tu)/(R\,Tb^2)$, where Ea is the effective activation energy, Tu the initial temperature and Tb the maximum flame temperature). These conditions are expressed in terms of mixture properties and give the possibility to divide mixtures into 'strong' and 'weak', depending on their ability to support effective flame acceleration under favourable geometrical conditions.

The critical σ^*, which depends on initial gas temperature and flame stability, was determined by results of multiple experiments at different scales, in different geometries.

The requirement of large-enough σ is a necessary but not sufficient condition for the development of a fast turbulent combustion regime. A sufficiently long flame path and/or favourable geometrical configuration promoting flame folding and stretching is necessary for the flame to actually accelerate to high velocities. If the flame has accelerated to velocities of about the speed of sound in combustion products, the conditions for spontaneous formation of a detonation can be reached.

In order to avoid uncertainties in the value of the energy activation, it has been proposed as an alternative to use a criterion relating σ and Tu [57]. This concept is considered valid for hydrogen/air/steam mixture without any other diluents, which is the mixture foreseen for severe accident conditions.

In the HYCOM-project [58], carried out in 1999–2001, a complementary experimental programme in medium and large scale facilities has been performed with various combustion regimes, ranging from slow to fast turbulent deflagration, which had not yet been covered by previous experiments. The main objective was to consider complex geometries and inhomogeneous hydrogen concentrations in a dry atmosphere and at ambient temperature. Detailed data were obtained revealing specific effects of scale, a multi-compartment geometry and venting. Experimental results showed that the flow geometry has some influence on the critical conditions for fast combustion regimes, however applicability of the σ criterion was confirmed also for complex enclosures.

Treatment of σ criterion uncertainties

There are some uncertainties connected with the estimation of flame acceleration limits:

- The σ criterion expressed above represents necessary but not sufficient conditions for effective flame acceleration. Other requirements are to be met as well so that the flame propagation can result in formation of fast combustion regimes. The most important of these are the requirements of a large-enough scale (flame propagation distance) and a favourable geometry (obstructions) for effective flame acceleration.

- Another type of uncertainty is connected with the spread of critical σ-values. For rich mixtures, the range for σ* is from 3.5 to 4.0. It should also be noted that no experimental data are available for rich hydrogen–air–steam mixtures at initial temperature T_u higher than 383 K.

- A third type of uncertainty is connected with a boundary between stable and unstable flames $\beta\,(Le - 1) = -2$. The exact location of this boundary (in terms of the mixture composition under given initial conditions) is difficult to define because of inevitable errors in the determination of Le and β.

Theses uncertainties can be taken into account by using conservative estimates, that is, by using the minimum σ*-values for each set of initial conditions. Additional experiments and analysis can help to in narrow the range of uncertainties in the application of the σ criterion.

Necessary criteria for DDT

Two necessary conditions to create a detonation from a fast turbulent deflagration have been revealed from experiments and described in reference [57]. Processes of DDT can be divided into two main phases:

- Phase 1 involves a variety of processes that create conditions for the onset of detonation,

- Phase 2 is the actual process of detonation, i.e. the onset of detonation.

These criteria constitute necessary, but not sufficient conditions for DDT to occur. If some or all of them are satisfied, it does not mean that detonation will definitely be initiated. However, if one the necessary criteria is not satisfied, detonation should not be expected.

a) Necessary criteria for Phase 1:

A number of requirements have been found which must be fulfilled to provide conditions for DDT. These are: the occurrence of fast flames, the critical flame Mach number and the minimum shock Mach number. The application of these requirements requires the calculation of the propagation of a turbulent combustion.

b) Necessary criteria for Phase 2:

The second important set of the necessary conditions states that the detonation can only occur if the physical size L the compartment containing mixture is sufficiently large compared to the chemical length scale that characterizes the sensitivity of the mixture. The usual choice of the length scale is the detonation cell size λ (see Fig.14).

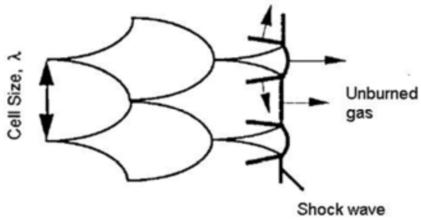


FIG. 14. Detonation cell size.

The necessary criteria for DDT described in Ref. [57] are expressed in the form

$L > \alpha\lambda$.

that is to say, the size L has to be sufficiently large compared with the detonation cell size of the mixture The value of the constant α depends on the particular geometrical configuration. A detailed definition of the characteristic size L of an enclosure that describes the effect of scale is given in Ref. [57].

The $L > 7\lambda$ criterion (the so-called 7λ criterion) has been proposed by the Russian Research Center 'Kurchatov Institute'. Experimental data generally showed a good agreement with this criterion over a wide range of scales and mixture compositions.

It should be noted that the correlation is only a necessary but not sufficient condition for DDT: if the 7λ criterion is not satisfied, detonation cannot be expected. In the opposite case, the development of the combustion process can result in both deflagration and detonation regimes.

Application of 7λ criterion and uncertainties

The application of 7λ criterion addresses particular issues related to the prediction of λ, based on the mixture composition and the characteristic containment size L. Various uncertainties, however, must be taken into account.

A first type of uncertainty is related to the concentration gradients expected in the containment as a result of the hydrogen transport and mixing processes. In the case of clouds of complex shapes with a strong hydrogen concentration gradient in a compartment, it is difficult to apply the λ criterion for DDT directly. One has to define what value of λ is to be used as the representative chemical length scale. Solutions for non-uniform mixtures are suggested in Refs [57, 58]. It should be noted that these solutions can only be applied as estimates. The effect of hydrogen concentration has been further examined in the framework of the EU HYCOM project [58].

Experimental data on the cell size are only available for some particular compositions and initial conditions. These measurements do not allow direct estimation of the cell size for arbitrary compositions and initial conditions. Analytical tools are needed to provide values of detonation cell sizes for the severe accident conditions in the containment. Two different approaches have been used to develop the methods for estimation of the cell size value. The most often used approach is based on fitting experimental data by an analytical function depending on initial pressure, temperature, steam and hydrogen concentrations. Another approach is based on the analysis of a correlation of reaction zone widths calculated from kinetics models with experimentally determined detonation cell sizes [59].

A second type of uncertainty is connected with the evaluation of the characteristic containment size. As shown in Ref. [57] on Flame Acceleration and DDT, detailed guidelines are provided for the determination of the characteristic containment size in case of a lumped parameter approach, for a number of particular geometrical configurations. But for more complex geometries, notably for a multicompartment containment, the determination of the characteristic length and the aggregation volumes is very difficult to estimate, especially if large openings are present between compartments. The determination is then mainly based on expert judgement. The consideration of venting and the effect of flow in complex geometries have been studied in the HYCOM project.

An example of the combined application of σ and $L/7\lambda$-correlations is presented in Fig. 15 for hydrogen–air steam mixtures at 375 K and 1 bar initial pressure. It illustrates flame acceleration limits (the minimum σ-values) evaluated via conservative estimates and the dependence on scale of the DDT limits (inside the DDT boundary, λ= 2 m, DDT is possible in rooms with a characteristic length L>7*2/1.5 ≈10 m).

4.3.7. Diffusion flames

Under severe accident conditions, hydrogen is released into a compartment in the form of a continuous hydrogen–steam jet. Ignition of a jet or plume of fuel can occur if the temperature along the combustible interface between the fuel and the surrounding–air (or oxidizer) reaches the auto ignition temperature.

Combustion can occur because either an ignition source exists, such as an electrical spark, or the mixture temperature is above the auto ignition temperature. This temperature is about 550°C in stoichiometric conditions. It increases with increased steam concentration and increased deviation from stoichiometric conditions.

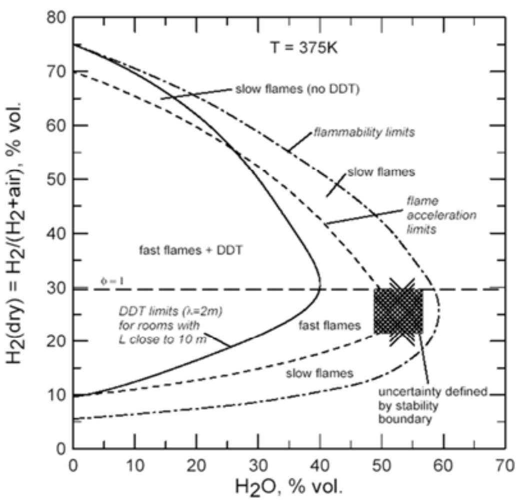


FIG. 15. Limits and possible regimes of combustion for hydrogen–air steam mixtures at 375 K and 1 bar initial pressure [57] (courtesy of OECD[1]).

1 OECD NUCLEAR ENERGY AGENCY, Flame Acceleration and Deflagration to-detonation Transition in Nuclear Safety, State-of-the Art Report by a Group of experts, NEA/CSNI/R (2000) 7, OECD, Paris (2000), p. 3.33, www.nea.fr.

The diffusion velocity of oxygen and hydrogen in the combustion area controls the reaction. Because continued diffusion reduces the pressure loadings, it is beneficial for the containment integrity. Moreover, since hydrogen is continuously consumed, the existence of diffusion flames prevents the build-up of hydrogen in the containment compartments.

With regard to the safety assessment, this combustion mode represents, however, a threat for the equipment and systems located in the vicinity of the hydrogen release location because of high thermal loadings. The temperature in the flame area can reach very high values, close to 2000°C, which may result in melting of metallic surfaces.

These phenomena are not well understood and their likelihood under severe accident conditions can be called into question. Indeed, if hydrogen can be released at high temperature (more than the auto ignition temperature), the release will often be accompanied by a considerable steam production, which will increase the auto ignition temperature even more.

On the other hand, the stability of the flame cannot be confirmed, taking into account the fluctuation of hydrogen release in the combustion area and the necessity of a sufficient amount of oxygen to maintain the combustion. A stable flame can anchor itself in the vicinity of the break only if the flow rate is less than a critical value. Stability limits are determined by the competing effects of chemical kinetics and fluid dynamics, which may result in either more heat generation or in quenching. Quenching can occur when flame stretching, caused by a non-uniform flow field and/or turbulent mixing, enhances heat transfer from the reaction zone to the unburned mixtures and lowers the reaction zone temperature below the limit where continuous propagation of the flame is possible.

4.3.8. Effect of carbon monoxide

The combustible gas of carbon monoxide can be produced in a severe accident from interaction of ex-vessel molten core material with concrete. Depending on the core melt scenario, the type of concrete and geometrical factors affecting the interaction, the quantities of carbon monoxide produced can vary widely, up to several volume percent in the containment.

Regarding containment safety studies it is essential to take into consideration the carbon monoxide production with its effect on flammability limits, ignition temperature, burning velocities, combustion in vessels and detonation cell widths. A CSNI Working Group has completed a report [60] to assess the effect of carbon monoxide under severe accident containment conditions. The main conclusions are summarized below:

- Flammability limits for CO-H_2-H_2O-CO_2–air mixtures can be determined accurately from Le Chatelier’s rule or from empirical curve fitting to the experimental data. It has been found that the presence of CO widens the flammability of hydrogen.

- Burning velocity for CO-H_2-H_2O-CO_2–air mixtures can be calculated reasonably accurately at low CO concentrations using available codes. However these codes have a limited range of applicability and cannot be used at low hydrogen concentration. Because the burning velocity is a key parameter for codes calculating combustion pressure, and uncertainties remain for the range of mixtures relevant to containment conditions under severe accident conditions (low CO and H_2 concentrations), this parameter needs to be determined experimentally.

- In has been observed that there are no large scale data on the development of combustion pressure in closed and vented vessels to validate predictions of combustion models for CO-H_2-H_2O-CO_2–air mixtures. Consequently, significant uncertainties in the predicted pressure loads from ignition remain.

- Experimental data on the detonation cell sizes of CO-H_2 mixtures to validate theoretical mixtures are not available. It has been shown that detonability appears sensitive to CO addition to the containment atmosphere and, thus, there are implications for reactor safety assessment.

- Theoretical studies confirmed that addition of steam and CO_2 reduces the detonation sensitivity of CO-H_2 mixtures by increasing the cell size, in agreement with experimental studies in H_2.

- It has been demonstrated that addition of CO significantly reduces the cell size for lean hydrogen–air mixtures and increases the cell size for rich hydrogen–air mixtures. Thus addition of CO to a lean hydrogen–air mixture increases its detonation sensibility.

- The cell size determination for CO-H_2-H_2O–air mixtures can be deduced from a measured or calculated cell size for a corresponding H_2-H_2O–air mixture, but supporting data in CO-H_2 mixtures are lacking.

4.3.9. Pressure loads associated with different combustion phenomena

Regarding reactor safety analysis, hydrogen combustion can involve wide time scales (between milliseconds in case of a detonation and several seconds in case of a slow deflagration) and pressures (between 4 and 30 times the initial pressure or more depending on shock wave reflections). The two main parameters of importance to reactor safety are the pressure load and the impulse load (the integral of pressure over time) of combustion. The effect of combustion inside containment can be divided into two main categories: static and dynamic loads. According to combustion propagation, this effect can be local (inside a compartment) or global (for the whole containment), which depends on time and natural frequency

For low hydrogen concentration, below 10%, flame speed is expected to be subsonic and laminar combustion will occur. In that case, laminar combustion leads to a quasi-static pressure increase, which is covered by the adiabatic complete isochoric combustion pressure (AICC). In particular, the AICC pressure calculation takes into account only the net changes in the masses of hydrogen, oxygen and water before and after combustion, it focuses on the energy balance and assumes the completeness of the combustion. This pressure can be considered as conservative for slow flames because: (1) heat losses are not negligible and are transferred to the structures, to the inert gases and to the steam, and (2) for hydrogen concentration below 8%, the hydrogen combustion is incomplete.

For higher hydrogen concentration, above 10%, experimental results have shown that flame acceleration could occur and reach the sound velocity. Fast hydrogen deflagration in an enclosure produces dynamic pressure with strong variation of time that, in some cases, may be high enough to threaten the integrity of the enclosure or its substructures. The peak pressure developed inside the enclosure depends on the size of the combustible gas region, the concentration of the combustible gas, the size of the enclosure and the arrangement of the obstacles.

For a sufficiently high hydrogen concentration, the flame can be accelerated by turbulence and, thus, reach levels well above sound speed, with a complex system of pressure waves. In that case, the peak pressure achieved in the enclosure can vary between the AICC pressure and very high pressure levels associated with DDT. The pressure level produced by DDT mainly depends on the flame propagation process prior to DDT.

The peak pressure alone is not sufficient to determine the vulnerability of a structure. Pressure records associated with slow and fast deflagrations display a more gradual pressure rise and subsequent decay than pressure records associated with DDT, which display a sharp rise followed by a rapid decay.

4.4. Analytical tools

After a description of physical aspects of various combustion phenomena, it appears relevant to give a global overview of computational tools used to simulate hydrogen combustion scenarios in reactor containment buildings, focusing on specific combustion models.

The size of a nuclear reactor containment makes it impossible to perform full scale combustion experiments in real scale. Moreover, because of the difficulty and expense of carrying out experiments at full scale, specific numerical simulations are playing an increasingly important role in the assessment of combustion hazards in the design process.

Turbulent combustion simulations remain an immense computational challenge because of the range of scales that must be taken into account in a direct computation. Indeed, the simulation of combustion is very complex in practice, with involvement of a large number of interactive sub-processes, including turbulent flows and chemical reactions. The mathematical description of a practical turbulent combustion process turns out to be highly non-linear and time- and space-dependent. Therefore, theoretical modelling and simulation is now mostly based on numerical solution where computers resolve the mathematical complexities.

4.4.1. Combustion in containment systems codes (lumped parameter)

Lumped parameter tools are widely used to describe relevant physical processes expected to occur during severe accidents, as was discussed in Section 3.

For the prediction of deflagration, the models used in lumped parameter tools can be classified as empirical or phenomenological:

- Empirical models are the first-generation hydrogen burn models, specifically developed for deflagration analysis in reactor containment with lumped parameter codes. In these models, burn times and completeness of burn are specified empirically, without resort to any analysis of flame propagation.

- Phenomenological models provide a compromise between the complexity of the detailed fluid dynamics and chemistry calculation with CFD codes and the absence of any flame propagation in the completely empirical models. In this approach, flame propagation rates are based on geometrically simplified assumed flame shapes and empirical burning velocity correlations (e.g. Peters correlation).

In general, a lumped parameter approach presents many limitations regarding combustion simulation. Because of lack of information about the local flow field and the turbulence field, and the effect of these two on the combustion rate, lumped parameter approaches have a limited capability to quantitatively predict detailed containment loads.

Due to the limitations of the empirical and phenomenological models, lumped parameter codes are mainly applicable to slow combustion regimes with flame speeds not exceeding 100 to 200 m/s.

Table 8 provides an overview of typical lumped parameter codes that are currently applied for the simulation of turbulent combustion or detonations.

TABLE 8. TYPICAL LUMPED PARAMETER CODES CURRENTLY APPLIED FOR THE SIMULATION OF TURBULENT COMBUSTION OR DETONATIONS

Lumped parameter codes	References
TONUS LP	IRSN/CEA, France
COCOSYS/(RALOC)	GRS, Germany
ASTEC	IRSN, France GRS, Germany
MELCOR	USNRC, USA
CONTAIN	Sandia National Laboratories, USA
Muphi-Burn	NUPEC, Japan

4.4.2. Combustion in CFD codes

Deflagration

Multidimensional CFD codes provide greater detail than lumped parameter codes, since the equations governing conservation of mass, momentum and energy are solved for smaller regions of the flow. Transport properties of the generally turbulent flows encountered in the containment are also treated. Accurate modelling of turbulent combustion requires a proper consideration of all the important physics and chemistry, such as turbulence and chemical reactions, multiple length scales, flame-acoustic interactions.

In general, two alternative methods have been developed for the simulation of turbulent combustion phenomena in a full scale containment. The first one is based on chemical reaction modelling in order to achieve closure of the mean conserved mass fraction equations, and the second one is based on the ‘forest fire’ model.

The chemical reaction modelling approach is the most-often used method in CFD codes for simulating combustion phenomena. This approach is based on conservation equations averaged with respect to the turbulent fluctuations of the flow variables. This averaging introduces high order moments and average reaction rate terms, which cannot be computed without closure schemes. Basic work in this area mainly focuses on the development of improved closure models while calculations are being made in a variety of applications. Several classes of combustion models are adopted to cope with the closure problem by averaging the non-linear reaction rates.

One simple method is to solve the transport equations of the mean conserved mass fractions with the mean chemical reactions directly modelled (eddy break-up and eddy dissipation-concept models). For the prediction of turbulent combustion, the eddy break-up [61 model and the eddy dissipation-concept model [62] is often used with adapted constants calculated via Said and Borghi correlations. The transition regimes are often expressed in terms of Damköhler number, which represents the ratio of chemical to turbulence time scale.

- The eddy break-up model and its extensions are employed in the majority of numerical models applied to confined combustion due to its simplicity and its very low computational expense. The reaction rate is related algebraically to known quantities without additional transport equation. Nevertheless, this model presents several deficiencies: the reaction rate does not depend on chemistry, the rate of chemical conversion is overestimated, especially in highly strained regions, and the transport of the turbulent flame by the flow and many other physical processes are not described.

- The eddy dissipation model for predicting gaseous combustion reactions in turbulent flows is based on the concept that the chemical reaction is fast relative to the transport processes in the flow. It is limited by the introduced assumptions, especially by the fast chemistry assumption. On the other hand, there is no kinetic control of the reaction process. Thus, ignition and processes where chemical kinetics may limit the reaction rate may be poorly predicted.

Another more complex and accurate method is to solve the transport equation and then relate the concerned mean non-conserved mass fractions to conserved scalar using the laminar flamelet concept [63] and a probability density function [64]. These much more sophisticated models are well established as being able to predict more accurately the flame front compared to traditional finite rate approaches. Nevertheless, these models, which require a detailed geometrical description of the containment and the use of more accurate turbulent models, are difficult to carry out for full size containment simulations.

These previous turbulent combustion models have been extensively discussed and described regarding the numerical requirements in the report on ‘Flame Acceleration and Deflagration To-Detonation in Reactor Safety’ [57].

For simulating various combustion regimes in a full scale reactor building containment, some combustion codes use the so-called ‘forest fire’ model [65]. This model includes a global constant, which represents an effective burning rate or an effective turbulent burning velocity, and a hypothesis on the starting time for the burning.

Detonation

For detonation problems, codes have been specifically developed to handle these phenomena. In particular, these codes must have effective algorithms for dealing with shock discontinuities and sharp gradients, with much faster reaction rates than corresponding deflagration rates and with transitions from subsonic to supersonic flows.

The following Table 9 provides an overview of typical in-house and commercial codes currently applied for the simulation of turbulent combustion or detonations. A detailed description of the most-often used computational codes for containment combustion applications is given in Ref. [57].

TABLE 9. TYPICAL IN-HOUSE AND COMMERCIAL CFD CODES CURRENTLY APPLIED FOR THE SIMULATION OF TURBULENT COMBUSTION OR DETONATIONS

Lumped parameter codes	References
FLAGS	Christian Michelsen Research
AutoReaGas	TNO and Century Dynamics Ltd.
CFX	AEA Technology Ltd., UK
CFX-TASCflow	AEA Technology Ltd., UK
EXSIM	Aalborg University Esbjerg, DK
Fluent	Fluent Inc., USA
IFSAS	Combustion Dynamics Ltd., Canada
COM3D	Kurchatov Institute, Russian Federation/FZK, Germany
COMET	ICCM GmbH, Germany
FIRE	AVL List GmbH, Austria
Bassim	Battelle IT, Germany
Gasflow	FZK, Germany
AIXCO-2D	RWTH – Aachen, Germany
DET-2D/3D	FZK and FZJ, Germany
STAR-CD	Computational Dynamics Ltd., UK
ACE+	CFD Research Corporation, USA
GLACIER, Banff	Reaction Engineering Int., USA
PHOENICS	Cham Ltd., UK

Various commercial fluid flow simulations codes and state of the art research codes are available for simulating parts of the whole area of interesting combustion regimes. Nevertheless a natural gap between these two levels of CFD codes exists. Commercial codes generally include in a powerful and user-friendly environment techniques and detailed models that have reached a sufficient level of maturity and technical robustness. Researches codes include more advanced dedicated models, but are usually not sufficiently flexible and user friendly to allow application to practical engineering tasks. In some areas this gap is being narrowed down, such as for non-reacting turbulent flow simulations.

Status of validation

The models used for prediction of turbulent combustion processes have been based on several experiments. The objective of the validation task is to compare different analytical tools regarding accuracy, efficiency and stability. In general, the selected turbulent combustion test includes different scales (small, medium and large scales).

For combustion codes with models used to achieve closure of system equations, it has been shown that the semi-empirical (eddy break-up) model is able to provide reasonable agreement with experimental data, if either the free constants in the model are benchmarked on experiments with different scales [65], or a theoretical extension is implemented in the code [66], which leads to a model without any free constants. For this model, the definition of combustion constants for full containment applications remains an open issue.

The validation of the presumed PDF approach [67] without any free model constants showed promising results as it could be realized for small- and medium scaled turbulent combustion experiments. A further improvement of both numerical methods and model optimization will allow the application to large scale problems within a reasonable running time.

For so-called forest fire codes, devoted to the simulation of combustion in large geometries with respect to the characteristic dimensions of the physical phenomena involved and based on laminar burning velocity input, interpretations exist on how to define this data and correlate it to turbulence. This model implemented in the CEA-IRSN code TONUS has been tested for different relevant combustion regimes under severe accident conditions, such as: slow subsonic deflagrations, fast choked deflagrations and detonations. It has been shown that this model gives a satisfactory estimation of the pressure loads on the walls.

In general, multidimensional combustion models have shown very encouraging results in the regimes for which they were developed. The present combustion models cover different parts of the Borghi diagram. Nevertheless, regarding applicability of combustion codes, no single code can describe the whole combustion process, from ignition via the flame acceleration regime to fully developed detonations.

Within the HYCOM project (integral large scale experiments on hydrogen combustion for severe accident code validation) within the 5th Framework Programme of the European Commission, a study has been conducted in order to investigate the accuracy of seven numerical codes that have been developed for combustion hazard assessments. The codes are CFX (GRS), TONUS 3D and TONUS LP (IRSN), COM3D and FLaccident managementE3D (FZK), REACFLOW (JRC) and B0m (KI).

The study includes two stages: (1) a validation stage against experimental combustion data and (2) a full scale combustion simulation in a real scale simplified modern PWR containment. The validation stage was instrumental in calibrating the combustion models against small scale and large scale experiments. It has been shown that for fast combustion regime all codes are capable of capturing the main features of hydrogen combustion, both qualitatively and quantitatively. More problems appear for slow deflagrations, but all the codes were able to capture the maximum overpressure. Overall, the validation stage was successful in achieving a quite good agreement between the simulations and the small and large scale experiments. However, non-uniform mixtures remain a difficult configuration for codes, especially when the concentration gradients cause a change in the combustion regime.

4.5. Experimental facilities

In order to apply the models presented in the previous section, effort has to be put on the validation of the numerical tools developed. The final objective for all tools developed in this context is to estimate the danger potential that can arise from a hypothetical release of hydrogen into the containment atmosphere of a NPP. Therefore, the results of numerical simulations need to be compared with appropriate experiments.

Numerous experiments have been carried out on test facilities of different scale in order to provide a data basis for code development. A wide range of hydrogen–air mixture conditions with and without steam has been tested in order to simulate reactor conditions.

A large amount of experimental data on turbulent flame acceleration is available at conditions representative for severe accident conditions in nuclear reactors.

Numerous experiments cover the most important combustion processes and regimes in several geometrical configurations: shock focusing, flame acceleration, and transition to detonation in obstructed areas, and flame propagation in small, medium and complex large scale geometries.

This section summarizes the main test facilities that were used to investigate various combustion phenomena. Although the experimental results presented in this section are not detailed, they are intended to give code developers a comprehensive overview of what kind of experiments were performed in various test facilities. In particular, shock-induced ignition and transition to detonation, accelerating flames in obstacle arrays, and turbulent combustion in complex large scale geometries are addressed.

4.5.1. Small scale facilities

Several tests have been carried out in small scale facilities (usually up to a volume of 1 m^3) in order to provide data information on for code validation, to perform detailed investigations of combustion phenomena and to visualize flame propagation by means of conventional measurement techniques or sophisticated optical measurement techniques. The geometries of these facilities are, in most cases, very simple (e.g. periodic obstacles in a tube) and can, therefore, be easily modelled at a very detailed level.

CHANNEL, DRIVER, TORPEDO and TNO-Delft experiments provided data on turbulent flame propagation regimes in obstructed areas at different scales [69]. Blockage ratios ranged from 0.1 to 0.9. Distances between obstacles were equal to the transverse size of each tube for all these facilities. Mixture compositions were varied in the tests. Experiments were conducted under normal atmospheric conditions.

The CHANNEL facility is a tube with a square cross-section of 80 × 80 mm and 5.28 m length. Rectangular obstacles were mounted along upper and bottom plates. Different hydrogen–air mixtures and stoichiometric hydrogen-oxygen, diluted by argon or helium were used in these tests.

The DRIVER facility is a detonation tube of 174 mm internal diameter and approximately 12 m length. Hydrogen–air mixtures and stoichiometric hydrogen-oxygen mixtures diluted with nitrogen, argon, or helium were used in this facility.

The TORPEDO facility is a 520 mm tube of 30.3 m length. Hydrogen–air mixtures and stoichiometric hydrogen-oxygen, diluted by helium were used in these tests.

The TNO-Delft facility is an 8 m long rectangular channel, 50 × 40 cm wide, with blockages in the form of square steel blocks. It has also the possibility to inject CO2 and N2 during combustion to study the effect of these inert gases on the flame speed (a substantial effect was found).

Numerous experimental investigations have been carried out on shock wave focusing phenomena in combustible media, which is one of the key problems of DDT. It has been found experimentally that a strong dependence exists between the mixture composition and the type of reflectors installed near the end plates of the ignition test shock tubes and the resulting shock wave intensity corresponding to different self ignition regimes.

Experiments are performed in order to verify reaction kinetic models relevant to self ignition phenomena. The transition from deflagration to detonation of the hydrogen–air–steam system depends on the physical-chemical properties of the mixture, the characteristics of the ignition process, and the interaction of ensuing deflagration waves with the environment. Recent investigations of the hydrogen–air self ignition mechanism have shown that the measured ignition delay times are partially in contradiction with the calculated data obtained with the established kinetic mechanism 69]. In particular, experimental results show that, in the region of 'low' temperatures and also in the region of practically interesting high-pressures, deviations of the calculated and measured ignition delay times occur of more than 2 orders of magnitude [70, 71].

Dedicated experiments for flame propagation investigation in obstructed areas have been performed in order to provide data over a wide range of flame regimes from the laminar flame after weak ignition, the interaction of flame propagation in obstructed channel and the flame acceleration by different multiple obstacles configurations up to detonation conditions for a wide range of hydrogen–air mixtures. To investigate the effect of obstacles on flame acceleration simple types of obstructed channels are used with repeated steps or obstacles, such as spiral, rings, baffles. To summarize, the following observations are made from the results of these tests:

- The results showed that the main parameter responsible for flame acceleration is the composition of the hydrogen–air mixture in the channel containing obstructions with a blockage ratio of 0.4 to 0.6 and smooth parts.
- These experiments revealed the influence of the obstacle step height on the change of flame velocity. Nevertheless the effect of distance is negligible.
- The sensitivity of flame velocity to steam concentration has been measured. Dilution by more than 30% steam leads to a significant deceleration of the flame down to subsonic values at the exit of obstructed part.

In the HYCOM project (integral large scale experiments on hydrogen combustion for severe accident code validation) within the 5^{th} Framework Programme of the EC, tests have been performed in the RRC KI research station 'Vargos' using combinations of DRIVER and TORPEDO facilities. These facilities provided capability to study flame propagation in obstructed channels in four geometrical configurations with two different blockage ratios BR = 0.3 and BR = 0.6 and initially uniform or non-uniform combustible mixtures. The spacing between the obstacles was equal to the tube diameter. These tests addressed characteristic features of turbulent flame propagation. Special attention was devoted to study the following separate effects under relatively simple geometrical configurations: (1) the effect of ignition position, (2) the effect of venting, (3) the effect of concentration gradients (positive and negative), (4) the effect of blockage ratio changes (positive and negative) and (5) the effect of channel cross-section changes (positive and negative).

4.5.2. Medium test facilities

Experiments have been conducted at the Sandia National Laboratories with hydrogen–air–steam and hydrogen–air mixtures in the heated detonation tube (HDT) to determine the region of benign combustion (between the flammability limits and the DDT limits).

The HDT is 12 m long and has internal diameter of 430 mm. Obstacles were used with 30% blockage ratio annular rings, and alternate rings and disks of 60% blockage ratio. The initial conditions were 383 K and 0.1 or 0.3 MPa pressure.

4.5.3. Experiments in large scale and complex geometries

A quite large number of experiments in large scale and complex geometries are needed to provide quantitative determination of interaction of different phenomena, scaling effects, multi-compartment effect, effect of venting, flame acceleration and DDT criteria in representative geometries and to validate lumped parameter and field codes.

In order to apply the numerical codes for the simulation of propagating flame fronts in realistic geometries, they have to be validated with experiments that have been performed in facilities with a scale of several orders of magnitude larger than a small scale explosion tube. Table 10 provides the sizes of a set of large scale facilities in comparison to the size of PWR containment.

TABLE 10. SIZES OF A SET OF LARGE SCALE FACILITIES

Test facility	Volume (m^3)	Volume Scale
Explosion tubes	1	1/70 000
Interconnected vessel (AECL)	2.3	1/30430
BMC (Battelle)	40–200	1/1750–1/350
FZK combustion facility	110	1/636
LSVCTF (AECL)	120	1/580
NUPEC Large scale	270	1/260
RUT facility (Kurchatov Institute)	480	1/145
PHDR (FZK)	535	1/130
PWR	70 000	1/1

Table 11 summarizes the recent experiments and provides a short summary of the test facility geometry, the applied instrumentation the investigated combustion phenomena and the mixture conditions. Detailed descriptions of these test facilities are provided in Annex III.

The hydrogen combustion behaviour and the corresponding loads in complex multi-compartment geometries have been investigated in the Europe's HYCOM programme (under the 5-th EURATOM Framework programme of European Commission), using the large experimental programme in the RUT facility of the Russian Federation, with combustion modes ranging from slow to fast turbulent deflagration. The tests, carried out in 1999–2001, had the objective to study the effects of area change, ignition location, venting and mixture non-uniformity on the behaviour of turbulent flames. The variables in the tests were hydrogen concentrations (positive and negative gradient) and igniter positions. Detailed data were obtained revealing specific effects of scale, multi-compartment geometry, and venting. It was observed that the confinement geometry had some influence on critical conditions for fast combustion regimes. Nevertheless, applicability of the flame acceleration criteria (σ-criteria) was confirmed for complex.

TABLE 11. COMBUSTION EXPERIMENT TEST FACILITIES

Test Facility	Country/ Operator	Geometry	Mixture	Pressure gauges, thermocouples, volume fraction, video	Test parameters
MUSCET	Germany, TU-Munich	286 × 286 mm, L = 6.7m	9%–16% Hydrogen	Photodiodes, Pressure Gauges	Visualization, flame-acceleration due to obstacles
L.VIEW	Italy/University of Pisa, TU-Munich	670 × 670 mm, L = 3.2 m	8.5%–10% Hydrogen	Video, LDV, schlieren, pressure gauges, thermocouples, volume fraction	Visualization, ignition and opening location, jet ignition, turbulence
AECL Interconnected Vessels	Canada/AECL	V_{sphere} = 2.3m^3	6–20 vol% Hydrogen	Pressure gauges	Jet ignition, independent hydrogen cone, in sphere and cylinder
LSVCTF	Canada/AECL	10 × 4 × 3m, V = 120m^3	8–14%H_2, Steam	Pressure gauges	Vented Combustion with different vent areas
HTCF	USA/BNL	ID 273 mm, L = 21.3 m	H_2-Air-(Steam)	Photodiodes, smoked foils, fast response thermocouples and piezoelectric pressure transducers	Effect of mixture's composition and high initial temperature on mixture's sensitivity to detonation and DDT, as well as effect of venting on DDT
Battelle Model Containment BMC	Germany/Battelle	D = 10 m, H = 10 m, V = 40 - 200 m^3	7–14% Hydrogen, 0–50% Steam, (CO_2)	Pressure gauges, thermocouples, IR-diodes, volume fraction, (Hot wire turbulence)	Slow and fast combustion, vented combustion, jet ignition, realistic obstacles
DN-400	Germany/Battelle	Diameter 0.4m, L = 8 m, V = 1 m^3	8.5–17% Hydrogen, 0–40% Steam	Pressure gauges, thermocouples, IR-diodes, volume fraction, hot wire turbulence	Scaling to BMC, realistic obstacles
PHDR	Germany/FZK	Typical L = 10m,V = 535m^3	8–12% Hydrogen, 34–30% Steam	Pressure gauges, thermocouples, volume fraction	Scaling to BMC
NUPEC Large Scale	Japan/NUPEC	Diameter 8m, V = 270m^3	8–15% Hydrogen, 0–60% Steam	Photodiodes, Pressure gauges	Ignition location, spray, elevated initial pressure, transient behaviour
RUT Facility	Russian Federation/Kurchatov Inst.	Channel: L = 34.6 m, W = 2.5 m, H = 2.3 m, 'Canyon:' L = 10.55 m, H = 6.3 m, W = 2.5 m, V = 480 m^3	$H_2 - Air$ -H_2O– Mixtures		Influence of mixtures sensitivity to detonation and DDT

5. RISK FROM HYDROGEN COMBUSTION

Hydrogen deflagration can pose various risks to the containment and other plants systems. Combustion can give large pressure spikes, varying from relatively low pressure loads, bound by the AICC loads, up to large loads from accelerated flames and detonations. Such acceleration can already occur above about 8% H_2, so that above that value the AICC load may not always be the bounding value.

5.1. Combustion loads and structural response

In the preceding sections, the various phenomena of hydrogen generation, distribution and combustion have been presented. In this section, the risk from hydrogen combustion will be further elaborated.

The major risk, which is considered here, is the risk for loss of containment integrity and failure of safety systems, due to the combustion of the hydrogen produced in the course of the accident. The risk is twofold: pressure loads of various magnitudes may occur, and thermal loads. Pressure loads may cause structural damage; thermal loads can cause damage to cables and components (instrumentation, pumps, valves, seals of air locks).

As has been discussed before, various modes of hydrogen combustion exist:

- Mild deflagrations, which occur in lean hydrogen mixtures;
- Fast deflagrations, which occur at higher hydrogen concentrations, or are caused by flame acceleration from flames travelling initially at lower speed, and/or jet ignition;
- Deflagrations that accelerate and transit to detonation (‘deflagration to detonation transition’, DDT), caused by the mechanisms described in the previous sections;
- Local detonation, at high hydrogen concentration, or as the consequence of a DDT process;
- Global detonation.

Thermal loads can be intermittent (free flames) or continuous (diffusion/standing flames). Free flames occur after ignition in a gas cloud; they typically last seconds. Standing flames may occur at a location where the hydrogen from the source mixes with air. A typical example is a BWR suppression pool surface, where standing flames can occur when hydrogen is driven from the drywell through the water of the suppression pool.

At low H_2 concentrations, typically 4–8% H_2, deflagrations produce only slow flames, and loads are quasi-static. They are basically calculated from the energy balance, the key parameter being the number of hydrogen moles that react with oxygen. Combustion is often not complete, i.e. not all hydrogen will burn. These deflagrations are mild deflagrations, bound by the AICC curve (see Section 4 for a description of these loads). For structural response, it can be assumed that the loads are static, i.e. no dynamic response needs to be taken into account.

Above about 8% H_2 concentration, flames may accelerate and larger loads may result. A typical increase of loads is given in Ref. [72]. In addition, combustion is more complete, so that loads also increase due to the fact that more hydrogen is burned. Note that flame acceleration is a complex process, and does not depend just on the hydrogen concentration, but also on the amount of blockage, the degree of confinement, the presence of diluent gases (steam, CO_2), etc., as has been discussed in Section 4.

Accelerated flames produce pressure spikes, characterized by a high pressure which lasts a very short time. Where flames accelerate in a confined volume – typically a reactor containment or its subcompartments – the pressure developed depends on the size of the H_2 gas region, the H_2 concentration, the size of the enclosure and the configuration of obstacles.

Flames may accelerate and transit to a detonation, as was discussed before (Section 4), or a direct detonation may occur. The latter one requires an adequate initiation energy. It varies from 4 kJ, as determined by stoichiometry in a dry atmosphere, to more than 10 000 kJ when the mixture contains 30% steam. Hence, direct initiation of a detonation is unlikely to occur in a reactor containment after a severe accident has occurred.

Detonations produce shock waves, resulting in high pressures, with a very rapid decay after the peak value. If the detonation results from a transition from deflagration to detonation, these loads can even be higher. Peak pressures of 250 bar have been observed in reflected shock waves, in an experiment initially at 1 bar pressure. Figure 21 represents the pressure history of accelerated flames and DDT, measured in the RUT facility [57].

In order to obtain the actual risk from these loads, the structural response of the containment (or other endangered structure), must be obtained. Higher peak loads do not necessarily result in higher structural loads: the peak pressure alone is insufficient to determine the vulnerability of a structure. Pressure records associated with DDT or a stable detonation display a sharp pressure rise followed by the decay, which is relatively rapid for DDT. Slow and fast deflagrations, on the other hand, display a more gradual pressure rise and decay. The details of the pressure histories can be very important in assessing the response of a particular structure.

A variety of structural analysis codes, often of the type of finite elements, is available to investigate the response of the structure to the dynamic load. The response will be dependent on the Eigen frequency of the structure, of which Table 12 gives an example [57].

Another method is to derive an equivalent static pressure from such dynamic analysis. An example is given in Fig. 16, where the equivalent static pressure is shown as a function of the frequency range [57].

TABLE 12. TYPICAL EIGENFREQUENCIES OF VARIOUS NUCLEAR REACTOR STRUCTURES

Structure type	Frequency (Hz)
Spherical shell containment (bending mode)	6–12
Spherical shell containment (membrane mode)	50

Concrete containment	5–8; 12–22
Stiff reinforced concrete substructures	<500
Technical installations	100–400

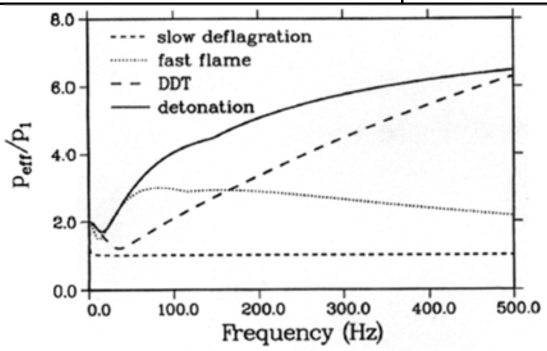


FIG. 16. Normalized effective static pressure for a frequency range relevant for nuclear reactor structures (pressures are normalized relative to the long term combustion pressure) [57] (courtesy of OECD[2]).

As can be seen, accelerated flames and DDT/detonation produce high loads on the structures.

Note that the curves presented are examples from various cases; it is important that these loads not be used in an actual application, but only loads that are unique for the plant considered.

5.2. Threats from combustion to the containment

5.2.1. Direct damage.

As has been discussed above, a proper analysis must be made to obtain the structural response of the containment from combustion loads. Static and quasi-static loads need only static analysis. Dynamic loads require a dynamic analysis. Whether loads are to be considered static or dynamic has been discussed above.

If the loads exceed the design strength, the containment may fail. Usually, the containment has a considerable margin to failure, so that damage will first occur at higher loads. Often, this margin can be expressed in a factor which usually is 1.5 to 2.0 in magnitude. In other words, the containment will not fail unless exposed to loads about 1.5–2.0 larger than the design loads.

The failure mechanism can be of different nature. As the containment exists of a main structure plus a number of penetrations (hatches, pipe and cable penetrations), failure may either be a gross failure of the containment or a failure of one or more of the penetrations. Concrete containments often show initiation of cracks as the first indication of failure. If the

2 OECD NUCLEAR ENERGY AGENCY, Flame Acceleration and Deflagration to-detonation Transition in Nuclear Safety, State-of-the Art Report by a Group of experts, NEA/CSNI/R (2000) 7, OECD, Paris (2000), p. 2.23, www.nea.fr .

cracks are large enough, they will prevent gross containment failure. Containment failure is often represented in a probability curve: the higher the pressure the larger the probability of failure, see Fig. 17. That is to say, once combustion loads are known, it is possible to calculate the failure probability of the containment.

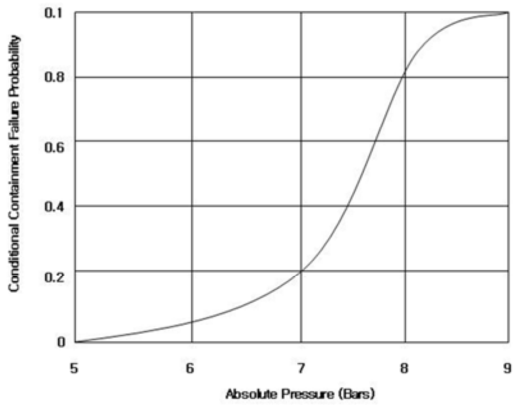


FIG. 17. Failure probability of the containment as a function of the pressure.

A typical example of pressure loads is given in Ref. [72], which indicates the AICC pressure loads on the large dry containments of French PWRs (with no PARs applied). The pressure loads resulting from hydrogen deflagration vary about 6.2–6.5 for 75% active cladding length and about 7.7–8 for 100% active cladding length.

It should be noted that these loads do not include any consideration of flame acceleration or DDT; if such processes are taken into account, higher loads may result.

Another potential direct damage mechanism of the primary containment is the combustion of gases outside it.

Hydrogen is an extremely volatile substance. As no containment is fully leak tight, it will leak to the surrounding areas, which often have the function of secondary containment. If the containment is bypassed (interfacing system LOCA or steam generator tube rupture) or damaged otherwise, even more H_2 can escape to the surrounding building. Hence, there is a certain risk that combustion may occur outside the primary containment. This may lead to combustion loads exerted on the containment from outside. Usually, containments have considerable margin against loads from inside, as they are in principle designed to carry the pressure loads from a large break LOCA. The pressure bearing capability for loads from outside can be substantially less: many primary containments are vulnerable to subatmospheric pressure or, in more general terms, to negative pressures differences with the outside. Hence, it is necessary to analyse such external loads carefully.

5.2.2. Indirect damage

Apart from the direct damage considered in Sec. 5.2.1, the containment may suffer indirect damage from combustion loads.

Notably in the case that the containment has many subcompartments, a local deflagration or detonation may occur that damages the subcompartment and through this may generate missiles (concrete blocks from the disintegrated compartment walls) that can endanger the containment integrity. This is particularly a concern for a free standing steel containment, as it is vulnerable to such heavy, flying objects. The resistance of a concrete containment to such objects is larger than that of a steel containment: upon impact, the missile may generate cracks rather than gross failure. To date, however, no analysis ever has been made on the damage potential of flying objects, generated in an H_2-explosion.

In most plants, the walls of the containment subcompartments have been designed for the pressure differences of DBA loads (large break LOCA, etc.). Often, it even is not known what other pressure differences these structures can bear, as the exact composition of the walls is unknown and, hence, a structural analysis cannot be done. Together with a potential accumulation of hydrogen in some compartments, the risk from indirect damage is difficult to estimate.

Under such circumstances, it may be worthwhile to develop mitigative measures to prevent possibly dangerous accumulations, e.g. by promoting convection of the gas content. This can be done by active means (fans, containment sprays), if available, or by forcing compartment doors to open (e.g. by using pneumatic devices) to promote natural convection. Note that the use of sprays also can result in a de-inertization of the containment atmosphere and, hence, provoke deflagrations. Therefore, such measures need to be investigated for their effects by appropriate analytical tools, i.e. whether the measures foreseen indeed result in the desired effect. For example, if hydrogen escapes to the containment from a high elevation, stratification may occur despite measures to promote natural convention at a lower elevation, such as opening compartment doors.

5.2.3. Failure of secondary containment

As has been discussed in sec. 5.2.2, hydrogen can escape to the buildings outside the primary containment, which often have the function of secondary containment. Apart from the damage that the hydrogen combustion may cause to the primary containment, it may also damage the secondary containment and the equipment inside. This can include important systems which are located there, e.g. the emergency core cooling system (ECCS). The secondary containment has not been designed to withstand large pressure loads, but it sometimes has been designed to large external loads (seismic, airplane crash) which is expected to generate margins here. Compartments can, however, still be vulnerable to combustion loads, as discussed before.

A mitigative measure may be to vent the secondary containment over appropriate filters, so as to reduce the H_2 content. In more general terms, severe accident management procedures-/guidelines have to address the issue of hydrogen accumulation and combustion in the secondary containment. Some of these sets of guidelines (e.g. the Westinghouse Owners Group (WOG) severe accident management guideline) indeed address this issue.

5.2.4. Failure of containment vent.

Many containments are equipped with containment vents, either filtered (many European plants) or unfiltered (both USA and European plants, most plants elsewhere). If pressure is relieved through the vent, steam may condense in the long lines or in the filter, and dry hydrogen may appear in vent appurtenances. Consequently, explosions are well possible and may lead to damage of the pipes and also of the filter itself and, hence, to an unfiltered release of radioactive substances.

Therefore, design measures have to be taken to protect the filter against combustion. To solve this problem, it is often proposed to pre-heat the pipes before the opening, to reach saturation conditions on the internal walls of the pipes before. Such a pre-heating procedure must consequently appear in the severe accident guidelines of the plant. Unfortunately, hours are usually needed before reaching the saturation conditions on the internal pipe walls. As an example, this pre-heating time is around 20 hours for the U5 French containment vent filter.

Another solution, applied in Sweden and Germany, is to heat parts of the filter, eventually continuously, so that an inerting steam environment is created.

Both solutions require electric power. As operation of the filter is expected to take place many days after the initiation of the accident, this should not pose a problem (there is probably ample opportunity to restore power, if it has initially been lost). Guidance is needed to remind plant workers to inert the appropriate parts of the containment vent in due time before its actuation.

5.2.5. Effect of temperature.

Apart from pressure loads, combustion of hydrogen (and CO) generates much heat, which can also endanger safety relevant equipment. Notably standing flames are a risk, as they are a more or less continuous source of heat. Also the exhaust plume of passive autocatalytic recombiners (PARs) can be hot and, hence, endanger equipment.

5.3. Scenario effects

In the preceding sections, effects of hydrogen combustion were considered from a physical point of view only, i.e. the various phenomena were not considered in the context of the actual scenario.

In a severe accident scenario, hydrogen is generated over a certain period of time, and a part of it (or all) may burn away in an early combustion, either spontaneously (i.e. by some arbitrary spark, generated by the start of a pump or the operation of a valve, or even by static electricity) or triggered by an igniter. But, apart from the hydrogen, also steam will escape from the primary system, which may render the containment atmosphere partially or wholly inert. Under such circumstances, the hydrogen may accumulate to appreciable concentrations, before it will be flammable as the consequence of the condensation of the steam, which will take place sooner or later in the accident, and either as a natural process or invoked by the use of containment spray systems.

Consequently, there is a variety of possibilities for combustion processes. If the containment is de-inert, multiple burns may occur, each having a low combustion load, and the integrity of the containment is not jeopardized, even if the design pressure of the containment is low. On the other side, to count upon such burns may require the presence of active ignition sources: spontaneous ignition is uncertain, if it occurs at all.

Strategies may be designed to burn the hydrogen before vessel failure is expected to occur, so that the amount of hydrogen still is limited (to about max. 50% ACL reacted). It can be expected that vessel failure may induce combustion of the hydrogen generated so far, but this cannot be assured for all scenarios. Hence, further accumulation of hydrogen after vessel failure cannot be excluded.

As said, hydrogen may accumulate to appreciable concentrations in a steam rich environment, before it will get burnable due to – natural or forced – steam condensation. In such cases, high combustion loads can be expected, possibly even exceeding the AICC values, as was shown in preceding sections and sections. If combustion will occur while there still steam is present, the loads may be lower, either due to the fact that the burn will not be complete, or due to the quenching effect of the steam on the flames, which reduces the flame speed.

Some of the accident management measures may even be counterproductive: if only a small amount of water is available for reactor coolant system injection and there still is unoxidized Zr in the core, such injection may just generate hydrogen and increase the risk for combustion rather than reduce it. This aspect is further discussed in Sec. 5.4.

As the possible hydrogen combustion is so much dependent on the scenario and may even depend on accident management measures, it is important to carefully select scenarios to find enveloping cases. The probabilistic safety assessment (PSA) can give here guidance, except that PSAs usually do not consider the effect of accident management measures beyond the emergency operating procedure domain. Hence, such effects need to be studied separately. An extensive study on the effects of accident management measures on the phenomena during a severe accident was undertaken by EPRI, in the framework of developing severe accident guidelines for the USA Owners Groups, of which a summary is given in [73]. Some further remarks on this are given in Section 5.4. Accumulation of hydrogen during appreciable times has to be considered, unless clear insights or active strategies are available that prevent this from happening.

Finally, there is also a long term aspect to be considered: hydrogen from radiolysis. The accident management measures also need to include this hydrogen source. There is a limited need for detailed guidance, as it can be assumed that by that time various essential systems (power, cooling water) have been restored, so that the technical support centre has much more flexibility to operate and take measures than in the short term, where the severe accident management guidance usually focuses.

5.4. Other factors relevant for the risk from combustion gases

5.4.1. Other substances than hydrogen.

Although the emphasis of this report is on hydrogen distribution and combustion, there is also risk from other combustible gases, notably from CO. This gas results from the core-concrete interaction; as has been explained in Section 2, its quantity is usually small in comparison with the amount of hydrogen generated.

5.4.2. Pressure build-up by non-condensables.

The total pressure in the primary containment is made up by steam, CO_2, CO and H_2. Although a major risk is with the combustion phenomena, it may also happen that combustion does not take place, e.g. because the atmosphere is inert or ignition is deliberately suppressed (which sometimes is done in severe accident management guidelines). Hence, combustible gases do also contribute to the risk of containment overpressurization (which phenomenon is not further discussed in this report).

5.4.3. Stratification of gases

The gases which are released to the containment – steam, CO, CO_2, H_2 – have different chemical composition, different molecular weight, and different temperatures. Hence, there is a potential for stratification. Whether stratification actually will occur, depends on the scenario (e.g. are various gases released at the same time or not), the location of the break (a high location is giving more easily rise to stratification, as has been shown in the HDR-experiments), the lay-out of the containment (i.e. whether it promotes convection or not) and accident management measures (e.g. actuating a fan or spray will mix the containment atmosphere). These factors need to be carefully considered during the analysis of the hydrogen risk and the design of mitigatory measures.

An example is a small break LOCA in a low elevation break location on the cold leg, where initially steam is released. Later on, the steam that results from evaporating water through the core may be consumed fully in the generation of hydrogen, thereby giving a release of almost pure hydrogen. This may not always mix with the steam already present in the containment: with air ingress at the break location, the hydrogen–air mixture may be heavier than steam and, hence, may not mix with the upper steam layer. In such a way, stratification may occur and sensitive mixtures could result [74].

Further effects of scenario selection are discussed in sec. 5.4

5.4.4. Effects from accident management

Also the accident management can be relevant for risk. Severe accident management consists of a number of actions, sometimes called candidate high level actions, as they are the prime actions that the technical support centre has to its disposal to execute. The list of the most common actions is as follows, in alphabetical order [75].

- Depressurize the reactor coolant system
- Depressurize the steam generators
- Inject into the reactor coolant system
- Inject into the steam generators
- Flood the auxiliary building
- Flood the reactor cavity/external reactor pressure vessel cooling
- Operate containment fan coolers
- Operate hydrogen recombiners
- Operate hydrogen igniters

- Restart the reactor coolant pumps
- Spray into containment
- Spray the auxiliary building
- Spray the outside of the containment
- Spray into the vessel (BWR only)
- (Steam) inert the containment
- Vent containment
- Vent the reactor coolant system

Some of these actions may also have an effect on the hydrogen generation. E.g. if only a small amount of water is injected, no cooling of the core may be achieved, but only further generation of hydrogen will occur. Also the sudden flooding of the overheated core may generate a hydrogen spike (see also Section 2). For this reason, some regulatory bodies (notably in France, Netherlands) require a 100% Zr-H_2O reaction, and assume the flooding is done at a moment the pressure operating relief valves are fully open, so that the H_2 is released directly into the containment.

Restarting a reactor coolant pump may also generate additional hydrogen, as it sweeps steam through the overheated core. Also late depressurization of the reactor coolant system may do so, as steam from the flashing of the remaining lower plenum water will be swept through the core.

Other possible actions are e.g. the initiation of the spray system (if present) which may de-inert an initially steam inerted containment atmosphere and provoke hydrogen combustion. Many plants use so-called computational aids to determine whether the containment will be brought in a flammable condition using the spray or vent system.

A number of plants have installed passive catalytic recombiners. Under elevated hydrogen concentrations (above about 10%), they may become igniters and initiate combustion, which may not have been foreseen by the designers. Their exhausts can be quite hot, as the recombination generates much heat, so that they can damage nearby equipment or even, if not properly located, the containment itself.

5.5. Sensitivity of various containments to hydrogen combustion loads

In this section, an overview is given of the potential vulnerabilities of various containment types for hydrogen combustion. Countermeasures, however, differ from country to country, as they also depend on national policies. It should be noted that the risk of hydrogen combustion to the various containment types can only be described here in general terms. A plant specific analysis is required to draw conclusions for an individual reactor containment.

5.5.1. *Large dry containment*

This type of containment is usually a robust structure, as it is designed to take the full pressure load from a large break LOCA without further provisions. Hence, many of these containments are not jeopardized by combustion loads, notably when these are AICC type. As these containments usually have a fairly open structure, at least in their upper parts, there is no big risk for flame acceleration. Some containments have, however, quite a number of compartments and, hence, can be sensitive to phenomena like jet ignition and flame acceleration. Mixing the containment atmosphere can be an effective measure to mitigate this concern. If large quantities of hydrogen (e.g. 100% Zr reacted) are expected or postulated, AICC loads can go up to relatively high values, which then warrants additional measures (e.g. the installation of PARs and/or igniters).

It should be noted that containments of some older plants have only a limited pressure bearing capability.

The failure mechanism is different for the various designs. Upon exceedance of the pressure bearing capability, a metal containment may suffer a breach, whereas a concrete containment first will develop cracks. The cracks may be large enough to relief the pressure, so that no further damage will occur.

5.5.2. *Ice condenser containment*

These containments are designed so that the ice will absorb the stored heat from the escaping coolant in a large break LOCA. Consequently, the design pressure is often low (about 2 bar). Hence, these containments are vulnerable to combustion pressures. Adequate hydrogen risk mitigation is an important feature at these plants. Often, igniters and/or PARs are installed to burn the hydrogen away before it can reach dangerous concentrations.

5.5.3. *Suppression pool containment (BWR)*

As the BWR suppression pools are designed to condense all the steam that escapes in a large break LOCA, the design pressure of most BWR containments is also relatively low.

Many BWRs, notably the General Electric Mark I and II designs and similar designs by other vendors, protect their drywell against hydrogen explosions by permanent inertization. Similarly, for the wetwell of the Mark I BWR (torus containment). For the BWR Mark III, there is a rather continuous flow of hydrogen, air and steam from the drywell to the wetwell (suppression pool). The steam condenses in the suppression pool, whereas air and hydrogen escape from the surface of the pool. This is a burnable mixture which – if not ignited – may build up a dangerous concentration of H_2 in dry air. Hence, the Mark III has igniters at the surface of the pool, which generates standing flames. The risk is now with the very high temperature in the immediate surroundings of that area.

5.5.4. *WWER confinement*

Typical for the older type WWER (type 440) is the small confinement around the primary system. The design pressure of this confinement is relatively low, as a small break LOCA was taken as the design basis accident. In addition, the WWER has a high amount of Zr, as the fuel elements are contained in Zr shrouds. Hence, the concentration of H_2 can be high after a severe accident and adequate H_2 management is required to avoid gross confinement failure.

Some WWERs have bubbler condenser towers, which are designed to condense the steam escaping from the design basis LOCA. They will also condense the steam out from a mixture flow of air, steam and hydrogen, as arises in a severe accident. Hence, flammable concentrations can be reached in these compartments and they need to be analysed for their capability to sustain hydrogen combustion loads.

The new WWER-1000 design has also a large dry containment and, hence, is less vulnerable to hydrogen combustion. As the containment is characterized by a number of compartments in the lower part, its needs to be studied whether or not conditions may arise that will lead to stratification and, eventually, flame acceleration /jet ignition.

5.5.5. Future designs

For the next generation of nuclear power plants, the general safety objectives defined imply to reinforce the ‘defence in depth’ of these plants compared to existing plants. These objectives notably call for a substantial improvement of the containment function, considering in particular the different possible failures of this function for core melt situations. In addition, the calculated core damage frequency is often in the range of 10^{-6} per reactor-year (or even lower), which puts the risk for loss of the containment function due to hydrogen burns on an even lower level.

The advanced designs are only briefly mentioned here, as the general focus of the present publication is on existing designs.

1) EPR

The EPR is a design by Areva, and is based on a common French-German safety policy, developed by the French en German Reactor Safety Committees, GPR and RSK.

The general strategy related to severe accidents consists of:

- ‘Practical elimination’ of accident situations which would lead to large early releases,

- Mitigation of low pressure core melt accident situations.

According to these principles, the approach related to the prevention and mitigation of the risks resulting from the production of hydrogen has been developed following an iterative process of several joint meetings of the French and German experts. In brief, these meetings have resulted in a position that global hydrogen detonation must be ‘practically eliminated’, the containment must be able to withstand fast local deflagrations, and provisions must be present to prevent DDT and local detonations.

Typical for the EPR is the robust double containment, the primary containment being a pre-stressed concrete structure, surrounded by a reinforced concrete secondary containment. The inner containment has a fairly open containment structure, which makes this containment type less sensitive to flame acceleration and transition of deflagration to detonation (DDT). The hydrogen is mitigated by PARs. It is important that hydrogen concentration not exceed

10%, due to the mixing effect of these PARs. Deflagration pressures are found not to exceed 5.5 bar, according to the designer. There are, however, also some compartments inside the containment, where typical effects associated with such compartments could be found: inhomogeneous hydrogen distribution, flame acceleration, and jet ignition, which might give rise to local explosions.

In view of the large safety margins of the design, the risk of a damaging hydrogen combustion is likely to be small.

2) ESBWR 1000

The ESBWR 1000 containment has a geometry which derives from the GE BWR Mark III containment. A difference is that it is a concrete containment with a steel liner; in addition, it features a passive containment cooling system. The reactor coolant system is equipped with various advanced and/or passive safety features (e.g. an isolation condenser to remove residual heat in a passive way); consequently, the CDF is expected to be low. The design pressure is 4.1 bar (absolute). The containment has some more compartments due to the presence of the passive cooling system and, hence, could be somewhat more susceptible to inhomogeneous hydrogen distribution over the containment than the Mark III, as well as other effects that arise with compartmentalization (flame acceleration, jet ignition).

3) AP 600 and AP1000

The AP 600 and AP1000 are advanced designs, with many safety features that are passive in nature and, hence, contribute to a low probability of severe accidents. The core damage probability is calculated to be about 10^{-6} per reactor-year.

In addition, some additional defence against phenomena in severe accidents is obtained. E.g., external reactor vessel cooling is expected to keep the core debris in-vessel, which, as a consequence, avoids the hydrogen generation which otherwise would arise from the molten core-concrete interaction. A hydrogen ignition system is designed to remove the hydrogen that will arise from core damage. The containment is a fairly open type of containment, and does not have a geometry which would promote flame acceleration or result in a DDT, if the hydrogen removal system fails. On the other side, the design pressure is moderate (3.1 bar for AP600 and 4.07 bar for AP1000), so the hydrogen removal system is important to assure containment integrity. It is expected to do so, because ignition will lead to mild deflagrations only, under the prevailing low hydrogen concentrations, which do not give rise to flame acceleration or DDT, as said.

Accidents with an initially largely inert containment atmosphere need, however, to be investigated, as they have the potential to accumulate hydrogen before any ignition will take place, and such ignition, occurring only when the steam has largely condensed, could then generate fairly large containment loads. This risk will presumably be eliminated at those plants that have installed passive autocatalytic recombiners, as these devices also remove hydrogen under inert conditions.

One should note that the containment is a single containment structure, where other new designs provide a double containment which give additional protection against impacts from outside (e.g. air plane crash). Such a double containment reduces also – to a limited extent –

the radioactive release if the primary containment develops leakages, e.g. as a consequence of a severe hydrogen burn/explosion. Given the low probability of core damage at the AP600 and AP1000, and measures against vessel failure, the risk from damaging hydrogen burns is likely to be small.

4) APR 1400

The design of APR1400, an advanced pressurized water reactor designed in the Republic of Korea, with a capacity of 1400 MW(e) is based on the experience that has been accumulated through the development of the Korean Standard Nuclear Power Plant (KSNP) design, 1000 MW(e) PWR.

The APR1400 has been designed in accordance with the established licensing design basis with an additional safety margin. The APR1400 has new advanced design features such as Direct Vessel Injection for safety injection, In-Containment Refuelling Water Storage Tank, Pilot-Operated Safety Relief Valve with spargers, and severe accident mitigation systems including safety depressurization and vent, in-vessel retention of molten corium, long term cooling of core debris, and combustible gas control inside the containment.

The APR1400 is designed to prevent vessel failure by external cooling. As such, the core melt probability is low, and the generation of hydrogen would be limited to the in-vessel phase. In addition, the containment is inerted, for further reduction of the risk from hydrogen combustion.

5.6. Treatment of hydrogen in the PSA

The problem of the generation of hydrogen and the consequences associated with it, are also treated in the PSA. For the generation of hydrogen, the various processes are modelled, and the consequences described.

PSAs usually use lumped parameter models to calculate the hydrogen distribution. Only a limited amount of nodes is used, as otherwise the computation time will be too long. To date, no PSA uses CFD calculations to better estimate the distribution of hydrogen in areas where such codes may reveal inhomogeneities.

Combustion is treated as AICC, if flammable conditions exist, which is usually derived from the Shapiro diagram. Detonations are usually only considered if the corresponding area of the Shapiro diagram is entered. To date, no PSA estimates the risk of flame acceleration or DDT. The assumption of ignition during the evolution of the event needs to be treated with caution. In a number of cases, PSAs assume ignition as soon as the mixture is burnable. This is not a conservative approach, as ignition does not occur unless an ignition source is present (outside the auto ignition limits). In those cases, the risk from hydrogen combustion can be severely underestimated.

PSAs usually do not treat the consequences of accident management beyond the emergent operating procedure-domain, as the execution of the accident management guidelines cannot be uniquely described, where this is a process of deliberation and decision making in the technical support centre. The technical support centre considers both positive and negative effects before taking any action, and actions are only taken if the negative consequences are acceptable. Hence, most PSAs to date do not give a full picture of the risk from hydrogen.

Containment failure is often considered using the probabilistic approach discussed before. But sometimes other assumptions are made, e.g. containment failure if the burn pressure exceeds a certain predetermined value or, very conservatively, if any burn occurs at all.

It should be noted that in many cases no inhomogeneities are expected that require the detailed approach of the CFD codes; lumped parameter codes are sufficient in those cases. Also the AICC model used is mostly adequate for the cases considered. Here, the PSA will give a good picture of the risk of an uninterrupted scenario. The effect of the various candidate high level actions, however, can both decrease as well as increase the risk, as has been discussed.

6. HYDROGEN MEASUREMENT

6.1. Objectives of a H_2 measurement system

Proper accident management may depend directly on insights in the hydrogen concentration if they are some accident management procedures linked to the knowledge of the hydrogen concentration in the containment. This could be the case for example when a guideline exists for activating a containment spray system. In such cases, it appears to be important to have instruments that can measure the concentration of hydrogen in the containment.

Nevertheless, the need for information of the government and safety authorities as well as of the crisis teams on the clear evolution of the accident, may also lead to the decision to implement such instrumentation.

The specialist meetings organized and the work performed during the last ten years in the area of the instrumentation to manage severe accidents, have brought about important information and were therefore instrumental in the progress made in the field. Most countries have adopted a pragmatic approach, i.e. to start from the plant ‘as is’ and to give guidance to the operators in order to help them manage core melt accidents with existing equipment, rather than implementing costly additional measures. This is for example the approach followed by the WOG in developing the severe accident management guidance that could be generically applicable to the majority of PWR plants employing a Westinghouse nuclear steam supply system and many others [76].

6.2. H_2 measurement systems

Many electrical utilities have installed a hydrogen concentration measurement system. There are two methods: (1) install a hydrogen measurement system inside the containment, (2) sample the gas of the containment and analyse this gas outside the containment.

Application varies for different containments. Generally, the following types of containments exist:

PWR-containments

There are three main kinds of PWR containments:

- the large dry concrete containment or metallic containment with a spray, such as Beznau (Switzerland), Doel 3–4 (Belgium), Kansai (Japan), Ringhals (Sweden) and Tihange (Belgium),

- the large metallic containment containing an ice condenser and a spray, such as Kansai (Japan),

- the spherical steel containment, such as Borssele (The Netherlands) and Gösgen (Switzerland).

WWER-1000 such as Kozloduy 5–6 (Bulgaria),

WWER-440-213 such as Paks (Hungary),

BWRs such as Cofrentes (Spain), Leibstadt and Mühleberg (Switzerland) and Swedish ones.

Beznau, Doel 3-4, Gösgen, Leibstadt, Ringhals, Tihange and Kozloduy are equipped with a hydrogen concentration measurement system inside the containment, whereas Doel 1-2, Kansai and Mühleberg have sampling systems. The Paks NPP (Hungary) has no hydrogen measurement system.

6.2.1. Hydrogen concentration measurement system inside the containment

Beznau, Doel 3-4, Ringhals, Kozloduy are using a hydrogen measurement system using catalytic reactions

6.2.2. Systems based on sampling

Accurate measurements can be obtained by a mass spectrometer using samples to measure the hydrogen, air and steam concentrations as shown in Fig. 18.

A risk with the use of sample lines is that they may get plugged, notably after vessel failure.

The weakness of the sample methods is the fact that more containment penetrations are needed to install the system, leading to an increased risk of containment leak. Electrical utilities are often reluctant to use such methods for this reason.

A new in-situ sampling technique has been developed together with the German utilities (In-Situ post-accident sampling system) [77] for Germany's nuclear power plants, to measure the atmosphere content in gas and aerosols. Presently, the post-accident sampling system is used in 9 German PWRs and 1 German BWR and in Kansai (Japan).

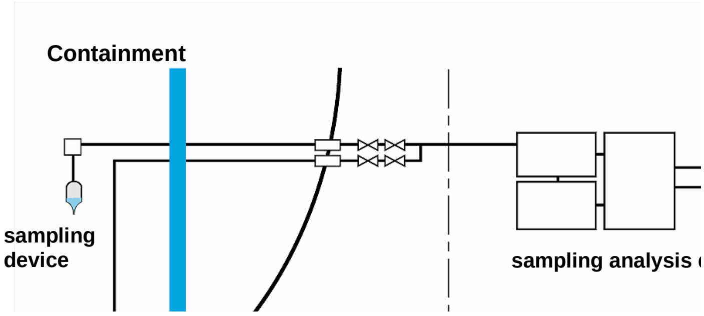


FIG. 18. Sketch of the post-accident sampling system.

6.3. H_2 measurement systems qualification

Concerning the hydrogen concentration measurement system inside the containment, they are preferably qualified for severe accident conditions, including the effect of CO and CO_2 gases, the presence of aerosols, etc. Nevertheless, as most countries have adopted a pragmatic approach, i.e. to start from the plant 'as is' and to give guidance to the operators in order to help them manage core melt accidents with existing equipment, none of the present hydrogen concentration measurement system inside the containment presently used in NPPs is fully qualified for severe accident conditions.

Systems based on sampling do not necessarily need to be qualified under severe accident conditions as the analysis of the sample content is done outside the containment.

6.4. H_2 measurement probe position

Great care must be taken regarding the position and the number of measurement points, as the hydrogen may be distributed not uniformly in the containment. It is essential to have more than one measurement location.

6.5. H_2 measurement evaluation without any H_2 measurement

If no hydrogen measurement is available, the hydrogen risk could be estimated using computational aids. An amount of Zr oxidation needs to be assumed, which then is transferred to a percentage of H_2 using a pre-calculated curve (see Section 7).

7. HYDROGEN CONTROL AND RISK MITIGATION

To avoid severe damage of the containment and thus loose the confinement function for radioactivity release some hydrogen control and risk mitigation measures exist. The main countermeasures are dilution of burnable gases, inertization of the atmosphere (dilution or removal of the oxygen) removal of the hydrogen by burning or recombination. The mitigation measures are described in more detail in Ref. [9].

Often engaged hydrogen risk mitigation measures are:

- Pre-inertization with nitrogen in most of the BWR containments,
- Passive autocatalytic recombiners in large dry PWR containments,
- Igniters for PWR ice condenser and BWR Mark III containments.

7.1. Inertization of the containment atmosphere

7.1.1. Pre-inertization

The pre-inertization of the containment is the countermeasure most of the BWRs have engaged. Many of the BWR plants have a small containment, which is not accessible during normal operation. In this case an inertization with nitrogen during normal operation did not endanger the staff and disturb the operation. Since the containment free volume is not too large the inertization and deinertization can be done in hours and the costs are bearable.

The hydrogen is produced during a severe accident by oxidation of the cladding and other metallic materials. If there is practical no oxygen in the containment (<5%) the risk of hydrogen combustion is near zero.

For inertization of the containment, e.g. after outage, the cold stored nitrogen is heated by an air heated vaporizer. It is fed into the containment by using the existing ventilation system.

7.1.2. Post-inertization

For the large PWR containments, especially when they are accessible, an inertization during normal operation is not practicable. For these some investigations for a post-inertization were made. Post-inertization (post-accident inertization) involves injection of non-combustible or combustion-inhibiting gases into the containment atmosphere, following the onset of an accident that has the potential of producing significant quantities of hydrogen. An early and rapid inerting has to be decided and introduced by the plant personnel before exceeding the flammability limits of the gas mixture in the containment. Such a measure is not independent from the accident precursor and the further evolution of the accident. Therefore, in addition to the provision of an engineered delivery system, a reliable set of criteria is needed for the initiation of such measures.

Because the quantity of diluent gas needed to inert the containment could be quite large, there are implications for containment pressurization. Nitrogen and carbon dioxide have been considered as candidate non-combustible (diluent) gases.

Complete inerting (i.e. combustion suppression at all hydrogen concentrations) is possible only when the carbon dioxide or steam concentration exceeds approximately 60 vol-% in air; inerting with nitrogen requires in excess of 75 vol-%. It should be noted that inerting by dilution assumes that the diluent is thoroughly mixed with the atmosphere in the containment by an appropriate diluent distribution system.

Post-inertization thus offers the possibility of complete prevention of hydrogen combustion but has associated practical obstacles to implementation. Up to now there is no NPP known which engages post-inertization.

7.2. Post-accident dilution

Post accident dilution is a concept that attempts to gain some of the benefits of complete inertization but with smaller amount of gas, injected strategically. Complete post inertization, described above, has considerable disadvantages, in term of containment pressurization, and uncertainties, in terms of operating procedures and criteria for activating the system. Where prevention of local detonation prior to complete mixing is the objective, a relatively small mass of inert gas, injected in the vicinity of hydrogen release can significantly reduce the detonability of gas mixtures in the region.

Post-accident dilution is essentially a strategy for purging selected local volumes identified by mixing analysis as trouble spots for accumulation of hydrogen. Inert gas purging used in this way could contribute to eliminating potential flammable or detonable pockets that arise prior to complete mixing. However, there exists uncertainty regarding combustion-induced redistribution of gas volumes and the feasibility of maintaining the inerted condition locally, after the first combustion occurs. One more benefit is that it decrease/suppresses flame acceleration and hence reduces loads.

Concepts for post-accident dilution of containment atmosphere with CO_2 have been analysed but no practical implementation has been reported so far. The Borssele plant (Netherlands) can use steam from the auxiliary steam boilers to dilute the containment atmosphere after an accident. Some plants have guidelines to inert/ dilute the containment atmosphere by venting steam from the reactor coolant system.

7.3. Early venting

Early venting is a process in which the containment is vented deliberately when the calculated combined pressure of steam, air and possible hydrogen combustion exceeds the containment pressure limits

This controlled opening of the containment in an early stage of the accident over a certain period of time is assumed to prevent the total loss of containment function by a large crack or the failure of structures.

7.4. Hydrogen removal

7.4.1. Deliberate ignition

The purpose of a deliberate ignition system is to initiate combustion wherever and whenever flammable mixtures arise, removing the hydrogen by slow deflagration while distributing the energy release spatially and temporally. The rationale for employing intentional ignition contains the assumption that eventual ignition by a random source is inevitable and that the potential damaging effects of combustion (i.e. combustion temperature and overpressures) increase with increasing penetration of the flammable range of compositions.

Different types of igniters are available:

- **Glow plug igniters**

  Glow plug igniters are simple electrical resistance heaters that produce a surface temperature of 800 to 900°C, which is a positive ignition source for flammable mixtures of hydrogen air steam. Glow plug igniters are reliable, robust and are the most energetic of candidate ignition sources for containment, producing ignition at very near the absolute limits of flammability. A characteristic of glow plug igniters is that they require a separate power source due to the high power requirement (typically 150 to 200W each). Glow plug igniters are installed in many nuclear power plants all over the world.

- **Spark igniters**

  Hydrogen is particularly suited to spark ignition, having the lowest spark ignition energy of any combustible fuel. Spark igniters can be designed to nearly match the performance of glow plug igniters and with a much reduced power requirement. For this reason spark igniters are well suited to battery power.

  Spark igniters are effective ignition sources. It is important that the frequency of sparking is commensurate with the time scale of local combustible mixture formation (hydrogen release, mixing and steam condensation rates). A low frequency is beneficial for the conservation of battery power. In particular, once ignition has occurred at one location, a very fast developing situation of combustion driven flow arises with flow velocities on the order of tens of metres per second.

  An open question in the use of spark igniters is that of compatibility with other electronic equipment, with regard to electromagnetic interference or spurious signals arising from spark discharges. Interference effects are likely to be small but need to be evaluated on a station-by-station basis and may affect igniter placement.

  In addition to these engineered spark igniters, spark ignition can also been provoked by switching equipment (valves, pumps, etc.), in accordance with appropriate severe accident management guidelines (accident managements).

  Spark igniters have been installed in Canadian reactors.

- **Catalytic igniters**

  Catalytic igniters employ the heat of H_2 – O_2 reactions at a spatial catalytic element to produce surface ignition temperatures high enough to cause ignition. Catalytic igniters are self-actuating, self powered and continuously available.

  The practical question regarding catalytic igniter performance are related to the range of mixture that can be ignited, the response time and their availability in terms of poisoning, fouling or mechanical damage. The range of operation is a particular concern in rich-limit mixtures where the margin between flammability and detonability is narrower than in lean-limit mixtures. At present no application of catalytic igniters is known. All type of igniters cannot ignite if the atmosphere is not flammable.

7.4.2. Spontaneous ignition

Even if no igniters are installed there is a high probability that the hydrogen ignites as soon as the atmosphere is flammable. Due to the small amount of energy which is needed to ignite a hydrogen air mixture, a small spark produced by any electrical or mechanical equipment is enough. Hot surfaces also can serve as igniters as well as static electricity.

These ignitions can not be foreseen and they can occur near flammability limits, than a mild deflagration will be initiated, or also far beyond the flammability limits. In the second case a fast deflagration can develop.

If spontaneous ignition occur when the amount of hydrogen released into the containment is not too much, it can reduce the hydrogen without doing any damage to the containment. If safety margins to containment failure are high enough, so that the pressure which will result from the combustion (p_{AICC}) will not exceed the maximum pressure for containment failure, taking no action and waiting for a spontaneous ignition also may be a possibility.

7.4.3. Catalytic recombination

Catalytic recombiners use catalysts to oxidize (recombine) the hydrogen and are operable outside the limits of flammability. Passive auto catalytic recombiners (PARs) have been developed and have become commercially available in the last decades. PARs are simple devices, consisting of catalyst surfaces arranged in an open-ended enclosure. In the presence of hydrogen (with available oxygen), a catalytic reaction occurs spontaneously at the catalyst surface and the heat of reaction produces natural convection flow through the enclosure, exhausting the warm, humid hydrogen depleted air and drawing fresh gas from below. Thus, PARs do not need external power or operator action. Installation requires only to place PAR units at appropriate locations within the containment to obtain the desired coverage.

PAR capacities are ultimately subject to mass transfer limitations and may not keep up with high hydrogen rates in some scenarios so that flammability limits can be reached or exceeded (e.g. in the immediate vicinity of the hydrogen release). Application of PARs does not remove the need to study combustion loads for a number of scenarios.

In a large dry PWR containment, about 40 recombiners are installed as shown in Fig. 19. It has to be stated that working in high concentrations (>8%) can initiate deflagration in the PARs due to the hot surfaces of the catalyst. Research is ongoing to create PARs with reduced probability of ignition. PARs are applied in many NPPs in the world.

7.5. Strategic combinations

7.5.1. Catalytic recombiners and igniters (dual concept)

A combination of deliberate ignition and catalytic recombination, which is known as the ‘dual concept’, was developed and tested in Germany. The test results indicated that such a combination ought to be effective in controlling the hydrogen concentration under inerted and non-inerted conditions inside containment. In this case it is recognized that recombiners cannot cope with high release rates and therefore igniters are used for initiating combustion at the flammability limits and to prevent formation of rich mixtures. This concept is implemented for Loviisa NPP in Finland and APR1400 in the Republic of Korea.

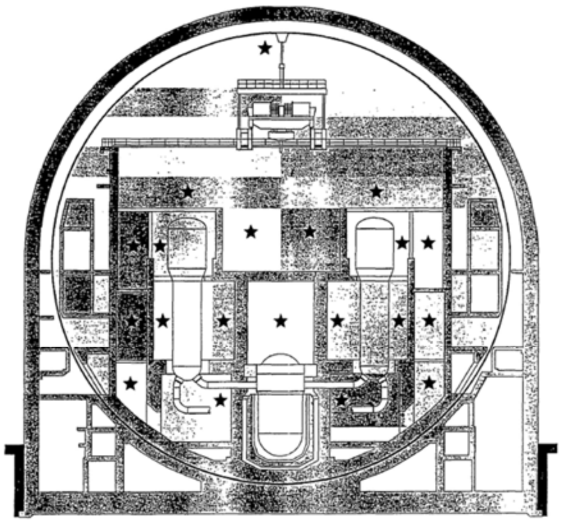


FIG. 19. Large dry PWR Containment (★: positions of catalytic recombiners).

7.5.2. Catalytic recombination and post-CO_2 Injection

Carbon dioxide is injected in such an amount that deflagration-detonation transition and detonation onset are prevented while catalytic recombiners remove the hydrogen over time. Hence, the containment structures and equipment have only to withstand the static loading caused by (accidental) deflagration. However, the injection of incondensable gases provides a higher initial pressure for deflagration. Thus, it is important that the injection of carbon dioxide be limited to such an extent that the combined pressure load from carbon dioxide and hydrogen combustion does not exceed the containment pressure capability.

7.6. Hydrogen control in severe accident management guide approaches

Hydrogen control and risk mitigation is an inherent part of the various severe accident management approaches. Often, use is made of a computational aid to estimate the risk from hydrogen combustion. An example of hydrogen control is given in Fig. 20.

If a H_2 measurement is present, the operator can immediately diagnose the risk for combustion. If such measurement is not available, he can make use of the pre-calculated curves for 25, 50 and 75% oxidation. Of course, the amount of oxidation is not known, but there may be reasons to assume it is either nearby 25%, 50% or 75%. For example, if the core is still in the vessel, the PSA may have shown the H_2 quantity to be about 25%. For ex-vessel scenarios, one could assume 50%. And for reasons of conservatism, or if a sudden flood of the overheated core has occurred, 75% of the Zr may be assumed to be oxidized.

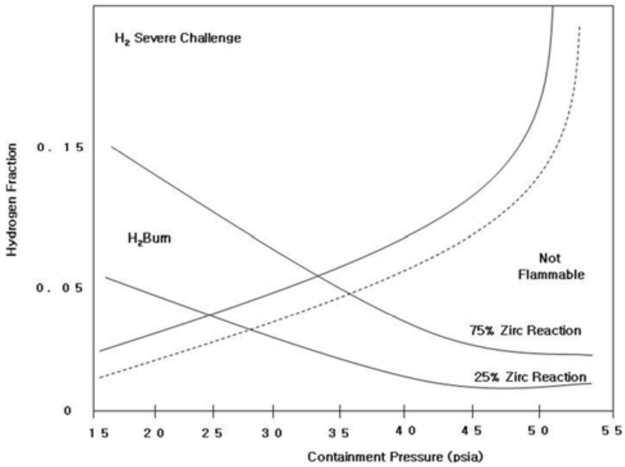


FIG. 20. An example of hydrogen computational aids.

The actual control of hydrogen depends on the method chosen. For example, if PARs are present, only limited guidance may be needed, as these devices work reliable and automatically. Without such devices, the operators may select other approaches. If ignition is deemed acceptable, the guidance will tell him how to do that. If igniters are present and functional, the guidance will tell him to switch them on. If no igniters are available, the operator may try to generate sparks by switching components on and off (e.g. by cycling valves). If ignition is not allowed, one could try to inert the containment by opening pressure operating relief valves and blow steam into the containment. Or one could interrupt power to all devices inside containment that might generate sparks during the period the atmosphere is burnable. Or one could isolate still operable containment heat sinks in order to promote containment atmosphere inertization.

The guidance is complete, i.e. it not only defines the actions to be taken, but it mentions also the cautions to be observed, and the equipment needed to perform the action.

The computational aid in Fig. 20 can be used to determine e.g. spray actions to decrease containment pressure or to wash out fission products from the containment atmosphere. From the picture it is immediately clear, how much pressure can be decreased before entering in some risky regime. If the containment is vented, also an amount of H_2 will be released. Hence, after such venting, the curve is no longer valid. Therefore, additional computational aids are available, which are applicable after containment venting (in whole or in part).

Another method in the severe accident management guidance is to homogenize the containment atmosphere, e.g. using fans. Also venting can be used to remove H_2, as already discussed. Below about 4%, thermal recombiners may be used to further reduce the H_2 concentration. Above this value, they can act as igniters. Hence, their use is then only allowed if ignition is allowed. Care is needed in using thermal recombiners, as they may be damaged by the burn, and cause radioactive releases.

Accident management guides have been developed to give guidance to the operator to deal with the problems, also for cases where no hardware changes have been made.

8. ANALYTICAL ASPECTS FOR HYDROGEN ANALYSIS

The methodology to assess the hydrogen risk in the reactor building and to perform the safety demonstration of the mitigation concept may include the following elements:

- Calculation of hydrogen production for relevant scenarios;
- Calculation of the time dependent gas and temperature distribution using suitable codes, preferably CFD codes;
- Calculation of global pressure loads that could result from an AICC;
- Assessment of the potential combustion modes other than AICC (i.e. flame acceleration, detonation) using appropriate combustion criteria, taking into account the geometrical details of the containment;
- If these combustion criteria are met, dynamic pressure loads have to be calculated; the combustion calculations are made within the validation range of the codes.

For a given plant, mitigation system, accident scenario and set of hydrogen–steam sources, the distribution analysis is able to identify the time frames and space regions with the potential for flame acceleration and DDT. In case of unacceptable risk, another mitigation measure is selected in order to reach a negligible threat for the containment integrity.

8.1. Introduction

Analytical tools have been developed to simulate the accident scenario and to describe the hydrogen release, transport and mixing, the hydrogen combustion and the effect of mitigation measures.

For two decades, lumped parameter codes have been used extensively for the calculation of hydrogen distribution and combustion of premixed gases. In this approach, gas distribution calculations are based on a multi-compartment (‘nodal’) representation of the containment, and combustion modelling is based on flame propagation prescribed by empirical correlations or by one-dimensional models. This fast and relatively easy analytical method is useful to study a large number of different event sequences for identifying the risk-dominating cases, as is e.g. needed in PSA studies. Nevertheless, these simplified methods have limitations due to their inherent lack of spatial resolution and their insufficient consideration of local flow information.

More recently, an increasing interest appeared in the application of 3D CFD codes to improve steam and hydrogen distribution and combustion predictions in nuclear power plants. These codes are also used as a supplement to or in combination with system codes in order to identify specific issues which would need further detail investigation. The higher precision of CFD predictions with respect to hydrogen distribution and combustion processes can be explained not only by the nature of the equations used (3D, fully compressible Navier-Stokes equations, including momentum balance and a complete set of fluid dynamic terms), but also by the much finer spatial resolution (typically 1 m^3 versus 1000 m^3 with a lumped parameter method) and the corresponding mixing effects.

Success in CFD combustion simulations is critically dependent on the accuracy of the numerical methods and physicals models used to describe the key physical processes, including the fluid turbulence, fluid mixing, heat transfer, chemical reactions and their interactions. Because of the large size of reactor containments, their multi-compartment structures and the complex physical phenomena and their time-dependency, the multidimensional combustion simulation remains a challenging area for the CFD codes. Consequently, application of CFD tools for hydrogen analysis started for qualitative purposes, but it is now increasingly used for quantitative analysis.

This section discusses the major analytical aspects related to hydrogen distribution and combustion calculations for the two computational approaches currently applied for the hydrogen analysis, as mentioned. It focuses first on the choice of the methodology for hydrogen and steam analysis in containment, the scenario and hydrogen risk mitigation devices. For each of the two types of computational tools, this section addresses important practical issues for large scale nuclear containment calculations, such as plant modelling and key physical models.

In addition, this section discusses numerical issues, the treatment of uncertainties, the user effect, and the use of sensitivity runs and benchmarking.

8.2. Definition of the problem

Thermohydraulic containment codes are used to support the development of accident management strategies, including the design of new accident prevention or mitigative devices. The reliability and effectiveness of these accident or mitigative measures may demand, in some cases, an accurate assessment of location and source rate of produced hydrogen as well as a reliable prediction of gas–steam–air distribution and hydrogen combustion phenomena

Ignition may occur in any location where the local concentration allows for combustion. The consequence of combustion on containment loading is clearly dependent on the hydrogen distribution. Computational tools are in general used in best estimate calculations, to obtain the best physical picture, because combustion risk depends on local hydrogen distributions rather than on global concentration.

The topic of evaluating hydrogen mixing and its distribution within the containment is an essential key in assessing the likelihood of a deflagration, flame acceleration and/or detonation and the potential threat to containment structures and equipments.

For evaluating the hydrogen risk in the containment, a roadmap has been suggested in the SOAR on flame acceleration and DDT [57]. This roadmap consists on several distinct sequential steps, as illustrated in Fig. 21:

- Definition of a set of accident sequences of interest for the nuclear plant design selected;
- Evaluation of hydrogen and steam source terms by using a system level simulation of the postulated accident and release scenario;
- Choice of a risk mitigation system, if applicable, such as PARs, igniters;

- An estimate of the hydrogen distribution and mixing with analytical codes in all the compartments of the containment, on the basis of the defined source terms;
- Evaluation of the flammability of the mixture and the potential self ignition in each compartment of the containment by using the Shapiro diagram and application of flame acceleration and DDT criteria for a quantitative measure of the possibility of these events;
- In some cases and despite the use of mitigation techniques, a significant risk for flame acceleration or DDT may still exist during some part of the transient considered. In those cases, a more accurate investigation with advanced numerical simulations of flames or detonations is generally needed in order to determine whether localized fast flames or detonations can threat the containment integrity;
- Determination of the thermal and mechanical loads of the combustion process (slow deflagration, fast deflagration, or detonation) on the containment shell, and storing temperature and pressure histories;
- Finally, evaluation of the structural response of the containment on the basis of the load histories obtained in the previous step.

The mechanical loads from fast flames can include pressure waves, impulses, and possibly impacts from combustion-generated missiles. If fast combustion modes cannot be excluded despite the risk mitigation system present, a detailed investigation of the local dynamic structural response is undertaken to demonstrate the containment integrity.

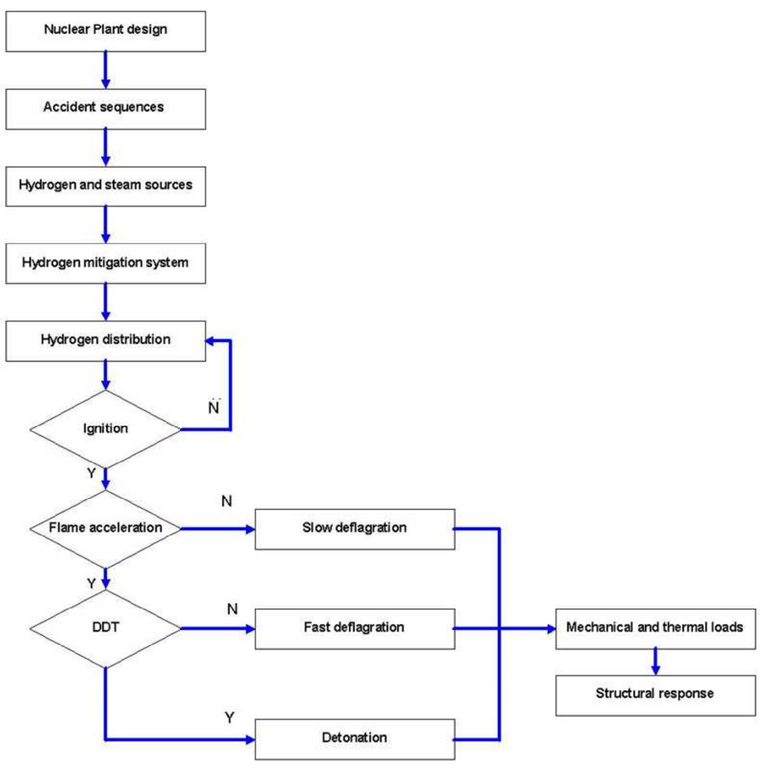


FIG. 21. Roadmap for hydrogen risk analysis under severe accidents in nuclear plants, including flame acceleration and DDT.

8.3. Conservative versus best-estimate calculation

The objective of the design basis analysis is to provide a robust demonstration of the fault tolerance of the engineering design and the effectiveness of the safety systems. This is done by carrying out a conservative analysis which takes account of the uncertainties in the modelling. In a conservative approach, the combination of assumptions, computer codes and methods chosen for evaluating the consequences of a postulating initiating event needs to provide reasonable confidence that there is sufficient margin to bound all possible results.

In accordance with the IAEA Safety Standards, analysis of beyond design basis accidents and severe accidents is preferably carried out using best estimate computer codes, assumptions, and data. Reasonably conservative assumptions are however still necessary to take into account uncertainties in understanding the physical processes.

In a best estimate approach, the combination of assumptions, computer codes and methods chosen for evaluating the consequences of a sequence is such as to provide reasonable confidence that the results likely reflect the evolution of phenomena. In adopting best estimate approaches, special attention is paid to ensuring that:

- Input parameters are in the range of what could be expected on the basis of current knowledge.
- Computer codes reflect an internationally accepted state of knowledge based upon established research and development; in particular, the modelling of phenomena is not controversial.
- All relevant aspects of the severe accident are considered, e.g. by the application of integral computer codes covering processes relevant phenomena that could occur following core damage.
- Uncertainties on the calculated values are estimated and, where useful, complemented by sensitivity studies.

The use of the best estimate approach for severe accident analysis is complemented by uncertainty analysis and, where relevant, by sensitivity studies. Sensitivity studies include a systematic variation of the code input variables and modelling parameters; they need to be used to identify the parameters which are important for the analysis and for which no appropriate uncertainty analysis is readily available; they also serve to show that there is no abrupt change in the result of the analysis for a realistic variation of inputs (‘cliff edge’ effects).

8.4. Choice of computer code

In the lumped parameter approach, energy and mass are transported through the flow paths, from one control volume to another, which is analysed by solving the momentum equations defined in each flow path. Because the momentum equation is treated only one-dimensionally and there is no exchange of momentum inside a control volume, the multidimensional effects associated with advection of momentum cannot be calculated. The qualities but also the limitations of the lumped parameter concept have been detailed in Section 3. In short, they cannot provide a detailed flow field and detailed combustion predictions. Hence, in general, combustion models used in this approach are only applicable to flame speed not exceeding 200 to 300m/s.

Nevertheless, this approach is widely used to describe relevant physical processes expected to occur during severe accidents and to perform investigations to identify the impact of uncertainties in data and modelling. In particular, this approach is used in order to (1) define key times during the progression of the severe accident scenario, (2) build a data base using core degradation and core-concrete interaction calculations for selected severe accident scenarios, (3) estimate the gas mixture composition in the containment, (4) evaluate flame acceleration and DDT criteria according to gas distribution calculations, (5) and give an estimation of the pressure transient during the combustion process for containment and equipment failure analysis.

The lumped parameter approach is, hence, often used to perform fast running estimations in the context of PSA studies.

Multidimensional CFD codes (also called field codes) have shown their potential for a more detailed analysis in various other domains and are able to overcome the limitations of lumped parameter codes here by locally solving the conservation (of mass, momentum and energy) and transport equations for the different species. These equations are coupled with turbulence and heat and mass transfer models to account for condensation. There is, therefore, an increasing interest in the application of 3D CFD codes in nuclear safety as a supplement to or in combination with integral codes. Examples of such codes are the TONUS code (CEA/IRSN) [78], the GASFLOW code (FZK) [79], and the general CFX field code [80]. The steady increase in computer power over recent years and the advancement of numerical methods has allowed CFD codes to become of practical use and has enabled nuclear engineers to model reacting flows in a realistic geometry with good spatial resolution.

Multidimensional computations can, hence, be considered as an interesting method for the prediction of gas distribution under severe accidents conditions. These newly emerging methods are generally able to calculate gas distributions with a better accuracy than lumped parameter codes. Lumped parameter and field codes can be viewed as competitive solutions methods. However, most analysts believe that field codes can usefully supplement the benchmarking of the more approximate flow computations calculated with lumped parameter codes. Nevertheless, the use of field codes for complex geometries can be limited by the size of the meshing and the duration of the calculation more particularly for long transient scenarios representative of severe accident conditions. Since computer power is increasing, more powerful tools can be envisaged in the near future. An intrinsic limitation is – still – the lack of sufficient validation at appropriate experiments. But also here progress may be expected. Further discussion on the limitations of CFD codes is presented in Section 8.11.

Meanwhile, the combination of both types of codes can combine the advantage of each or them (such as TONUS code (CEA/IRSN) [78] and COCOSYS code (GRS) [81]). The lumped parameters code is used to analyse the entire accident in a more global way, while the 3D code is used to analyse specific phenomena (such as jets, stratification, and flame acceleration simulation) over limited periods of time.

8.5. Choice of the accident scenario

For a given plant and mitigation system, an essential first task is the selection of representative sequences regarding hydrogen risk among all severe accidents physically possible, and by this way covering the other accident scenarios. Two approaches – deterministic or probabilistic – can be used to select the appropriate scenarios from a potential great number of accidents that could lead to a significant hydrogen production.

In the deterministic approach, a limited number of sequences is selected with the objective to cover the major accident classes (LOCAs and transients), and to cover detrimental properties of the H_2–steam source (large integral H_2 mass and release rate) and adverse containment conditions (e.g. a low steam concentration at the beginning of the H_2 release). Based on these considerations, the list of selected accidents – which depends on the type of the reactor and the containment – includes as a minimum: (1) large break LOCA, (2) small break LOCA, (3) loss of feedwater with primary-system depressurization, (4) loss of secondary feedwater with primary-system depressurization, (5) station blackout with depressurization of primary circuit, and (6) steam generator tube rupture with an open secondary circuit.

The probabilistic safety approach (PSA level 1, level 1+ or level 2) allows to set up a hierarchy between accident sequences taking into account the core degradation process and the frequency of core damage in the PSA level 1, or the containment damage process and the frequency of containment damage in the PSA levels 1+ and 2.

In order to find the plant vulnerabilities to hydrogen risk and design risk mitigation systems such as recombiners, the selection of relevant scenarios and corresponding boundary conditions (mass and energy release) can be done in view of the various containment damage mechanisms by hydrogen deflagration (‘hydrogen containment risks’), as is presented in Table 13.

TABLE 13. PARAMETERS WHICH AFFECT RISK OF HYDROGEN COMBUSTION

Hydrogen containment risk	Main parameters
Slow deflagration risk (AICC pressure assessment)	Hydrogen mass and release rate Steam release (low steam is unfavourable for risk from fast combustion) Release location
Fast deflagration risk (dynamic pressure assessment)	Hydrogen mass, release rate, location and timing[3] Steam concentration (high amount of steam is unfavourable because of initial pressure but favourable to suppress combustion)
Thermal loads resulting from hydrogen combustion or recombination	Hydrogen mass, location of igniters/recombiners

[3] A high release rate may result in – temporary – inhomogeneous hydrogen distribution, notably a risk factor in compartmentalized containments with release in a compartment; the timing is relevant with respect to the time of release of steam, as steam may mitigate or prevent combustion.

In addition, for a set of accident sequences covering a broad range of initiators and plant faults one has to take into account key influencing parameters to be investigated in order to investigate the plant vulnerability and check the robustness of the mitigation concept (such as variation on hot and cold leg LOCA, actuation of reactor system pressure relief valves, actuation of in-vessel reflooding and its timing[4], availability of containment heat removal/sprays).

8.6. Modelling for the mitigation system for hydrogen

For a given plant, the next important question for the hydrogen analysis concerns the mitigation system under consideration, if any. If no such system yet has been selected, this section can be skipped. If after completion of the analysis in the remaining sections of this section the risk from hydrogen combustion warrants such a system, a selection is made and the analysis done as described. The main hydrogen risk mitigation systems have been discussed in detail in Section 7. In the present section, only the modelling of PARs is considered.

For PARs, special numerical models have been developed and implemented in various computational tools to simulate the behaviour of catalytic recombiners in accident scenarios. They evaluate the recombination rate, give a tool to optimize the recombiner design and determine the optimal number and location of the catalytic recombiners inside the containment.

Three approaches for PARs in a given containment can be used:

- An empirical model or correlation for hydrogen recombination rate, based on experimental tests. This model gives an approximation of the global hydrogen recombination according global variables, such as hydrogen concentration, oxygen concentration, atmosphere temperature, and total pressure. The main disadvantages of this approach are that the local environment of the PAR is neglected and the validation of the model is limited to the field covered by the tests.

- A one-dimensional theoretical model of PAR behaviour, based on a mathematical description of the different physical processes which take place inside the catalytic box.

- A global approach, which integrates the coupled action between the recombination and the local thermohydraulic conditions.

8.7. Hydrogen and steam sources

The analytical aspects and remaining uncertainties related to hydrogen production are discussed in detail in Section 2.

8.8. Hydrogen distribution

With known hydrogen and steam sources, the next task is to calculate the transport and distribution of hydrogen and steam, and their mixing with the air in the containment, in order

[4] The relief valves might be just open at the moment of reflood, which may enhance the release of hydrogen generated by the reflooding to the containment.

to determine the temperature, pressure, and composition of the H_2 air–steam mixture as function of time and location. Two practical methods (lumped parameter and CFD) are discussed in detail in Section 3. The temperature and gas distribution calculation process has a number of elements, depending on the methodology used, which are relevant for the quality and accuracy of prediction.

8.8.1. Lumped parameter approach

In carrying out containment lumped parameter calculations, the following matters need to be considered: (1) plant modelling aspects, such as nodalization, junction and structure modelling, and (2) relevant physical aspects, such as heat and mass transfer modelling.

Plant modelling

The prediction of the thermohydraulic behaviour and the hydrogen distribution in the containment requires a detailed representation of the containment, including internal structures and flow connections between the volumes.

Plant nodalization

An appropriate representation of the containment is an essential step in the modelling process and a key requirement to obtain reliable results. In principle, a good representation of the containment with a lumped parameter approach is possible with a very detailed nodalization, possibly containing hundreds of nodes. Nevertheless, a fine nodalization requires a high effort to generate the input data and the computer CPU time can become quite large (but still much less than a fine 3D calculation). In contrast, a coarse nodalization requires less effort and computer time, but may be in error. Therefore, a compromise between a detailed and a coarse nodalization has to be found.

Generally, the amount of detail in the nodalization depends on the problems investigated: pressure build-up, pressure differences, long term temperature and gas distribution, combustion consequences, mitigation devices design. For physical processes where slow convective flows are dominant (mainly), the description of convective processes (e.g. buoyancy and density driven slow convection) requires a more detailed nodalization.

In general, the adequate arrangement of zones, junctions and structures is obtained from the plant drawings. For this purpose, certain rules for the spatial discretization are generally applied: (1) if possible, each physical compartment of the containment is assigned to one node, (2) the nodalization is detailed enough to describe the essential convection loops in the containment, (3) if local effects are expected in a compartment (i.e. plume formation, stratification in the dome, dead end compartments) a further subdivision in nodes is needed. For example, the plant modelling of a typical 1000 MW(e) PWR, used for detailed analysis in PSA studies, typically requires 50 to 100 nodes.

User-induced uncertainty, caused by the choice of nodalization, is an important concern. This will be further discussed in the section related to user effects.

Junction models (staggered mesh)

The junction models describe the flow interaction between the user specified control volumes. The types of junction models are specific to the lumped parameter code used for the containment analysis.

When modelling physical compartments, the junctions between two compartments are determined by the geometrical characteristics of the junction cross-section. On the contrary, when modelling virtual sub-volumes of a large gaseous volume such as the containment dome, the modelling of these sub-volumes includes a certain degree of freedom for the user to select them.

In general, CPU time consumption is strongly dependent on the junction characteristics such as cross-section area, length of the junction and local resistance coefficients.

Structure models

The containment structure and the internal structures (e.g. walls, floors and metallic or non-metallic heat sinks inside the containment), as well as the water stored within the containment, act as a passive heat sink. Under severe accident conditions, the rate of heat transfer to structures is an important parameter for the determination of the pressures and temperatures.

The heat exchange between wall structures, thermally conducting systems and their surrounding zones is a key phenomenon of the thermohydraulic containment behaviour. This exchange is generally calculated with convection, condensation and radiation transfer correlations. The primary heat transfer mechanism is by the condensation of steam on exposed surfaces, and the thermal conductivity of the structure plays an important part in the determination of the rate of heat transfer. All conditions that could affect the transfer of heat to structures, such as effects caused by coatings or gaps, has to be considered in the design of the containment and/or the mitigation concept.

In order to simulate the conduction of heat in structures, the wall structures must be subdivided into layers. The arrangement and number of layers have a direct influence on the calculation of the wall temperature, and thus on the mass of the condensed steam and on the pressure.

Heat and mass transfer modelling

Heat and mass transfer between the containment atmosphere and the structures, and the coupling between this process and the mixing process are essential for the containment thermohydraulic behaviour, in particular where convective flows are dominant. Most of the advanced lumped parameter codes and CFD codes use a mechanistic approach for modelling the mass and energy transfer, as opposed to the purely empirical approach based on global correlations mainly used for the design of the containment (i.e. the Tagami and Uchida correlations). Mechanistic approaches are generally based on heat and mass transfer analogy (i.e. Nusselt, Collier correlations). Most of these models have been validated by performing lumped parameter simulations on separate-effects tests. These comparisons have shown that the analogy methodology produces quite accurate results.

The challenge for the code user is to select the optimal heat and mass transfer model suited for: (1) complex and a large scale geometry, (2) various wall structures (metallic and non-metallic) and (3) various convection regimes (forced/mixed/natural) associated with post-blowdown events. Even if the convection pattern is known, the correlations for turbulent convective heat and mass transfer can be uncertain, especially if the flow regime is in a mixed convection region where experimental data to support modelling methods are poor.

8.8.2. CFD approach

The modelling of a large scale reactor building with CFD codes creates numerous issues with respect to grid generation. In this process, the computational domain needs to be subdivided in a large number of computational cells. Grid generation can be considered as the essential and most time-consuming part in the CFD analysis process.

The grids must be fine enough to provide an adequate resolution both of the geometry and the important flow phenomena. This may be achieved by local grid refinement in critical regions with changes in geometry, regions with high flow gradients or with large changes, such as regions with a high shear. Nevertheless, given the limitations of the computational hardware resources and running time, compromises in the selection of the mesh size are nearly always inevitable.

8.9. Ignition modelling

In a flammable mixture in the containment, ignition is needed to initiate combustion. The physical aspects of the hydrogen ignition have been discussed in Section 4. A reliable prediction of the ignition process is important because it defines the end of the non-reactive phase of the accident and the beginning of the reactive phase, which can create the potential for containment damage. Ignition sources arise from local energy concentrations such as a spark, local hot gases, or hot surfaces.

Ignition sources can be subdivided in random ignition and deliberate ignition (i.e. with igniters). When igniters are included in the analysis, location and time of the ignition event will be determined by the evolution and expansion of the hydrogen air–steam cloud in the containment. With a correctly designed igniters system, ignition will occur in a region with low hydrogen concentration, shortly after hydrogen release has begun.

Without deliberate ignition, the location and time of the ignition event is not predictable in a deterministic way. A number of potential ignition sources can exist in the containment in a severe accident condition, such as electric equipment, bursting pipes, local hot gases, hot surfaces, core melt particles, and PARs. In this case, the consequences of random ignition must be analysed with respect to time and location. Regarding pressure and thermal loads, accidental ignition has to be assumed at the most unfavourable moment and at the most unfavourable location, leading to a flame propagating toward positive gradients of hydrogen and to maximum flame acceleration.

Modelling of ignition is essential for predicting the initiation of the combustion process. Although ignition constitutes only a relatively small part of a calculation, it is necessary that ignition models adequately describe the main features of the process, such as the auto ignition temperature, ignition on hot surfaces, flow induced hot spots and spark ignition. In particular, mechanistic modelling of the ignition event requires the resolution of the ignition kernel with detailed chemistry treatment and information on fluctuations of local gradients of mixture and temperature. Currently, information on these scalar fluctuations is not easily available for full scale containment configurations.

8.10. Combustion modelling

A weak ignition in a combustible mixture can result in the generation of a variety of different combustion regimes, ranging from slow laminar flames to detonations. In the first phase, a laminar flame propagates at the laminar burning velocity. The effect of obstacles or boundary layers induced turbulence can transform wrinkled flames into accelerated turbulent flames. The flame acceleration process can be sufficient to possibly lead to DDT. The description of all these complex combustion processes is summarized in Section 4. The key parameters influencing flame acceleration are: (1) mixture composition, (2) turbulence generation, (3) confinement and (4) length scale.

Two criteria derived from a large experimental database allow a realistic assessment of the potential for flame acceleration and DDT during a severe accident scenario. The advantages of their application will be outlined in the next subsection.

First, the two different approaches which are currently applied in reactor containment analysis are discussed. The first one is based on conventional lumped parameter codes which allow a fast and easy analytical method for screening a large number of severe accident scenarios. The second one is based on CFD tools, which allow a more detailed and accurate combustion prediction.

DDT and detonation are considered as the most destructive phenomena. Their prediction via dedicated computational tools is of crucial importance and a main objective in the safety assessment. Specific approaches have been the subject of intensive development for the past two decades. The main issues related to DDT and detonations are addressed below.

8.10.1. Flame acceleration and DDT criteria applications

The application of simple criteria for flame acceleration, DDT and for propagation of detonation, described in Section 4, is considered to be a useful tool for an estimate of the potential combustion regime without the need for combustion calculations:

- The conservative σ criterion for flame acceleration, described in Section 4, which uses the expansion ratio of the gas mixture, can be used to determine the potential for flame acceleration. If the σ criterion is not fulfilled, flame acceleration to sonic velocity is excluded. If the σ criterion is satisfied DDT may or may not occur, i.e. the criterion is a necessary but not sufficient condition for DDT to occur.

- The λ criterion, which uses the detonation cell size and a characteristic length, can be used to determine the potential for DDT. If it is not satisfied, DDT is not possible, but a fast turbulent combustion is possible and an appropriate calculation must be performed in order to provide the mechanical loads. If it is satisfied, a detonation is possible and a detonation type calculation is appropriate.

Additional work is underway to evaluate the effect of scale and mixture properties on the criteria for hydrogen combustion and flame acceleration, as their application is of great interest for safety assessment. The flame acceleration process, which requires resolution of the laminar to turbulent transition, is complex and CPU time consuming, the direct simulation of the transition between combustion regimes is still not mature, and for detonation onset, the resolution of the initial hot spots with strong ignition would be necessary.

The application of the criteria allows the selection of the most probable combustion mode and the corresponding numerical models and codes directly from the hydrogen distribution calculation.

For situations which are not excluded after the application of the criteria, detailed combustion calculations have to be performed with suitable simulation tools.

8.10.2. General data for combustion analysis

The purpose of this section is to present important data needed for combustion analysis in actual NPPs and, more particularly, for the application of macro criteria developed for flame acceleration and DDT. These criteria are presented and discussed in Section 4.

It has been shown that the main parameters which influence the development of combustion process (such as flame acceleration and DDT) are the composition of the mixture, the thermohydraulic conditions and the geometric configuration. Containment thermohydraulic and hydrogen distribution simulations allow characterizing the mixture composition in the containment and the initial turbulence level before the combustion process occurs. Both mean and gradients values for combustible gases (hydrogen or carbon monoxide or both), diluents (steam or carbon dioxide or both) and oxidant concentration are considered for mixture combustion analysis.

The mixture composition is strongly affected by the initial thermohydraulic pre ignition conditions, of which relevant parameters are the initial temperature and the degree of initial turbulence. The mixture sensitivity increases with a higher temperature (reaction rate, detonation cell size, less efficient turbulence quenching). For turbulence, the main effect can be considered to be the balance between the initial turbulence and the flame-induced turbulence and mixing. The initial pressure is normally not relevant for the behaviour of a flame front, but it can be of importance for the value of the absolute pressure obtained during a combustion process.

Geometrical conditions play a crucial role in the flame acceleration and DDT processes. In particular, experimental results showed that the size of obstacles, the distance between subsequent obstacles and the degree of confinement (all of them geometrical discontinuities in the combustion path) are sensitive parameters. In an actual NPP geometry, data such as the blockage ratio or the spacing of obstacles cannot always be defined because of their complexity. The main characteristics of such a geometry are the very irregular arrangements, compared to the well defined experimental conditions.

Long channels and explosion tubes used in the RUT [82] and FLaccident management [83] facilities are considered as quasi one-dimensional. Recent experiments performed in the HYCOM project [84] have allowed to study combustion phenomena in non-uniform mixtures and in a multi-compartment geometry under conditions and scaling representative for severe accidents in NPPs.

8.10.3. Combustion modelling in lumped parameter approach

The lumped parameter code is based on the division of the geometry in compartments, interconnected through atmospheric junctions. Mass and energy balance equations are solved in the compartments, and a simplified momentum equation is solved in the junctions.

The description of the combustion is essentially reduced to computing the flame speed over the characteristic length of the control volume. In this approach, the combustion model can be based on a spherical propagation of the flame in each compartment, and on the evaluation of the turbulent flame speed via a specific correlation.

Numerous experimental investigations have been performed in order to evaluate burning velocities under laminar and turbulent conditions and many authors have proposed correlations for turbulent combustions (such as the Peter correlation), essentially based on parameters such as the laminar flame velocity, the expansion ratio and the fluctuation velocity. In general, these correlations include the effect of: (1) the turbulence intensity, (2) the effect of mixture of the composition and its chemistry, and (3) the effect of the geometry.

The passage of flames between control volumes is in general determined on the basis of additional propagation conditions derived from Shapiro's diagram. This approach is used by the IRSN/CEA TONUS code [78].

8.10.4. Modelling of turbulence and combustion interactions in the CFD approach

Turbulence and combustion are strongly coupled in the solution of premixed combustion problems. Two interactions between turbulence and combustion can be outlined. The first one is the effect of combustion on turbulence. There are many ways in which combustion can affect the physics of turbulence and, hence, the modelling of turbulent transport processes, e.g. through the production of density variation, through buoyancy, through dilatation due to heat release in a chemical reaction, and through influence on molecular transport properties. The second is the effect of turbulence on combustion, which include fluctuating characteristics in heat and mass transfer and, more particularly, chemical reactions.

Modelling of all these complex interactions between flow mixing, heat transfer and chemical reactions is now a particularly strong challenge for full scale containment calculations. This sub-section deals with turbulence modelling for combustion analysis, with particular reference to the assessment of the risk from hydrogen combustion in reactor buildings.

Turbulence models

Important advances have been made in the detailed numerical modelling of complex turbulence states and in direct simulation of turbulence and flow interactions. Nevertheless, no single turbulence model is universally accepted as being superior for all classes of problems. The choice of the turbulence model will depend on considerations such as the flow regime, the established practice for a specific class of problem, the level of accuracy required, the available computational resources, and the amount of time available for the simulation. To make the most appropriate choice of a model for a given application, it is essential to understand the capabilities and limitations of the various options.

A complete time dependent solution of the exact Navier-Stokes equations for high Reynolds number turbulent flows in complex geometries is unlikely to be achieved for several years to come. In general, two alternative methods are developed to transform the Navier-Stokes equations in such a way that the small scale turbulent fluctuations do not have to be directly simulated: Reynolds averaging and filtering. Both approaches introduce additional terms in the governing equations that need to be modelled in order to achieve closure of the equation system.

Currently, the Reynolds averaged Navier-Stokes methods are the most broadly used methods for complex industrial CFD simulations, and for some years to come in the prediction of hydrogen distribution and combustion in the reactor building. In short, RANS equations represent the transport equations for the mean flow quantities only. Additional terms (Reynolds stresses) must be introduced in these averaged equations to represent the effect of turbulence. A frequently used method employs the Boussinesq hypothesis to correlate the Reynolds stresses with the mean velocity gradient. The most popular models using Boussinesq hypothesis are the standard turbulence k-ε (where k is the turbulent kinetic energy and ε its dissipation rate) and different versions of k-ω (where ω is the specific dissipation rate) based models [84]. This approach has a relatively low computational cost but presents several deficiencies. A more elaborate turbulence model, the Reynolds Stress Transport Model is based on the solution of the transport equations for each of the Reynolds stress tensor terms. In many cases, models based on the Boussinesq hypothesis (standard turbulence k-ε and different versions of k-ω) perform very well, and the additional computational expense of the Reynolds stress model is not justified. However, the RSM is clearly superior for situations in which the anisotropy of turbulence has a dominant effect on the mean flow (i.e. highly swirling flows and stress driven secondary flows).

In the filtering approach, large eddy simulation (LES) provides an alternative approach in which eddies are computed in a time-dependent simulation that uses a set of filtered equations [85]. Filtering is essentially a manipulation of the exact Navier-Stokes equations to remove eddies that are smaller than the size of the filter, which is usually taken equal to the mesh size. Like the Reynolds averaging process, the filtering process creates additional unknown terms that must be modelled separately to achieve closure. The advantage of the LES method is that, by modelling less of turbulence, the error induced by turbulence model will be reduced. Nevertheless, because of the large computer resources required to solve the energy containing turbulent eddies, LES applications have so far mainly concerned simple geometries. Application of LES to complex industrial fluid simulations and, more particularly, to nuclear safety applications is actually in its infancy. Moreover, most successful LES applications have been done using a high-order spatial discretization, with great care taken to resolve all scales larger than the inertial sub-range scale. The degradation of accuracy in the mean flow quantities with less well defined meshes and less well-resolved LES is not well documented.

Turbulent combustion modelling

Numerous ways have been developed to compute reacting flows, and several levels of CFD techniques for solving turbulent combustion may be found in the literature. Reactive flow calculations require the solution of two sets of equations, for the turbulent flow and for the chemical evolution of the reactive species, which are coupled. The temperature field is controlled by the chemical reaction and the corresponding heat release and also the transport coefficients and thermodynamic state functions depend on temperature, pressure and local gas composition. The difficulty is that chemical conservation equations require some kind of additional modelling and the broad range of combustion in the containment cannot be tackled with a unique method.

Two alternatives methods are generally proposed for simulating turbulent combustion phenomena for a full scale containment: the mean rate reaction models and the 'forest fire' model [85], which have been discussed in Section 4. The most frequently used turbulent combustion models based on mean rate reaction modelling are the eddy break-up (EBU) models and their extensions [61], the eddy-dissipation model [86], the flamelet models [87], and probability density function method 88].

It should be stressed that these methods are limited to the description of the mean flow field. The LES method could constitute an attractive alternative for numerical simulations of large coherent structures, especially when combustion instabilities occur. Moreover, LES methods are potentially applicable to studies of combustion dynamics allowing a better description of the turbulence/combustion interactions because large structures are explicitly computed. While LES is well established in aerodynamics, its applicability to combustion still raises unsettled questions and, up to now, relatively few studies have addressed LES of reacting flows.

Table 14 provides an overview of typical combustion models implemented in multi-dimensional computational tools used for containment combustion analysis.

TABLE 14. OVERVIEW OF COMBUSTION MODELS USED IN THE CODES

Combustion models	Computational tools
Arrhenius Model	GASFLOW, COM3D (FZK), TONUS (IRSN/CEA)
Eddy break-up model	TONUS 3D (IRSN/CEA)
Eddy dissipation concept model	GASFLOW, COM3D (FZK), REACFLOW(JRC) CFX4-5 (AEAT)
Flamelet model	AIXCO (RWTH-Aachen)
Probability density function model	CFX4-5 (AEAT)
Forest fire model	TONUS 3D (IRSN/CEA), FLaccident management 3D (FZK), B0M (KI)

8.10.5. DDT modelling

The DDT phenomena have been extensively studied and most of them are understood qualitatively. However, quantitative methods have not yet been established for an accurate assessment in large scale containments. As discussed in detail in Section 4, DDT is a very complex process associated with turbulent reacting flows and shock wave interactions, where rigorous closure solutions still are in a distant future, so that practical approaches are needed for safety analysis.

For DDT simulations, the major problems are related to the different time and length scales of the physical-chemical processes involved, which are difficult to describe for the atmosphere in a realistic containment geometry. It is well known that the likelihood of DDT increases with the geometrical scale and that for the numerical treatment huge computer resources are necessary to gain a sufficiently high numerical resolution both in space and time. Therefore, one approach could consist of dividing the potential DDT processes into the main stages, e.g. for slow, fast, and rapid flames in the sub/super-sonic regime, and to develop suitable software tools capable of numerically defining DDT conditions or criteria to control the resulting combustion mode and the load response.

In that frame, a modern field code cluster on the CRAY computer complex has been established at FZ Jülich for the numerical simulation of various hydrogen combustion processes, including DDT [89]. Several improved modern field codes have been gathered to simulate DDT related processes on the basis of:

- D3UNS code (FZJ) for the distribution mode (concentration),
- General purpose field code CFX from AEA-Technology for the deflagration mode (flame acceleration),
- Flamelet combustion code AIXCO from RWTH-Aachen for the DDT mode (auto ignition),
- HOCKIN code from FZJ for the DDT mode (shock ignition),
- Detonation codes DET (FZKarlsruhe) for the detonation mode (propagation),
- IFSAS (CDL-Canada) code for the fluid-structure analysis (loads).

Test cases of CFD verification and DDT validation have been performed for high speed deflagration in the large scale RUT facility, using the codes CFX and AIXCO, and on the small scale DDT experiments of SWL/RWTH (ahead of the flame), using the codes SHOCKIN, DET and IFSAS.

8.10.6. Detonation modelling

The simulation of a detonation induced by obstacles is a very challenging problem, characterized by many shock and wall interactions that can cause quenching of flames and re-initiation of combustion. The phenomena of detonation wave propagation and interaction with obstacles have been investigated numerically and modelled with specific codes. In general, three-dimensional non-structured high-order time-accurate compressible flow solvers for the reactive Euler equations have been developed for detonation applications. This technique has been implemented in the TONUS code. One to three-dimensional applications have been performed, and comparisons with experimental data showed good agreement between simulation results and measurements.

8.11. Numerical issues

The numerical technology for simulating complex compressible flows has advanced to quite a mature state over the past two decades. Numerous references discuss the basic ideas, the advanced analysis and techniques for practical applications in combustion, also including finite volume and finite element approaches.

The equations that govern the initiation and propagation of flames and explosions are time-dependent and highly non-linear. To avoid undue time step restrictions, semi-implicit or fully implicit schemes are generally considered, which often require solution of large system of non-linear equations at each time step. Much work was spent during the last two decades to further develop the various algorithms. Two numerical approaches for low Mach numbers are often applied:

(1) SIMPLE type algorithms [90] and related approaches – such as the pressure implicit second order scheme [91] – which are currently used quite successfully for combustion applications,

(2) Second-order projections-type methods [92].

Here, we summarize only the key aspects of numerical issues associated with CFD calculations, such as convergence, stability and computational costs.

8.11.1. Convergence

Numerical convergence is an issue with all CFD software, due to the iterative nature of the solution procedures used. In particular, iteration is necessary to handle the non-linearity of the equations that govern fluid flow, heat transfer, and related processes. For any given conservation equation, an approximate solution is obtained at each iteration step, which results in a small imbalance in the conservation statement. During the course of the iterative solution algorithm, this imbalance, under normal circumstances, decreases as the solution progresses. This imbalance is called the residual.

Finally, it is important to keep in mind that the accuracy of a well-converged solution is depends also on the quality of the adopted grid and the sophistication of the used physical models. A coarsely gridded simulation of a complex 3D system will not provide precise flow features, no matter how well-converged the solution is.

8.11.2. Stability

Discretization of the convection operators in the flow conservation equation is an important issue in CFD. The choice of the discretization scheme directly affects both the stability and the accuracy of the resulting numerical solution. Instabilities may appear in flow regions where convection is strong compared to diffusion, and are also triggered where sharp gradients of the flow variables are encountered in the computational grid. This spatial instability appears as over-shoots and undershoots in the solution variables and typically occurs upstream of flow regions subject to strong flow variations.

Many schemes have been developed to stabilize these oscillations in CFD computations. The underlying characteristic of all schemes is that they employ a different amount of numerical diffusion to stabilize the overall convection scheme. The diffusion has the effect of weighting the convection operators towards the upflow regions.

Recently, a new class of schemes has been developed to seek both stability and high-order accuracy by the use of a linear combination of low and high-order schemes (hybrid schemes), using in a first approach so-called ‘blending factors’. In a second approach, the presence of strong gradients or oscillations determines the degree of ‘blending’ with the objective of allowing just enough numerical diffusion to stabilize the solution without compromising its accuracy.

The design of convection schemes that produce a high order accuracy *and* a good numerical stability remains a challenge, especially for more advanced turbulence and combustion modelling.

8.11.3. CPU time

Lumped parameter simulations with coarsely defined coupled control volumes and homogeneous heat sinks are naturally less CPU time consuming than 3D calculations that predict more precisely the hydrogen distribution and local flow effects.

The average CPU time for a simulated accident of one day with a lumped parameter code is generally about some hours depending mainly on the number of containment nodes, number of junctions, hydrogen risk mitigation models, spray activation, hydrogen combustion. In these conditions, the fast running lumped parameter codes allow parametric variations.

The CPU time for 3D calculations with the use of parallel processors will become short enough to take advantage of this new state of the art in the modelling of the steam hydrogen distribution in reactor containments. Presently, calculations performed with the 3D GASFLOW code for a transient of about 2 hours with 184000 computational cells take about one week of CPU time.

Computational costs vary drastically with the choice of the grid mesh (coarse – fine), and the turbulence and combustion models used for simulating complex turbulent combustion phenomena.

In that frame, the use of CFD codes was limited in the past years by the complex geometry of the containment and the sometimes excessive costs and times involved in such calculations. Presently, application of CFD codes for analysis of steam and hydrogen distribution and combustion in nuclear power plants is increasing (using both specific ‘in-house’ codes as well as commercial codes). This trend will be continued by the development and validation of specific models, and the use of advanced algorithms for large machines with parallel-operating processors.

8.12. Treatment of uncertainties

For the purpose of the present analysis we distinguish three major types of uncertainties. The first category includes uncertainties due to the random nature of the operating environment and lack of control of a process, such as random ignition. More knowledge about the statistical distribution of the various parameters can reduce this type of uncertainty. The second type of uncertainties is related to the lack of physical knowledge of the phenomena, which leads to methodological uncertainties. The third type of uncertainties concerns modelling uncertainties which are caused by the use of approximate codes for simulating complex phenomena, using approximate methods and correlations.

8.12.1. Modelling uncertainties

By definition models are incomplete representations of the process being modelled. Consequently, there will always be uncertainties associated with the results of a calculation.

The lumped parameter approach is based on the use of discrete control-volume and flow-paths models, for which a set of conservation equations (ordinary differential equations without space dependency) must be solved for each time step, using dedicated numerical methods.

The CFD techniques are used to describe fluid flows by solving the mass, momentum and energy equations with a higher level of sophistication. Although the underlying physical equations and numerical techniques vary, they commonly involve the replacement of the original equations by a discrete representation (meshing grid), followed by the numerical solution of these approximate equations using a computer. The discretization process, which is the very basis of these techniques, leads necessarily to approximate solutions. Moreover, for complex fluid flows the equations are only an approximation of the true physical processes. The effects of turbulence cannot be represented in a mathematical accurate sense, but are generally modelled by approximate theories.

In addition to the errors and uncertainties that are introduced by the use of numerical models, the user can also introduce errors and uncertainties during the different important steps in the computational process. These steps typically include for a CFD calculation: (1) problem definition, (2) selection of the solution strategy, (3) elaboration of the computational model (definition of geometry, generation of computational grid, definition of boundary conditions and physical properties, definition of initial condition, selection of turbulence model, selection of wall functions, selection of combustion model), and (4) analysis and interpretation of results.

The AIAA Guidelines for the Verification and Validation of computational fluid dynamics simulations [93] provides a useful distinction between errors and uncertainties in CFD codes. The AIAA guide defines uncertainty to be ‘a potential deficiency in any phase of activity of the modelling process that is due to the lack of knowledge’ and error to be ‘a recognizable deficiency in any phase or activity of modelling and simulation that is not due to lack of knowledge.’

The deficiencies and inaccuracies of CFD simulations can be related to a wide variety of errors and uncertainties, from user errors to inadequacies in the modelling strategy and model equations. The main sources of errors and uncertainties in results from simulations can be divided into two distinct sources: modelling and numerical:

Modelling uncertainties are due to assumptions and approximations in the mathematical representation of the physical problem (such as geometry, mathematical equation, coordinate transformation, boundary conditions, turbulence models, etc.) and incorporation of previous data (such as fluid properties) into the model.

Numerical errors and uncertainties are due to the numerical solution of the mathematical equations (such as discretization, artificial dissipation, incomplete iterative and grid convergence, lack of conservation of mass, momentum and energy, internal and external boundary non-continuity, computer round-off, etc.).

The ERCOFTAC best practice guidelines, which give advices for achieving high quality industrial CFD simulations using the Reynolds-Averaged Navier-Stokes Equations, proposed the following classification based on seven major sources of error and uncertainty:

- Model error and uncertainties

  These are defined as the uncertainties due to the difference between the real flow and the exact solution of the model equations. This includes errors due to the fact that the exact flow equations are not solved but are replaced by a physical model that can be quite far off from reality. For hydrogen distribution and combustion simulations, the well-established errors are the errors from turbulence modelling, heat transfer condensation coefficient, simplification of a complex combustion process to a few simple equations, errors from the burning rate modelling.

- Discretization or numerical error

  These are defined as errors due to the difference between the exact solution of the modelled equations and a numerical solution on a grid with a finite number of cells and without a well-sized time step. In general, the greater the number of grid cells, the closer the results will be to the exact solution of the modelled equations, but both the fineness and the distribution of the grid points affect the result. In short, discretization errors arise because we do not find an exact solution to the equations we are trying to solve but a numerical approximation to it.

- Iteration or convergence error

  These are defined as errors due to the difference between a fully converged solution on a grid with a finite number of cells and a not fully-converged solution. The equations solved by CFD methods are generally iterative, start from an initial approximation to the flow solution, and are followed by iterations to the final result. This result is expected to satisfy the imposed boundary conditions and the equations in each grid cell as well as globally over the whole domain, but if the iterative process is incomplete, errors arise. In short, convergence errors arise because of low CFD calculations experience of users, shortness of time or inadequate numerical methods, which do not allow the solution algorithm to complete its progress to the final converged solution.

- Round-off error

  These are defined as errors that arise due to the fact that the difference between two values of a parameter during some iterative scheme is below the machine accuracy of the computer. This is caused by the limited number of computer digits available for storage of a given physical value.

- Application uncertainties

  These inaccuracies are introduced because the application is complex and precise data needed for the simulation are not available. Examples of this are uncertainties in the precise geometry, uncertain data that needs to be specified as boundary conditions and uncertainties as to whether the flow is likely to be steady or unsteady.

- User errors

  These errors are defined as errors that arise from mistakes by a less experienced user, which generally decrease with increasing experience of such user.

- Code errors

  These are defined as errors due to bugs in the software, programming errors in the implementation of models or compiler errors in the computer being used. Such errors are often difficult to find, as CFD software is highly complex, typically involving hundreds of thousands of lines of code for an in-house or commercial tool.

Most of the effort to reduce uncertainties in the hydrogen risk assessment has been directed towards improvement of the modelling of the physical processes. This has resulted in the use of more detailed simulation tools, such as CFD codes. The alternative approach to the reduction of uncertainties is to perform a large number of simulations involving variations in relevant parameters. Ideally, if the time and availability of input data permits, a combination of both approaches has to be considered.

8.12.2. User effect

When comparing the results of lumped parameter and 3D code predictions with experimental data, inadequacies of the codes will be found that underline the problems related to the code reliability and its practical usefulness. In general, discrepancies between experimental and computational results can be attributed to model simplifications and deficiencies, approximations in the numerical solution, inadequacies in the chosen nodalization or the selection of the grid, uncertainties in boundary and initial conditions, and the user effect.

The publication of the NEA/CSNI Status Report for the ‘good practice for user effect reduction’ [94] proposed a definition of user effect. The user effect can be defined as follows: “User effects are any differences in calculations that use the same version and the same specifications for a given plant or facility”.

For lumped parameter approach, the major sources of user-induced uncertainty are the choice of nodalization used to model the geometry of the facility or containment and the modelling of the flow paths between interconnected control-volumes.

In some cases it has been observed, that modelling the region with only a few nodes can result in an apparent improvement of the results; in other cases using additional nodes provided a significant improvement of the simulation. In general, this last improvement in the predictions with added nodes is due to an improved accuracy. Nevertheless, this trend is not systematic: in some cases, the additional nodes resulted in a more favourable placement of a computational node in relation to a measurement location.

The connections between two physical compartments are related by the geometrical characteristics of the connection cross-section. The calculation of the gaseous flow rate in these flow paths is based on user-introduced pressure drop coefficients, in some cases arbitrarily fixed, i.e. without engineering judgment. On the other hand, when modelling virtual sub-volumes of a large gaseous volume such as the containment dome, with the objective to improve the prediction of the hydrogen stratification, the modelling of these sub-volumes includes a certain degree of freedom for the choice of the user.

In general, these problems of nodalization and flow paths modelling can be studied through sensitivity calculations where a number of nodalization schemes are tried until convergence in the result is obtained. Unfortunately, time constraints can limit these studies.

The result of a CFD problem solution is dependent on the mesh quality and resolution. So, in the design of a CFD simulation in large scale containment decisions are required on computational meshing strategy and grid generation. This issue constitutes one of the most frequently mentioned sources of user-induced uncertainty in CFD. In general, mesh size constraints coupled with requirements on local resolution (e.g. near wall structures for predictive heat transfer calculations) yield a prohibitive number of computational cells for long term transient calculations. For complex containment geometries, limitations in computer resources and time constraints presently limit the number of cells from about 100 000 cells to 500 000 cells. With these limitations applying a mesh refinement study to estimate the numerical error in the simulation is rarely done.

8.12.3. Use of sensitivity analysis

The purpose of sensitivity analysis is to quantify the uncertainties in the results of an analysis and to identify the governing parameters by an examination of the sensitivity of the results to changes in these parameters. One can also evaluate the effects of the model input parameters and code model limitations on phenomena or processes which have not been studied in detail.

Code applications were often evaluated during post-calculations of experiments in ‘International Standard Problems’ (ISPs). The differences found between calculated and measured parameters were assessed with respect to achievable numerical accuracies and the uncertainties in existing simulations of these experiments. Most of these differences can be explained by three factors: analytical limitations of the applied codes, the effect of the user of the code and uncertainties in the available initial boundary conditions of the experiments. The individual contribution of the simulation uncertainties and the analytical model limitations has not been evaluated yet. This difficult step requires considerable effort, to be achieved only in the future. More particularly, an appropriate methodology still has to be developed for the interpretation of identified sources of uncertainties for their effect on thermohydraulic plant analysis.

Meanwhile, numerical sensitivity studies may be considered to assess the calculated margins and to identify their main contributors. A sensitivity study for an adopted analytical simulation model would cover these following aspects: (1) variation of the selected nodalization concept, (2) variations of some optional code parameters (e.g. flow resistance factors), (3) variations of some optional models (e.g. correlations for heat and mass transfer), (4) deviations from initial and boundary conditions.

Moreover, for multi-dimensional calculations, uncertainties are studied by performing specific sensitivity analyses. Such a sensitivity analysis is typically composed of multiple simulations with a code to determine the effect of the variation of relevant components (numerical aspects, models, and initial and boundary conditions) on the output quantity of interest, by examining e.g. (1) the spatial grid convergence, (2) time convergence, (3) the effect of spatial differencing methods, (4) the effect of model uncertainties, such as the various turbulence models, heat and mass transfer correlations and combustion models, and (5) deviations from initial and boundary conditions.

8.13. Benchmarking

The validation of adopted analytical models for hydrogen transport, distribution and combustion requires a careful consideration of the physical processes and detailed comparisons of the calculated results with experimental datasets that include these processes.

Before using a computational code it is necessary to build confidence in the results obtained from the model. This confidence is obtained by performing verification and validation of the code. Verification is a process that confirms that the model is technically correct and consistent with all the source documentation. Validation is a process in which a series of validation exercises is executed where the results of the calculations are compared with well-characterized experimental data. The objective of the validation is to determine the accuracy of the physical and numerical approximations in the models, to improve the reliability of the calculated results and/or to improve the numerical efficiency of the calculation method.

Several steps are often mentioned to assist in the validation and verification of complex lumped parameter and CFD code models. These steps can be described as follows:

- Define a set of primary parameters and primary physical phenomena affecting these parameters and establish the corresponding modelling requirements;

- Determine the desired accuracy for primary parameters and other quantities of importance for the selected application;

- Establish the appropriate governing equations and the corresponding physical modelling requirements;

- Identify and acquire appropriate, well-characterized benchmark data to establish a standardized database to validate computer models;

- Perform computations for the selected experimental conditions and determine the sensitivity of the model to the numerical and modelling assumptions;

- Document the validation effort results to the extent necessary to provide other code model users with knowledge of the model's capabilities, including the overall accuracy of the calculated results and the sensitivity of the solution to internal parameters, such as numerical damping and computational grid refinement.

- If possible, use apart from dedicated experimental programmes, also data sets of the ISP

International Standards Problems [95], organized by OECD, are chosen for the comparative analysis exercise because they provide a good representation of the state-of-the-art knowledge in experiment, code development and simulation uncertainty. On the other hand, they have unlimited distribution, a large representation of codes and codes type (lumped parameter and CFD), and are designed to address general concerns regarding code performance for thermohydraulic and hydrogen distributions.

Normally, specific experimental programmes suitable for code development and uncertainty assessment, have limited distribution and code participation (one or two codes are represented).

A CSNI Working Group has completed a 'SOAR on Containment Thermohydraulic and Hydrogen Distribution' [96] whose objectives were to assess the current capabilities of the codes to calculate flow, temperature distribution and gas concentration distribution inside the containment, to address strengths and weaknesses of analytical methods predicting the effectiveness of chosen mitigation techniques and to take into consideration accident management actions with their possible feedback on processes in containment. In this SOAR, some conclusions related to the past usage of ISPs have been presented.

ISP exercises have identified a potentially serious problem associated with lumped parameter codes: these codes tend to overmix light gas stratification mixtures, even with more detailed nodalizations. This problem is currently addressed by modelling improvements and validation with re-calculation of ISPs. The improvements in stratification modelling have been encouraging but still require additional validation, especially with new geometries and under blind test conditions.

Encouraging computational results with CFD codes have been obtained in a number of post test calculations on previous ISP tests. First results show that these codes have generally been able to calculate gas transport and distributions under natural-convection conditions (where mixing and transport flows are quite small) with better accuracy than some lumped parameter codes. To acquire additional confidence in the CFD code applications will require more cross-comparison exercises with the more improved lumped parameter codes, using new ISP data sets, designed for integrated effects with specially designed high-resolution 3D instrumentation and well defined initial and boundary conditions.

The physical processes occurring in a reacting flow are among the most complex of all flow phenomena. As a result, the validation of CFD codes that analyse these flows require special attention. The computation of large scale, transient, containment flow fields is very time consuming. Nevertheless, development of tools that enable analysis of the complex phenomenon of combustion in a containment is essential. A quite large number of experiments (see Annexes III and IV) suitable for the validation of thermohydraulic codes, flame acceleration models and DDT criteria are underway.

8.14. Effect of scaling

The effect of scaling is until now an important open issue in the containment analysis. Considerable international efforts have been undertaken to validate computational tools on a large number of experiments with different sizes. First, a better understanding was needed of the dominating processes in thermohydraulics and their geometrical dependency.

In the subsequent combustion modes, the gas–steam composition distribution has been identified as a leading parameter, characterizing atmospheric mixing and gas transport prior to ignition. Other important phenomena have been identified which depend on natural convection and gas distribution, such as condensation and heat transfer to structural surfaces.

Several phenomena which influence the hydrogen distribution and combustion depend on the geometry and the thermohydrauylics conditions, such as buoyancy driven gas flow, water condensate drainage flow, heat and mass transfer and cell size used for the detonation criteria. In general, these phenomena can be characterized by relevant non-dimensional characteristic quantities, such as the Reynolds, Peclet, Mach, Grashoff, and Damkohler numbers.

Moreover, the sensitivity of codes for effects of scaling depends on the models and/or empirical relationships built in into the codes and their dependency on the adopted nodalization concept (control volumes for the lumped parameter codes and meshing grid for the CFD codes). This point is notably relevant for the CFD-codes, as the size of the mesh size has to be compatible with the simulated physical phenomena, and thus may depend on non-dimensional characteristics quantities. Nevertheless, in practice it is observed that the choice of the mesh size is rather determined by computational limitations.

The accumulated experience by containment code users has made it possible to optimize the key decisions in applying the codes for predictions of experimental phenomena in various test rigs, from their knowledge of the main parameter influencing the important physical processes. Nevertheless, most post-calculations of test rigs of various sizes have shown that adjustment of a number of free parameters is required, which renders the extrapolation to reactor conditions more questionable. Furthermore, the scale dependency of applied nodalization schemes/meshing grids in combination with other code options or models has rarely been investigated.

As experimental data on global convective flows obtained from small scale facilities may not be representative for plant application and also geometric similarity is not generally maintained, some important physical effects leading to buoyancy driven flows inside the containment have not be studied appropriately (e.g. the effect of self-heating radioactive fission products). Hence, one must take care before applying a strategy which is successful for a specific small-sized test facility to a nuclear power plant.

The following methodology has been proposed in the SOAR on Containment Thermalhydraulics and Hydrogen Distribution [97] to deal with the effect of scale. The methodology is mainly based on a set of counterpart tests at reduced but different geometrical scales and at thermohydraulic conditions most close to the conditions expected in a real plant. Such tests would be characterized by the following basic requirements:

- Availability of test rigs at various scales with sophisticated measurement techniques and designed to study the effect of scaling;

- Identical test objectives (e.g. the same type of scenario are studied by the partners involved);

- Similar testing conditions need to apply and care has to be taken that dominating phenomena are neither suppressed nor over-emphasized during the experiment.

Unfortunately, larger test facilities suitable for far-reaching counterpart test activities have recently been dismantled (HDR and BMC Facility). Smaller and less compartmentalized facilities now are forthcoming as candidates for counterpart testing (e.g. TOSQAN, MISTRA and THAI facilities).

9. REMAINING ISSUES IN HYDROGEN RISK MITIGATION

Hydrogen risk cannot be separated from the reactor containment strength. For those containments with a low containment strength or identified weak local points, the hydrogen combustion loads could induce a risk. Consequently, the volume of the experimental programmes in various countries is somehow linked to the perception of the hydrogen risk in these countries.

For significant hydrogen sources that may not be accommodated by mitigation means associated to DBA, the uncertainty is largely dominated by the unknown extent of Zr oxidation during the in-vessel core degradation phase.

9.1. Introduction

Hydrogen risk cannot be separated from the reactor containment strength. For those containments with a low containment strength or identified weak local points, the hydrogen combustion loads could induce a risk. Consequently, the volume of the experimental programmes in various countries is somehow linked to the perception of the hydrogen risk in these countries.

In Europe, following the methodology to detect the hydrogen risk as described in Section 2, hydrogen combustion has been identified as a risk by various designers, utilities and regulatory bodies and, hence, insights are requested and potential mitigative measures studied, e.g. using PAR's or igniters. In a number of countries, the hydrogen source is required to be 100% ACL oxidation, as flooding of an overheated core is considered as an accident management measure, which aggravates the risk. This is also reflected in research programmes supported by international bodies, such as the EC. In addition, European industry is involved in the development of new reactors, where the requirement is that severe accidents with off-site consequences are virtually excluded. As there is no uniform position in Europe, the national interest in the research programmes varies.

In the USA, the hydrogen risk during a severe accident is not considered an area for which further research is warranted: it has been analysed that containments of USA plants can either withstand the induced hydrogen combustion loads with enough safety margins (for the large dry PWR containments, for instance), or effective measures are taken such as inertization (for the Mark I and II BWRs) or igniters (at Mark III BWR and ice condenser

PWR). The USA analysis did not include advanced methods such as the use of CFD codes to find a more refined hydrogen containment distribution, or loads from flame acceleration, as it was assessed that the safety margins were large enough to cover such uncertainties. Moreover, a maximum of 75% ACL oxidation reacted was used for the hydrogen source (see Section 2).

In this section, we are looking for those aspects that are relevant for the hydrogen risk. Until further R&D results and associated new modelling are available, the uncertainties are to be addressed in a proper way by means of selected scenarios and sensitivity calculations (see Sections 2 and 5).

9.2. Remaining issues on hydrogen amount and production rate

The issue of hydrogen sources must be considered as a whole and cannot be separated in in-vessel and ex-vessel issues. For significant sources that may not be accommodated by mitigation means designed to cope with a DBA, the uncertainty is largely dominated by the unknown extent of Zr oxidation during the in-vessel core degradation phase.

The in-vessel hydrogen production amount and especially the hydrogen production rate are the main factors influencing the risk. Where the hydrogen production is generally well simulated during the first phase of the accident scenario – when the core geometry is still intact – there is still some lack of knowledge related to the late phase of the core degradation, especially regarding (U-Zr-O) melts and B_4C melts oxidation, and hydrogen production during late reflooding of the core.

Some experimental work on (U-Zr-O) mixtures oxidation is has been studied the frame of the COLOSS project of the EC-FWP-5, such as the SKODA-UJP experiments using solid U-Zr-O alloys ingots (Annex I).

High hydrogen production rates associated with reflooding have been estimated from the TMI accident and recorded in some integral experiments (CORA, LOFT). It is expected that the current FZK QUENCH experiments will extend the knowledge database (see Annex I). But since this programme does not use prototypic materials and investigates mainly rod-like geometries, there will be still some remaining uncertainties. The R&D on in-vessel reflooding is still an open issue.

Ex-vessel hydrogen (or H_2 + CO) production is not considered to be an issue for the hydrogen or (H_2 + CO) release in the containment, because, whatever the DCH or MCCI tools used for calculation, all the released vessel metallic Zr (or Zr + Cr) will be fully oxidized within around one hour after the vessel failure.

9.3. Remaining issues on hydrogen distribution

Adequate prediction of hydrogen distribution within many containments is of high importance since it is the basis to assess the risk of dynamic local phenomena. Lumped parameters codes have some shortcomings (e.g. in the release phase and in strong stratifications) and CFD codes are currently not well validated.

The scaling effect is until now an important open issue in the containment analysis. Considerable efforts have been undertaken internationally to validate lumped parameter codes on a large number of experiments of different sizes for the scaling of hydrogen distribution aspects, and now the validation of CFD tools for more detailed in-containment calculations is in progress. In this context, new containment test facilities using different scale volume geometry (TOSQAN, MISTRA, THAI, PANDA) with extended and dedicated instrumentations for CFD codes validation have been built.

The OECD-ISP-47 exercise [120], performed from 2002 to 2005, is the first full Containment Thermohydrauylics International Standard Problem exercise. The main objective of the ISP-47 exercise is to demonstrate the actual capability of CFD and lumped parameter codes to handle containment thermohydrauylics in conditions representative of severe accidents, e.g. to predict hydrogen distribution under LOCA conditions. A systematic approach has been developed using different available facilities. The facilities used are (see Section 3):

- The French TOSQAN test facility ~ 7 m^3
- The French MISTRA test facility ~ 100 m^3
- The German ThAI test facility ~ 60 m^3
- The Swiss PANDA test facility ~ 200 m^3.

The test facilities are shown and described in Annex II.

For Step 1, the TOSQAN open benchmark results indicate that the model predictions generally fit the experimental results obtained during condensation steady-state conditions with good accuracy. However, some of the major transient phenomena are not always reproduced by the models. Some multi-dimensional models reproduce the kinetics of the transient stratification whereas most lumped parameter models only reproduce the final level of concentration.

In the MISTRA blind benchmark, lumped parameter models, which usually incorporate fog modelling, give reasonable results if the nodalization is sufficient to capture the main findings of the flow pattern. From the CFD contributions, open questions concerning simulation of a rising jet and the thermal behaviour of the steel vessel wall were identified. Mean values such as total pressure are predicted rather well by all the codes. Some computations reproduced the gas temperature profiles well; others showed large deviations that are mainly due to overpredicting the superheating. This overprediction has only a minor effect on the calculated helium concentrations, which are generally well-reproduced.

In the Step 2 ThAI benchmark, major improvements in the predictions have been achieved by several participants when moving from blind to half-blind calculations, mainly by refinement of the nodalization and more systematic treatment of the injection jet entrainment. In particular, the atmospheric stratifications during the phases in which the injection jets are located inside the upper light gas cloud are reproduced well by several lumped parameter models. Generally, however, they are underestimated by most LP and CFD contributions. The very challenging conditions leading to maintain the stratification in the phase which has the steam injection at the lower nozzle are in most cases not met, neither by CFD nor LP contributions. The reason why two lumped parameter models have been able to predict this stratification blindly is related to nodalization and entrainment simulation.

In view of the high quality of the ISP-47 tests it is recommended that containment codes are validated against ISP-47 tests before using the code for the assessment of hydrogen distribution in plant applications. This recommendation pertains to lumped parameter codes as well as to nuclear research and industrial CFD codes.

9.4. Remaining issues on hydrogen combustion

A mitigation strategy only based on hydrogen recombination cannot always prevent the σ and eventually the 7λ criteria to be reached, notably in the vicinity of the hydrogen release location.

Concerning hydrogen combustion, a reliable prediction of the potential occurrence of DDT or a fast deflagration is still not well possible. The σ and the 7λ criteria are often used, however, the validity of those criteria for strong hydrogen concentration gradients is limited. Moreover, as the σ criterion has been defined from small scale experiments in tubes, the criterion is not validated for complex geometries. Further validation efforts are, hence, done in the European experimental and code validation programme called HYCOM (see Section 4). Moreover, extensive research is carried out at the Kurchatow Institute in Moscow, dealing with flame acceleration and DDT (see Section 4).

Sigma criteria for assessing flame acceleration

In the framework of the EU-HYCOM project (see Section 4), the experimental results show that critical conditions for fast combustion regimes can be influenced by the flow geometry. Both promoting and suppressing effects can be observed. The promoting effect of a converging flow geometry is not strong, and the σ criterion is applicable for multi-compartment geometry within the postulated limits of accuracy. The suppressing effect is typical for volumes with venting or divergent flow geometry. It was found to be strong in earlier studies. Over-conservatism of the σ criterion for open areas or areas with venting can be significantly reduced, if this effect is taken into account. A reduction of existing uncertainties in σ criterion is possible if it is applied with the reference to the actual state of the unburned mixture during flame propagation. This would require that the application of the σ criterion be combined with CFD combustion analysis. The EU-HYCOM project concludes that additional work would be also necessary for reduction of uncertainties in the criteria itself.

Much work has been done in the frame of the EU-HYCOM project in order to refine the assessment criteria. Nevertheless, some uncertainties remain on:

- The temperature effects, mainly for rich mixtures, close to self ignition,
- The effect of complex shaped 3-D cloud development in real buildings, which is different from most 1-D type experiments,
- The effect of concentration gradients,
- The effect of venting, considering the nature of the boundaries of the critical hydrogen cloud, which boundaries can be partly solid structures or partly gas, and the effect of blockages and vortex generating structures.

DDT criterion

The lambda criterion validation has not been performed in the frame of the EU-HYCOM project. Consequently, the present level of confidence in the use of the lambda criteria for reactor application is lower than that of the sigma criterion.

Uncertainties associated with the definition of the cell size value of the lambda criteria still remain, in particular in case of complex and partly confined geometry. Furthermore, the validation of the lambda criteria for strong hydrogen concentration gradients is not complete. Further validation efforts are still required.

Slow combustion

The hydrogen risk is not limited to fast combustion, and the loads generated by a slow combustion can also endanger directly or indirectly the containment integrity. Important validation work is still required to adapt the actual combustion CFD codes to the description of ‘slow’ combustion in lean mixtures: until this work is done, neither the best-estimate nor the conservative assessment of the direct or indirect consequences of ‘slow’ combustion can be ensured.

Very little data are available concerning combustion when the spray system is activated. Moreover, the CFD simulation of the effect of the spray remains an open issue with regard to hydrogen distribution and combustion. Therefore, in order to assess the impact of the spray on hydrogen risk, an important effort is needed to:

- Evaluate the effect of the spray on hydrogen combustion behaviour in non-uniform mixtures and multi-compartment geometry,

- Evaluate criteria and limiting conditions for flame acceleration in non-uniform mixtures and multi-compartment geometry under spray operation.

9.5. Remaining issues on analytical aspects

The objective of the EU-HYCOM project was to validate models and codes on experimental data and the identification of ranges of applicability of modelling approaches (e.g. lumped parameter and CFD techniques) and to demonstrate the code capabilities by full scale plant analysis. Detailed post test analysis work performed in this framework has identified remaining differences between code results and experimental data:

- Non-uniform mixtures are still a challenging situation for the codes, especially when they are accompanied by a change in the combustion regime, e.g. of fast to slow deflagration. Further model development and validation work are certainly necessary in this area to handle correctly the real containment situations, where the gas distribution can be strongly non-uniform,

- Very lean hydrogen mixtures are outside the validation range of the codes, and many uncertainties remain concerning their basic properties regarding combustion. Extrapolation of the parameters fitted to reproduce the behaviour of richer mixtures is risky. Even if fast combustion regimes cannot be expected in these mixtures, slow deflagrations in large open volumes filled with a lean mixture contribute largely to the slope of the pressure rise and to the value of the peak pressure,

- The validation range of the codes remains limited to idealized situations and their application to realistic reactor applications is at its beginning.

10. CONCLUDING REMARKS

The generation of large amounts of hydrogen is a typical phenomenon associated with severe accidents in NPPs. Amounts can vary, depending on the type of nuclear power plant and the accident considered. Quantities range from about 100–1000 kg. H_2 and above, and it is clear that such amounts pose a risk to the integrity of the containment or confinement. However, there is no unique answer to the question how to mitigate the risk from hydrogen generation and combustion, as this question depends not only on a number of physical factors, discussed in the previous sections, but also on the perception of the risk by the utility and on the regulatory climate in a country. From the preceding sections, a number of conclusions can be drawn.

Generation of hydrogen

The generation of hydrogen in the early phase of the accident is fairly well understood, i.e. at the beginning of the oxidation of the Zr cladding material, until the core starts to slump. The late phase is less well understood, as is the amount of hydrogen created ex-vessel by the reactions with Zr and Cr. The following observations hold for these phases:

A very rough order of magnitude of the mass of hydrogen created by full Zr oxidation could be up to 1000 kg of H_2 for a PWR of about 1000 MW(e), and 3 to 4 times more for a BWR of the same power level.

It is commonly agreed that the hydrogen average source rate, without core reflooding, is typically about 0.2 kg/s for a 1000 MW(e) PWR, and that this value is sufficiently accurate as long as the core geometry remains intact. Most of the international severe accident codes presently use the Zr oxidation Urbanic-Heidrick correlation because it gives better results when compared to integral tests such as PHEBUS. The Zr oxidation parabolic models are presently used in many codes also beyond the state of intact geometry and consequently these codes seem to underestimate H_2 production during core reflooding.

During DCH, it can be reasonably assumed that 100% of the remaining Zr is oxidized in the cavity pit or in the containment.

During MCCI, it can be reasonably assumed that 100% of the remaining Zr and Cr masses in the corium will be oxidized within the first hour (or even less) following the beginning of MCCI, and it is not possible to exclude that hydrogen produced ex-vessel can be accumulated in the containment with the in-vessel production. During core concrete interaction, CO can be released, depending on the composition of the basemat concrete. So, the results are highly plant specific. The so called 'flammable mixture' in the containment must take into account the sum (H_2 + CO) in the risk evaluation due to hydrogen burning.

In order to deal with the great amount of uncertainty in the calculation of the in-vessel hydrogen source by the core degradation codes, two ways presently exist, depending on the purpose of the calculations:

- In order to detect the hydrogen risk on a NPP, a common way is to run a core degradation code (or several codes) on representative sequences of severe accidents, using a certain assumed quantity of Zr (or metal mass) oxidized at the time of the vessel lower head failure. This ‘assumed quantity of oxidized metal or Zr’ is often derived from national regulations. This method is often used by safety authorities, but there is no international consensus on this quantity. For instance, to identify the H_2 risk in France, containment calculations with 100% Zr ACL are performed.

- In order to implement a hydrogen risk mitigation system, utilities often run a core degradation code (or several codes) on representative sequences of severe accidents and directly use the hydrogen output given by the calculations. The calculations are ‘best-estimate calculations,’ and both a deterministic and probabilistic approach can be used to select the proper scenarios.

Such ‘best-estimate calculations’ are always performed with a good knowledge of the code modelling concerning the parameters which play a major role in the hydrogen release:

- The thermohydrauylics in the core during core degradation (e.g. is there a 1D or 2D thermohydraulic modelling of the steam flow redistribution around a channel blockage?).
- The choice of the Zr oxidation correlation of the fuel rod clad (e.g. is there a correct modelling of the oxygen diffusivity around the clad? Has the correlation been agreed among experts? Is it only used for intact geometry?).
- Onset of ceramic melt relocation (e.g. is there a code criteria or option allowing a longer time before onset of melt relocation?),
- Oxidation of U-O-Zr melts (e.g. is there a dedicated oxidation law?),
- In-vessel reflooding (e.g. what kind of modelling is used?).

Concerning the ex-vessel hydrogen sources, the main parameters for the ex-vessel hydrogen sources during MCCI are the masses of Zr and Cr available for MCCI. Sensitivity calculations need to be done on these parameters.

Distribution of hydrogen

The hydrogen distribution is influenced significantly by the following parameters:

- Containment layout,
- Location of the hydrogen source,
- Conditions in the containment (temperature distribution) during hydrogen release,
- Release rates and combination of the release with other gases and steam.

Since the mode of hydrogen release depends strongly on the accident sequence, for the design of a hydrogen risk mitigation system at least two different and enveloping sequences for the plant have to be chosen.

The different types of analytical tools available for the analysis of hydrogen distribution all have both advantages and disadvantages.

Fast running ‘integral codes’ or ‘system codes’ are able to analyse even accident sequences with a problem time of some days in an adequate computation time. This fast computation is due to the more simple physics and models, and paid for by less accuracy. This type of computer code is most suitable for parameter studies of whole accident sequences, when higher uncertainties are tolerable.

‘Lumped parameter codes’ are relatively fast running codes with a large validation base for the used models and an extensive user community, representing a considerable resource of experience. They cannot predict some of the details of local/regional gas mixing. This disadvantage can be reduced by highly experienced users. This type of computer code is successfully used for the analysis of the containment behaviour during the whole accident sequence. Due to the number and variety of verified models the predictions are reliable and accepted by reviewers all over the world.

CFD codes are able to predict local/regional steam gas concentrations. Their main disadvantages are the very detailed input needed and the long running times, which make parametric sensitivity studies impossible in practice. The main application for this type of code is for special effects when ‘lumped parameter codes’ fail (e.g. for combustion). Their validation basis is limited due to a lack of well-instrumented experiments.

‘Hybrid codes’ which combine the advantages of the ‘lumped parameter codes’ and the CFD codes possibility seem to be very attractive; but the first results of such calculations are not satisfactory.

The distribution experiments performed in the past were usually integral experiments in compartmentalized containment-like facilities. They were used for validation of the lumped parameter codes and for this purpose the instrumentation was designed. The needs of CFD codes, with their better solution, cannot be fulfilled with these tests.

Future experiments have to be extremely well instrumented to serve as a base for CFD code validation.

Combustion of hydrogen

All combustion modes are potentially possible in a severe accident scenario: (1) for low hydrogen concentration below about 8%, flame speed is expected to be slow and the deflagration produces a quasi-static pressure loads. (2) Above about 8%, combustion is complete and combustion may accelerate leading to higher loads, (3) above 10%, acceleration up to sound velocity has been found in many experiments and, (4) in an extreme case flame acceleration, supported by turbulence, can reach detonation conditions, DDT. Regarding reactor safety, flame acceleration and deflagration to-detonation transition can be extremely destructive and have the highest potential damage for internal containment structures and safety systems required for severe accident management. Direct initiation of a detonation is not possible within containment due to the high energy required.

The occurrence of flame acceleration and DDT depends on the mixture composition (concentration of reactants and diluents), the initial conditions (pressure, temperature and turbulence), the geometrical configuration and, most importantly, the physical size (or scale) of the reactive system. Much effort has been focused on development of macroscopic criteria for flame acceleration and DDT derived from dedicated experiments. The applications of these criteria, which define necessary conditions for the corresponding phenomena to occur, allow identifying the expected combustion regime: slow flames, fast flames or detonation.

Because of the large degree of conservatism of these criteria, the combustion process has to be explicitly calculated using dedicated models and codes (Lumped parameter or CFD codes) to describe flame acceleration and DDT. Lumped parameter codes, extensively used for prediction of hydrogen distribution and combustion of premixed gases, are nevertheless limited for detailed prediction of containment loads. CFD codes have shown very encouraging results: for fast combustion regime CFD codes are capable of capturing the main features of hydrogen combustion from the qualitative and quantitative point of view. Nevertheless slow deflagrations and non-uniform mixtures are still challenging situations for codes.

Risk from hydrogen combustion

Hydrogen deflagration can pose various risks to the containment and other plant systems. Combustion can give large pressure spikes, varying from relatively low pressure loads, bound by the AICC loads, until large loads from accelerated flames and detonations. Such acceleration can already occur above about 8% H_2, as indicated before, so that above that value the AICC load may not longer be the bounding value.

AICC loads are quasi-static, i.e. the structural response can be calculated assuming loads are static. Loads from accelerated flames or detonations require a dynamic analysis, i.e. the dynamic characteristics of the structure need to be taken into account. A simplified approach is using an equivalent static load.

Apart from such direct damage, the containment may also suffer indirect damage. This can happen if a local explosion destroys a compartment, after which the missiles from this compartment penetrate the containment or damage lines that go through it.

Another damage mechanism is leakage through the containment wall, which may result in a hydrogen burn outside the containment. The associated load is, in fact, a negative pressure on the containment, for which load the containment usually has only a low resistance. Note that these outer structures, often secondary containment, also can be damaged.

Finally, combustion produces much heat, which can damage various structures, systems and components. A point of concern is the exhaust of PARs, as these can be very hot.

Under unfavourable conditions, thermal stratification can occur that prevents the hydrogen from mixing with the steam. This can occur if mass releases from the primary system are widely apart: e.g. in a small break LOCA, one may first see the steam and only much later the hydrogen. Hence, scenarios have to be included that can give rise to such phenomena. A typical risk is also if the containment initially is inert, due to the steam, so that hydrogen can accumulate considerably. Combustion will then first occur once the steam is largely condensed, i.e. at a fairy large H_2 concentration, which then may result in large loads.

Large dry containments, that have a fairly large volume and a relatively high design pressure, are not very much at risk, as the loads do not exceed AICC values, and often, no specific measures are needed. Some designs are sensitive to local effects, e.g. due to the presence of compartments. Mixing the containment atmosphere will help to mitigate local effects.

Smaller containments with low design pressure such as the ice condenser and suppression pool type containments, and the confinement of older WWERs (type 440) are vulnerable to combustion loads. Often, igniters are placed (ice condenser) or containments are partially or wholly inerted (BWRs). For future designs, it is usually required that the risk from hydrogen combustion is negligible.

The treatment of hydrogen combustion in PSAs goes usually not beyond the consideration of AICC loads. Sometimes, ignition is assumed as soon as the mixture is burnable, without assured ignition sources. This is an oversimplification as it rules out that hydrogen can accumulate, and then burn at a higher concentration.

Measurement of hydrogen

Proper accident management may depend directly on insights in the hydrogen concentration.

Two different methods are available to measure the hydrogen concentration in the containment after an accident. The first method is to install the hydrogen measurement system inside the containment, the other method is to sample the gas of the containment and to analyse this gas outside the containment. Qualified measurement systems for both methods are commercially available.

If no hydrogen measurement is available, the hydrogen risk could be estimated using computational aids. An amount of Zr oxidation needs to be assumed, which then is transferred to a percentage of H_2 using a pre-calculated curve

Hydrogen control and hydrogen risk mitigation

Often engaged mitigation measures are:

- Pre-inertization with nitrogen in most of the BWR containments,
- PARs in large dry PWR containments,
- Igniters for ice condenser and Mark III containments.

Post-inertization and post-accident dilution with inert gases was studied but is not applied up to now.

The removal of hydrogen by PARs is a method which does not need any operator action or external power. Installation requires only to place PAR units at appropriate locations within the containment to obtain the desired coverage. PAR capacities are ultimately subject to mass transfer limitations and may not keep up with high hydrogen rates in small volumes, for example, as could exist in the immediate vicinity of the hydrogen release.

Since thermal and pressure loads produced by the recombiners are significantly smaller than those produced even by an early ignition and a slow deflagration, recombiners are the first choice of all hydrogen removal systems.

The strategic combination of different mitigation systems was studied but the application of those systems has not been done so far.

Even without any hardware for hydrogen risk mitigation it may possible to deal with the problem by appropriate severe accident management guidelines. Ignition may be provoked by sparks from switching components, inertization/dilution obtained by the release of steam, or expected containment loads diminished by a timely containment venting. The guidelines describe the various actions needed.

Analytical aspects

Analytical aspects related to the methodology used for hydrogen risk assessment have been discussed in Section 8. For pressure and thermal loads, analytical aspects focus in particular on the modelling for a hydrogen risk mitigation system, practical concerns related to hydrogen distribution calculation, ignition modelling and combustion analytical aspects. The accurate prediction of pressure and temperature loads resulting from hydrogen combustion requires: (1) gas and temperature distribution calculations within a detailed representation of the containment, its internal structures and connections with validated models, (2) combustion ignitions assumed at the most unfavourable moment and at the most unfavourable location, (3) hydrogen combustion calculations with models inside their validation range.

Errors and uncertainties introduced by analytical calculations, divided in modelling and numerical sources, have to be taken into consideration in the calculational process. In addition to uncertainties, introduced by numerical models, the user can also introduce errors and uncertainties during the different important steps in the computational process: choice of the containment nodalization and flow paths modelling for the lumped parameter approach, and choice of meshing strategy, grid refinement and turbulence model for the CFD application. Sensitivity analysis constitutes an important method for evaluating the effects of model input parameters and code model limitations on phenomena or processes that have not been studied in detail. However, this important step, which requires a considerable effort, is rarely taken. Much effort has been focused on validation of models for hydrogen transport, risk mitigation and combustion applications. This validation process requires a careful consideration of the physical processes encountered in phenomena and detailed comparisons of the calculated results with experimental datasets that include these processes.

Finally, the effect of scaling is until now an important open issue in the containment analysis. Considerable efforts have been undertaken internationally to validate lumped parameter codes on a large number of experiments with different sizes for the scaling of hydrogen distribution aspects, and now the validation of CFD tools for more detailed in-containment calculations is in progress. In this context, new containment test facilities (TOSQAN, MISTRA, THAI, PANDA) with extended and dedicated instrumentations for CFD codes validation have been built.

Remaining issues in hydrogen risk mitigation

Hydrogen risk cannot be separated from the reactor containment strength. For those containments with a low containment strength or identified weak local points, hydrogen combustion loads could pose a risk. Consequently, the volume of the experimental programmes in various countries is somehow linked to the perception of the hydrogen risk in these countries.

For significant hydrogen sources that may not be accommodated by mitigation means designed to cope with a DBA, the uncertainty is largely dominated by the unknown extent of Zr oxidation during the in-vessel core degradation phase. If the hydrogen production is generally well simulated during the first phase of the accident scenario – when the core geometry is still intact – there is still some lack of knowledge related to the late phase of the core degradation, especially regarding (U-Zr-O) melts and B_4C melts oxidation, and hydrogen production during late reflooding of the core. Experiments are performed to solve these problems.

Adequate prediction of hydrogen distribution within containments is of high importance since it is the basis to assess the risk of dynamic local phenomena. Lumped parameters codes could have shortcomings (release phase and strong stratifications) and CFD codes are not currently well validated. Scaling effect remains an important open issue in the containment analysis. Validation efforts are still needed to qualify heat transfer and turbulence models and to enhance the validation of CFD codes with regard to distribution phenomena.

A mitigation strategy only based on hydrogen recombination cannot always prevent the σ and eventually the 7λ criteria to be reached, notably in the vicinity of the hydrogen release location. Concerning hydrogen combustion, a reliable prediction of the potential occurrence of DDT or a fast deflagration is still not well possible. The σ and the 7λ criteria are often used, however, the validity of those criteria for strong hydrogen concentration gradients is limited. Moreover, as the σ criterion has been defined from small scale experiments in tubes, the criterion is not validated for complex geometries. Some uncertainties remain on:

- The temperature effects, mainly for rich mixtures, close to self ignition,
- The effect of complex shaped 3D cloud development in real buildings, which is different from most 1D type experiments,
- The effect of concentration gradients,
- The effect of venting, considering the nature of the boundaries of the critical hydrogen cloud which can be partly solid structures or partly gas and the effect of blockages and vortex generating structures.

Uncertainties associated with the definition of the cell size value of the lambda criteria still remain, in particular in case of complex and partly confined geometry. Furthermore, the validation of the lambda criteria for strong hydrogen concentration gradients is not complete. Further validation efforts are still required.

The hydrogen risk is not limited to fast combustion, and the loads generated by a slow combustion can also endanger directly or indirectly the containment integrity. Important validation work is still required to adapt the actual combustion CFD codes to the description of slow combustion in lean mixtures: until this work is done, neither the best-estimate nor the conservative assessment of the direct or indirect consequences of slow combustion can be ensured.

Very little data are available concerning combustion when the spray system is activated. Moreover, the CFD simulation of the effect of the spray remains an open issue with regard to hydrogen distribution and combustion.

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Annex I
EXPERIMENTAL FACILITIES TO INVESTIGATE HYDROGEN SOURCE

Several experiments were performed to investigate the hydrogen production due to in-vessel Zr clad oxidation:

- USA and Canada
  - Severe Fuel Damage (SFD) series in the Power Burst Facility,
  - DF-4 test in the Annular Core Research Reactor and the Full Length High Temperature (FLTH) series at the National Research Universal Reactor.
  - Loss-of-Fluid Test (LOFT) LP-FP-2 experiment also provided fundamental data on melt progression and hydrogen release.
- Germany
  - CORA series, including tests with either BWR or PWR control rods materials,
  - QUENCH tests, on going presently, dedicated to the hydrogen release during the core late reflooding.
- France
  - PHEBUS FP tests add to the validation matrix of the hydrogen production during the early and late phases (molten pool) of the core degradation.

All these tests apparatus are documented in different open publications from national or international institutions. Consequently, the selected experimental facilities quoted and used in the field of the in-vessel reflooding, which is presently a new field of R&D in the world, have been more detailed in this Annex than the other experimental test series.

I-1. Experimental facilities to investigate H_2 release from U-Zr-O alloys oxidation: SKODA-UJP Test Series

The objectives of these tests are to map the oxidation behaviour of selected U-Zr-O alloys under Ar/steam mixture between 300°C to 1500°C. The oxidation kinetic is determined by the on-line measurement, based on gas thermal conductivity, of the generated hydrogen produced during oxidation. These tests are conducted under the EC 5th PCRD frame, in the project named “COLOSS.”

I-2. Experimental facilities to investigate H_2 sources: the CORA Test Series

The objectives of the CORA series carried out in Germany, at Forschungszentrum Karlsruhe (FZK), between 1987 and 1993, were to investigate the early-phase core degradation in light water reactors (PWR, BWR and WWER designs). The series of 19 tests covered absorber behaviour, quench, the effect of heat-up rates, varying steam supply and initial pre-oxidation.

A fuel rod bundle of representative PWR, BWR or WWER design of overall length 2 m (heated length 1 m) is surrounded by a permanently installed high temperature shield. Decay heat is simulated by electrical heating with tungsten rods installed within the alternately-positioned heated rods. Coolant (superheated steam and argon) is injected laterally at the bottom of the heated section. Quench is simulated by raising a water filled cylinder around the rods. On-line measurements are made of temperatures, pressures, rod powers, hydrogen production, supplemented by video recordings of the melt progression. Comprehensive destructive post test examinations determine such quantities as blockage formation and material distribution.

Each test is conducted in 4 phases:

- Pre-heating in argon to about 600 K;
- Initiation of electrical heating and of steam injection;
- Raising of electric power to give an initial heat-up of 0.2–1.0 K/s, leading generally to an oxidation excursion, with relocation of control rod material and U/Zr/O melt and blockage formation (peak temperatures ~2200 K);
- Cooling in argon or quench by water, with power switched off. The transient phase typically lasts 1500–9000 s. The range of experimental conditions is surveyed in Table A-2.

From the main phenomena covered in the CORA series, hydrogen production may readily be deduced. Non-prototypic features such as the temperature dependence of the axial power distribution, the artificial axial stability afforded by the tungsten heaters, and the varying bypass flow, must be accounted for in interpreting the test results.

I-3. Experimental facilities to investigate H_2 sources during in-vessel reflooding: QUENCH Test Series

The general objective of the QUENCH programme carried out in Germany, at FZK, is to provide an extensive experimental database on quench of an overheated LWR core while in a mainly rod-like state, giving improved understanding of the effects of water addition at different stages of the rod degradation. More detailed aim is the determination of the hydrogen source term. The bundle experiments summarized here are supplemented by an extensive series of single rod quench experiments and by measurements of hydrogen absorption and release by Zr cladding. The main parameters so far considered are heat-up rate, degree of cladding pre-oxidation, flooding rate and temperature at the onset of quenching.

A fuel rod bundle of representative Western LWR design of overall length 2.5 m (heated length 1 m) is surrounded by a permanently installed high temperature shield. The fuel rod simulators contain sintered zirconia pellets. Decay heat is simulated by electrical heating with tungsten rods installed in all but the central rod of the 21 rod array. Superheated steam with argon as a carrier gas is injected at the bottom of the test section; the quench water (or cold steam) for cooling enters through a separate line at the bottom. On-line measurements are made of temperatures, pressures, rod powers, hydrogen production. The hydrogen produced is measured by two independent means (mass spectrometer and Caldos device). Comprehensive destructive post test examinations determine such quantities as extent of oxidation, crack patterns in oxide films, blockage formation and material distribution.

The test sequence consists of the following main phases:

- An initial heatup in steam/argon to about 1000 K until the bundle is stabilized;
- A second heatup and pre-oxidation phase (if required, typically at 1400–1600 K);
- A transient phase during which an uncontrolled oxidation excursion may occur;
- Finally a quench phase induced by reflooding the bundle from the bottom, or by injection of cold steam. When reflooding with water, water is injected at a high rate to fill the lower plenum rapidly, then the desired injection rate for the bundle section is applied.

Attention is paid to the consistency and accuracy of the H_2 source term measurements.

I-4. Analytical Tests done in FZK to support the QUENCH tests

An extensive programme of single rod quench tests is being carried out on pre-oxidized Zr single rod specimens at FZK (Karlsruhe, Germany), in support of the QUENCH test series and release of H_2 by metallic Zr. Both QUENCH and H_2 experimental programmes are accompanied by detailed modelling support from the Russian Academy of Sciences (IBRAE).

The main objectives are:

- Provision of an extensive experimental database for the development of detailed mechanistic models for quench of a degraded core in a rod-like geometry;
- Investigation of the physico-chemical behaviour of the overheated fuel elements under different flooding conditions;
- Examination of the behaviour of the cladding-cracking of the oxide layer results in oxidation of the new metallic surfaces and additional hydrogen production.

The main experimental parameters quantified are the extent of pre-oxidation and the temperature of the tube before cooldown.

The tube specimen of length 100 to 150 mm (either open or closed end), which may be filled with zirconia pellets, is suspended by a thin rod inside a quartz tube. The quartz tube is surrounded by an induction heating coil. Water quenching of the heated specimen is carried out by raising a water filled cylinder in a similar manner to that in the CORA facility, a valve prevents evaporation of the quench water before the quench phase. In an alternative configuration, cold steam is injected at the bottom of the facility in the cooldown phase.

The specimen is pre-oxidized in an argon/oxygen (20 vol.% 0_2) or an argon/steam mixture to the desired extent (up to 50% of the cladding wall thickness) at 1400°C in the QUENCH apparatus, raised or lowered to the test temperature (1000 to 1600°C) by heating inductively in argon, then quenched by raising the quench cylinder at 3 to 30 mm/s or cooled rapidly by injection of steam at up to 2 g/s at 150°C. The temperature of the specimen and the hydrogen production are continuously recorded. Video recording of the quench process is supplemented by post test metallographic and scanning electron microscope examination to establish the physico-chemical condition of the specimen, e.g. to determine how much cracking of the oxide film has taken place.

Correlation of the generated hydrogen with the physico-chemical state of the specimen before and after the test, with the test conditions, provides information concerning the dominant mechanisms occurring during the quench of oxidized Zr. Investigation of the cracking (fragmentation) of oxide films on quench, which leads to the exposure of fresh Zr metal surfaces, renewed rapid metal oxidation, temperature increase and strong hydrogen production, is of particular interest. Comparing the results of quenching specimens pre-oxidized in argon/oxygen and argon/steam gives insights into hydrogen absorption/release phenomena and their effects in quenching. Comparing results of water-quenched and steam cooled tests provides information on the influence of thermohydraulic conditions; in addition the thermohydraulic conditions in the steam cooled tests are more precisely defined.

I-5. Experimental facilities: PHEBUS SFD Test Series

Between 1986 and 1989, six Severe Fuel Damage (SFD) tests were conducted in the PHEBUS reactor at Cadarache, France. The objective of this programme was to investigate the early phase of core degradation using fresh fuel rods of representative 17×17 PWR design. In particular were investigated: Cladding oxidation with related H_2 generation and clad damage, chemical interactions between non-fuel materials (spacer grids, AIC control rod) and between fuel and cladding, melt relocation and core blockage, fuel rod oxidation and fragmentation under rapid cooling. Onset of solid debris bed formation was also observed.

The test train is located in a SFD loop crossing the central part of the PHEBUS driver core which supplies the nuclear power. The fuel rods were 1.3 m long with a central 0.8 m long fissile zone. The rods were held in place by two Inconel or Zr spacer grids. The test bundle is surrounded by an insulating zirconia shroud with an inner octagonal Zr liner. The outer pressure tube is cooled by an independent pressurized cooling circuit.

On-line measurements are made of temperatures (fuel centreline, cladding, shroud and coolant), coolant flow rates, pressures and hydrogen production. An important effort has been done to determine the power evolution and the axial power profile during the tests for intact and degraded geometries (measurement of the driver nuclear power, measurements and calculations of the coupling factor between the driver core and the bundle in various geometries, gross gamma scanning).

Post test examinations (PTE) of axial and radial sectioning of the bundle determined such quantities as clad oxidation, chemical interactions, blockage formation and material distribution.

In general, PHEBUS-SFD test sequences include the following phases:

- Pre-transient phase to reach nominal conditions for the driver reactor circuit and the cooling circuit of the pressure tube. Then, initial conditions are reached in the SFD circuit feed by steam or helium;

- Heat up phase of the transient raising the nuclear power and driving the gas injection (steam, helium or hydrogen) as foreseen in the test protocol;

- Final power shutdown and bundle cooldown in a gaseous atmosphere (either steam or helium);

- Post test destructive examinations of the bundle.

The piloting of both the gas flow injection and the nuclear power enabled different SFD conditions to be reached in order to favour, for each test, a limited number of degradation phenomena such as, in particular, H_2 production.

Non-prototypic features are common to small bundle tests such as unprototypical radial and axial power profiles. Unplanned design constraints induced uncertainties in the radial heat losses through the insulating porous zirconia shroud which have complicated the post test analyses.

I-6. Experimental facilities: PBF-SFD Test Series

Between 1982 and 1985, four severe fuel damage (SFD) tests were conducted in the power burst facility (PBF) at the Idaho National Engineering Laboratory. These four in-pile experiments were the first tests performed as part of an internationally sponsored light water reactor SFD research programme initiated by the US NRC.

The specific objectives of the PBF-SFD series of tests were to:

- Investigate fuel rod damage following severe cladding oxidation, melt relocation, and fuel rod fragmentation;

- Measure the release rates, transport, deposition of fission products;

- Determine the magnitude and timing of hydrogen generation;

- Determine the behaviour of irradiated fuel rods compared with fresh fuel rods and to evaluate the effects of control rods.

The PBF reactor consists of a driver core and a central flux trap contained in an open tank reactor vessel. An independent pressurized water coolant loop can provide a wide range of thermohydraulic conditions within the flux trap test space.

An in-pile tube fits in the central flux trap region to contain the test train assembly.

The PBF-SFD test trains were designed and built by the Pacific Northwest Laboratory and assembled at the INEL.

The fuel rods were 0.9 m long and representative of a 17×17 PWR design. The rods were arranged in a 6×6 square lattice, without the four corner rods. The rods were held in place by Inconel grid spacers. The test bundles were contained in an insulating zirconia shroud, sandwiched between inner and outer Zr walls.

The rods were cooled by a measured coolant flow (water/argon) into the bundle, which was boiled away by fission heat to produce steam. An independent flow cooled the outer shroud.

The test train was instrumented to measure fuel and control rod cladding and centreline temperatures, coolant temperatures, shroud temperatures, fuel and control rod internal pressure, and coolant flow rates and pressures. In addition, a fission product and hydrogen measurement system was also included. Post test examination (PTE) included gross gamma scanning, neutron tomography, and destructive sectioning.

In general, the PBF-SFD test sequences of operations include the following phases:

- Power calibration measurements;
- High power operation for fuel conditioning and long-lived fission product inventory generation;
- Shutdown;
- Low power operation to build up a short-lived fission product inventory;
- Coolant boildown;
- High temperature transient;
- Power shutdown and test assembly cooldown;
- Bundle storage;
- Post test bundle examination.

With reduced makeup flow to the test assembly, fission power ramp and the additional heat generated from metal/steam reactions, test section temperatures rose rapidly resulting in clad failure; Zr melting; fuel liquefaction; materials interaction; melt relocation; and the release of hydrogen, aerosols, and fission products.

The PBF-SFD tests were the first in-pile fuel damage tests, and they provided most of the early understanding of degraded core phenomena. The tests are mainly relevant for early phase melt progression phenomena.

The tests had substantial uncertainties in the steam boil-off rate and some unplanned features in some tests (for instance, breach of the shroud wall), which have complicated the post test analyses.

I-7. Experimental facilities: ACRR-DF test series

The ACRR-DF (damaged fuel) experiments, were performed for the US Nuclear Regulatory Commission like the ST experiments, were in-pile tests that made use of the ACRR central irradiation cavity to fission heat a fuelled test bundle. The tests were conducted in the period 1982 and 1989.

The objectives of the DF tests were to obtain quantified information on fuel damage processes as a function of the particular severe accident conditions. The severe fuel damage processes investigated included fuel heat-up in flowing steam, clad heating by oxidation with steam, hydrogen generation, fuel pellet attack by molten cladding material, metallic melt relocation and blockage formation, and the nature of the degradation of the fuel rod geometry.

The DF tests were carried out in the ACRR (Annular Core Research Reactor), a pool type reactor with a dry central irradiation cavity capable of driving experiments with fissionable material under steady state, pulse or programmed power transient mode.

The DF test bundles were fabricated of from 9 to 14 half metre long fresh UO_2 fuel rods. The rod bundle was contained within a flow channel made from low density zirconia fibre. The insulated assembly was housed within a steel pressure vessel and situated in the central irradiation cavity of the ACRR. Steam was fed into the bottom of the fuel bundle as the fuel rods were fission heated by the ACRR driver core. Fuel temperatures were measured with W/Re and Pt/Rh thermocouples, hydrogen generation was measured in the tests, and an end-on view of the damage process was provided by a video recording system.

A typical DF test would begin with a preheating period without steam addition, followed by a slow fission heated initiation period with steam being fed into the test bundle. The initial heatup rate was typically on the order of 1 to 2 K/s. As the bundle temperatures increased, the ACRR driver core power would be increased to maintain the desired 1 or 2 K/s heating rate.

When the bundle temperatures increased above about 1700 K, a localized temperature escalation due to rapid Zr oxidation would typically be seen. This escalation would exhibit a heat-up rate on the order of 10 to 20 K/s. Clad melting followed rapidly with melt relocation and blockage formation. Test termination would follow soon after melt relocation had been detected. Following completion of the experiment, the test bundle would be stabilized with epoxy and examined both by radiography and by destructive metallurgical examination.

The processes quantified in the DF experiments include cladding oxidation behaviour, hydrogen generation, fuel pellet erosion by molten cladding, blockage formation by relocating molten metallic and metallo-ceramic materials, and the degree of degradation of the fuel rods.

As with most in-pile tests, all of the DF tests had some unplanned features which complicated post test analysis (for example, test DF-1 experienced condensation of steam within the test section, which later revaporized, causing uncertainties in the knowledge of the steam flow rate for the test).

I-8. Experimental facilities: NRU-FLHT Test Series

Between 1985 and 1987, four full length high temperature (FLHT) tests of the coolant boilaway and damage progression (CBDP) programme were conducted by PNL in the NRU reactor at Atomic Energy of Canada Ltd. (AECL) Chalk River using highly instrumented and insulated assemblies of 12 full length (3.7 m) light water reactor (LWR) fuel rods. The objectives of the CBDP programme were to:

- Obtain data for evaluating the effects of coolant boilaway and core damage progression in an LWR;
- Iinvestigate integral severe accident phenomena along a full length bundle.

The FLHT test hardware consists of the following four components plus the NRU reactor: test train assembly, steam closure cave (SCC), effluent control module (ECM), and a data acquisition and control system (DACS).

The FLHT test operations include up to five phases:

- Pretest installations and checkout with reactor at zero power;
- Commissioning and calibration with reactor at zero power;
- Reconditioning operation (FLHT-4 and –5 only) with reactor at full power;
- Coolant boilaway/severe damage transient with reactor at constant 5% of full power;
- St test examinations.

The planned operation of the boil away includes bringing the reactor to low power (~5% of full power) with 1 kg/s bypass flow and 0.13 kg/s bundle coolant flow. After calorimetry and stabilization at 23 kW or 30 kW bundle nuclear power, the plenum section is drained and heated, and the assembly inlet flow is reduced to 9.4 g/s to arrive at a steady-state dryout front position ~0.7 m below the top of the fuel column. The bundle calorimetry and plenum drain/heat-up operations are pre-transient operations that are conducted before the boilaway transient.

The coolant boilaway is started by making a rapid reduction in the bundle inlet flow to ~1.3 g/s. The hold time from the first attainment of cladding melt temperatures (2100 K) to the termination of the experiment varies from test to test.

The four FLHT tests have contributed data on SFD behaviour due to a dynamically changing coolant level with full length fuel and a constant fission power level, although most of the bundle degradation occurred with a constant water level from make-up flow. All the tests have resulted in extensive and severe fuel rod damage, with the severity and extent of the damage increasing with each subsequent test.

The relatively large radial heat losses from the test section are non-prototypic and may affect the melt relocation, refreezing, and remelting.

I-9. LOFT LP-FP Test Series

The Loss of Fluid Test Facility (LOFT) was first conceived by the USAEC in 1962. Following the completion of the facility in 1976, a series of thermohydraulic -type tests was carried out under the sponsorship of the USNRC, to study large and small break accidents. The TMI-2 accident strongly stimulated additional research, especially on processes occurring in severely damaged cores. As a consequence, the OECD/NEA called for a new cooperative LOFT Project, which started in 1983. The technical programme was agreed to include 8 experiments. The first 6 were devoted to thermohydraulic issues, and the remaining two included damage to the fuel and releases of fission products. These last two tests were named the LP-FP series, and their specific objectives were:

- Perform integral tests to study PWR core behaviour during LOCA-type sequences with delayed operation of the ECCS;
- Make tests as prototypic as possible, simulating actual sequences in a PWR scale model, and including all phases expected during the accident: reactor scram, fuel heatup, fuel damage, and recovery by ECC initiation;
- Attain fuel temperatures high enough to produce fuel damage and fission product inventory release.

Facility description

The LOFT facility was essentially a small PWR with a thermal output of 50 MW. The active nuclear height was 1.7 m, which is half that used in commercial plants. The facility was designed to model a Westinghouse plant, with 4 loops, on a volumetric scale of approximately 1/50 (the vertical scale for the fuel being 1/2.2).

The standard configuration of the LOFT system provides for the simulation of a large LOCA.

The single intact loop, comprising circulating pumps, steam generator, pressurizer and connecting pipe work, represents the 3 intact loops of a commercial plant. The broken loop is fitted with two quick opening valves which provide flow path for escaping coolant equivalent to the two exposed ends of a broken pipe. The fluid escaping through the quick opening valves is conducted to the burst suppression tank which simulates the containment of a full sized plant. LOFT was provided also with a scaled version of the ECCS. The standard LOFT configuration was changed for the second LP-FP test. The broken loop was removed and a blowdown line was connected to the hot leg, and discharged into a suppression vessel. The blowdown line was to simulate the discharge through a break in the LPIS.

The standard central assembly of the LOFT core consisted of a 15×15 array of Zr clad fuel pins with dimensions corresponding to those in common commercial use. The core and particularly the central assembly were highly instrumented with nuclear flux detectors and thermocouples of various types.

The objectives of the FP-02 test would inevitably lead to very severe fuel damage, and it was obviously necessary to restrict the high temperatures to the interior of the assembly. The design was based on an 11×11 array of test fuel pins surrounded by a 25.4 mm thick heat resisting shroud. The shroud consisted of zirconia tiles within a Zr cladding. The assembly contained 100 pressurized fuel rods (enriched to 9.744% U235) and 21 Zr guide tubes, 11 of which contained stainless steel clad control rods.

LP-FP-2 Test Description

The pre-irradiation phase allowed the fuel to attain a mean burnup of approximately 420 MWd/tU. The test was initiated by scramming the control rods, and turning off the reactor coolant pumps. The LPIS line discharge was opened, and the fuel temperatures rose and passed 2100 K at 25 min. The experiment was terminated 4.5 min afterwards by initiating the ECCS. This quenched the fuel surfaces, but the central molten region took several hundred seconds to cool.

The LP-FP-02 test attained high temperatures. It was an integral test, in which many processes involved in early and late phase PWR core degradation were present.

I-10. PHEBUS FP (bundle aspect only)

The PHEBUS FP programme is led by the IRSN and the Commission of the European Communities with international participation from USNRC, COG, NUPEC, JAERI, KAERI, HSK and PSI.

The objective is to investigate the main phenomena governing degradation of fuel as well as fission product release, transport and behaviour in the containment during a beyond design basis accident occurring in a light water reactor. The scope involves release of FPs from degraded irradiated fuel as well as FP/aerosol physics and chemistry both in the primary circuit and in the containment building. The bundle aspect involves the late phase of core degradation up to the fuel melting with the related FP release (volatiles and non-volatiles).

These tests will enable investigation of specific phenomena not observed in the previous PHEBUS SFD programme: simultaneous Zr oxidation escalation melting interaction with UO2 in an oxidizing environment, effect of control rod materials (Ag-In-Cd or B4C), chemical interactions at high temperature, solid debris bed evolution up to molten pool formation, and UO2 oxidation by steam and air.

The first three tests of the programme, FPT0, FPT1 and FPT4, were performed in December 1993, July 1996 and July 1999 respectively in the Phebus reactor at Cadarache, France.

The test train is located in a loop crossing the central part of the Phebus driver core which supplies the nuclear power. In tests FPT0, FPT1, FPT2 and FPT3 the fuel rods are 1.13 m long with a 1 m long fissile zone, are held in place by two Zr spacer grids and are arranged in a 5×5 square lattice without the four corner rods. The absorber rod in the centre of the bundle contains Ag-In-Cd in the first three of these tests and B4C in FPT3. Only the first test FPT0 was performed using trace-irradiated fuel. For the rest of the matrix, irradiated fuel rods (~ 23 GWd/tU to 33 GWd/tU) are used.

The test bundle is surrounded by an insulating zirconia shroud with an inner circular ZrO2 or ThO2 layer, an external ZrO2 layer and a pressure tube of Inconel coated on the internal face by flame-sprayed dense ZrO2. These three annular structures are separated by two gaps under cold conditions. The outer pressure tube is cooled by an independent pressurized cooling circuit. The rods are cooled by a measured gaseous flow of steam imposed at the entrance.

The FPT4 test uses a debris bed configuration (0.36 m height) with two parts: passive (0.12 m height) and active UO2 including ZrO2 fragments (0.24 m height).

Measurements in the bundle involve mainly temperatures: fuel centreline and cladding (for fresh fuel rods), control rod, stiffeners, shroud and coolant. After failure of the rod thermocouples, the bundle temperature is controlled by shroud thermocouples located inside and on the outer surface of the external ZrO2 insulating layer. It is expected that two ultrasonic thermometers would enable improved control of bundle temperatures at different levels. These tests are foreseen with 18 rods with intermediate burn-up (no thermocouples) and 2 fresh fuel rods to enable the implementing of some rod thermocouples allowing a direct measurement of fuel temperature. Coolant flow rates, hydrogen production and FP are measured in the circuit. In particular, an on-line aerosol monitor device enables the detection of major events of the core degradation. The measurement system for the power of the driver core and fission chambers located around the bundle can also detect significant core material relocation events.

Measurements in the debris bed FPT4 test involve mainly temperatures in the fuel, shroud and coolant. After failure of the fuel thermocouples, the temperature is controlled by shroud TCs located inside and on the outer surface of the external ZrO_2 insulating layer. It is expected that several ultrasonic thermometers installed in this test would enable control of the debris bed temperature at different levels.

Gamma scanning examinations of some fission products and activation products of bundle structures enable the mean axial profiles of fuel and control rod mixtures to be measured. In addition, a large set of tomographies are performed enabling a rapid and precise overview of the bundle degradation and of the final axial distribution of bundle materials on the basis of their densities. Final destructive examinations enable cross and axial cuttings for more detailed quantification of the bundle degradation.

The test sequence of operations for the tests FPT0, FPT1 and FPT2 are similar:

- Pre test bundle examinations;

- Irradiation phase for producing short-lived FPs. This phase lasted 9 days with a bundle power around 230 kW for FPT0, and about 7 days with a power ranging from 180 to 230 kW for FPT1;

- Shutdown;

- Preparation phase for the transient (34 hours for FPT0) with measurement of the coupling factor between the experimental bundle and the driver core;

- Pre-transient phase with different temperature plateaux for thermal calibration of the bundle;

- Transient phase with nuclear power increase;

- Final coolant phase with a shutdown and a moderate steam cooling;

- Post test bundle examinations.

The test sequence of operations for FPT4 is quite different:

- Pre test bundle examinations;

- Measurement of the coupling factor between the experimental debris bed and the driver core by a calorimetric method;

- Pre-transient phase with different temperature plateaux for thermal calibration of the debris bed;
- Transient phase with nuclear power increase (successive power plateaux);
- Final coolant phase with a shutdown and a moderate steam cooling;
- Post test bundle examinations.

The heat-up phase of FPT0 was characterized by a sharp clad oxidation escalation (10K/s) with peak temperatures as high as 2700 K. After oxidation, the further power increase and gas flow rate reduction enabled fuel temperatures greater than 2300 K to be achieved. Different large fuel relocation events were identified on-line by various measurements, in particular by the on line aerosol monitor device. The radiography and the 52 tomograms of the final state of the bundle showed a severe core degradation far beyond any previous experiment.

The fuel degradation during the heat-up phase following the oxidation runaway was characterized by a step by step slumping down of the fuel located in between the two spacer grids, involving almost all the inner rods and part of the outer ones. This happened at a temperature of about 2500 K, far below the urania melting point. The relocation led to the formation of a molten pool on the lower grid. A final relocation of the molten material below the lower grid was observed just at the end of the experiment.

It is clear that FPT0 degradation results concern the transition from the early phase to the late phase of core degradation. In addition FP release and aerosol production were found to be significantly affected by the core material interactions and core degradation events which appear to be at least as important as the fuel temperature itself.

The second test, FPT1, with irradiated fuel was performed with similar bundle conditions regarding the temperature and the atmosphere evolution. A similar degradation pattern was observed, with early fuel slumping down. Fuel swelling of irradiated fuel (243 GWd/tU) was observed. The mass in the molten pool was lower than in FPT0, due to earlier termination of the experiment. Non-destructive post test examinations (more than 400 tomograms) allowed a 3D reconstruction of the damaged fuel bundle. Destructive post test examinations are still in progress.

For the third test FPT4, indications are that a large molten pool formed below the debris mid plane, with a large cavity at bed mid-height and probably a vault on top of the bed. Further data will emerge in due course.

Annex II
EXPERIMENTAL FACILITIES TO MEASURE HYDROGEN DISTRIBUTION

II-1. HDR test facility in Germany

Regarding hydrogen distribution, in the HDR facility in Grosswelzheim, Germany, the blow down experiment T31.5 and the hydrogen distribution experiments E11 were performed. The test facility was a former prototype plant.

The decommissioned HDR containment is, with 11,300 m^3 free volume and a typical PWR total height, the largest scale and is often considered the most representative experimental facility, although the large number of sub-compartments and the large height to-diameter aspect ratio differ significantly from PWR containments. It is well instrumented but complex in internal layout with concrete and steel structures. Figsures II-1 and II-2 reveal the two major flow paths, namely the left hand side spiral staircase and the right hand side staircase, both connecting to the large (5000 m^2) dome region.

The LBLOCA blow down experiment T31.5 was performed in the HDR Facility in December 1987 and was subjected to code comparisons as ISP 23 [II-1]. It represents the transition from the short term, DBA related focus on peak and differential pressures to long term, severe-accident issues of natural convection, cooling and gas distribution and, as such, constitutes a milestone in terms of hydrogen distribution experiments. A review of previous hydrogen distribution experiments [II-2] concluded that the combination of important issues controlling the hydrogen distribution mechanisms is:

- Sufficiently large scale of the experimental facility with multiple compartments and a large dome volume;
- Multiple steam and hydrogen releases at different elevations with high hydrogen release rates;
- Condensing vapor environment;
- Efficiency of mitigation measures.

II-2. NUPEC test facility in Japan

The NUPEC model containment at the Tadotsu Engineering Laboratory [II-3], consists of a one-quarter linearly scaled PWR dry, insulated steel containment vessel with a free volume of 1300 m^3. It has 25 subcompartments, separated by steel partitions, including a large dome with 70% of the total free volume and an internal containment spray system, reflecting a simplified four loop Japanese PWR containment.

The purpose of the hydrogen mixing and distribution test, part of the programme to evaluate containment integrity, was to investigate hydrogen distribution phenomena in a model containment and to validate analysis codes. The main characteristic of test M-7-1 was a direct containment spray cooling during steam and light gas injection. For safety reasons, helium gas was used as a hydrogen simulant. The main items of study in the test were natural-convection effects, effect of steam release and spray water, and effects of break and sensor locations.

The test parameters were based on scaling considerations as follows:

- Total helium volume was scaled by containment volume (1/64) from the quantity of hydrogen released because of the 100% Zr-H2O reaction in a four loop Japanese PWR.

- Helium and steam release rates were scaled by containment volume (1/64) of actual release rates. The release rate profiles were stylized: The helium flow was ramped from 0 to 30 g/s over 15 min and back to 0 over another 15 min for a total release of 27 kg; the initial steam flow was 0.08 kg/s, decreasing to 0.03 kg/s at 30 min for a total release of 99 kg.

- Spray water release rate was scaled by area (1/16), not by volume, from the actual release rate in a four loop Japanese PWR. A constant flow rate of 70 m^3/h (19.4 kg/s) was used over 30 min. Spray nozzles were of the same type as those used in the real containment.

Measurements of gas concentration (29 locations, typically at the centre of each compartment, but five locations in the dome (four across a horizontal plane and one above), using gas chromatography), temperatures (34 within compartments and 146 on structures, using thermocouples), and inter-compartment flow rates (10 locations, using hot-wire wind gauges) were detailed and – except for the flowmeters – were well suited for lumped or distributed parameter analysis. Measurement uncertainties consist mainly of random instrument errors because systematic errors (biases) are believed to be removed by the calibrations conducted before each experiment. The standard deviations of the measurements are 0.2°C for temperatures and 1079 Pa for dome pressure. The standard deviation for helium concentration is 1% of the measured value plus 0.002 vol.%, based on dry laboratory calibration; the steam volume error must be considered in addition to derive the total helium concentration error in the containment vessel. Mass and energy balances were documented and showed good agreement between measured and calculated (based on inlet flows) values [II-4].

In M-7-1 after a long steam preheating phase, which heated the containment vessel to 70°C, the 30 min steam–helium and simultaneous water spray injection was conducted and measurements were taken until 120 min. Because well mixed conditions were quickly obtained after the 30 min steam–helium and simultaneous water spray injection, the test phase of interest was only about 40 min in test M-7-1. All measurements and modelling results in ISP 35 were presented for this 40 min time frame [II-8]. This is a rather short time period in view of severe accident scenarios, compared to the HDR tests, resulting from the use of steel internal structures (short term heat sinks) rather than the concrete structures (long term heat sinks) predominant in the HDR and Battelle Model Containment (BMC) facilities.

Higher helium concentration during the release period is always well mixed with the remainder of the containment including the large dome. Immediately after the release, all rooms come to the same concentration of about 13%.

NUPEC tests M-4-3, M-8-1, and M-8-2 [II-3, II-6] were performed to complement M-7-1 test and thus had similar operating parameters, with distinct differences. The objective of test M-4-3 was to investigate the mixing effect of hot gas and steam being injected at a low elevation in the absence of internal spray cooling [II-3]. The helium concentration is slightly higher in the release room and in the two downstream compartments, similar to the helium concentration in test M-7-1, during the release period. The remainder of the containment slowly becomes well mixed during the injection period, except for the three dead-end compartments CV 1, 16 and 22, which exhibit very low helium concentrations.

The objective of M-8-2 was to investigate how a spray system improves mixing characteristics and whether helium stratification can be prevented, even if the gas and steam are injected from a high elevation point. The only difference in test M-7-1 was the gas injection position. The gas injection position of test M-7-1 was the SG base compartment CV 8 (lower compartment) and that of M-8-2 was the upper part of the pressurizer (upper compartment). Compared with test M-8-1, the key difference of test M-8-2 was the spray system actuation and a much lower steam injection rate.

II-3. Battelle Model Containment

The Battelle Model Containment (BMC) was built as a nearly 1:100 model of a PWR containment to study the impact of blow downs after LBLOCA to the building. Although the PWR Containments which were the basis for its design are steel containments it was a concrete building.

From all tests carried out in this facility the long term hydrogen mixing experiments (bibles tests), the VANAM tests M2 and M3 and the F2 test are described here.

The long term mixing experiments were performed in the Battelle Model Containment as verification experiments on hydrogen mixing by inherent natural convection in the short and long term (up to 100 d) after a large break LOCA in the Biblis reactor [II-7]. The goal of these experiments was to demonstrate the initiation and stability of an overall natural-convection circulation under conditions of adverse temperature stratification conditions (short term) and small favorable temperature differences (long term). The Biblis containment is represented by the rotationally symmetric BMC, with an inner region consisting of a sump and a vertical chain of rooms, open to the dome region, and an outer annular region, also open to the dome and connected to the inner region by relatively restrictive openings near the floor.

Temperature and velocity measurements were performed along the proposed circulation loop, in addition to concentration measurements of injected hydrogen, to determine the convective flows in two different test conditions.

In the short term phase, an initial adverse temperature stratification exists, caused by preferential heatup of the upper regions of containment from the break, which was generated in the BMC experiments. Hydrogen measurements show that good mixing is nevertheless obtained after about 30 min after each hydrogen injection phase. During the hydrogen releases the sump temperature is above the atmospheric temperature; thus a combination of sump evaporation and the buoyancy of the injected hydrogen itself would contribute to an overall circulation with upflow in the centre and downflow in the annulus. Therefore, one cannot really talk about an ‘adverse temperature gradient’ during the hydrogen injection phases. Velocities in this test were below the sensitivity of the turbine flowmeters.

In the long term phase (several days after the LOCA) the atmospheric temperature is cooler than the sump temperature because of heat removal by the concrete structures. Clearly, the relatively high sump temperature drives a fast and effective convection (0.6 to 0.8 m/s), which mixes the injected hydrogen almost instantly, despite the small (1 to 3 K) temperature difference between the centre and annular region. Peaks observed in the velocity measurements correspond to the hydrogen injection periods, showing the beneficial effect of the added buoyancy on the convective flow. Excellent radial symmetry is maintained in these tests. Although one might question the representation of actual short- and long term (100 h) conditions of a severe accident in these relatively short experiments, these tests provide useful data for assessing hydrogen distribution under a range of boundary conditions. It is expected that the simultaneous measurements of concentration, temperature and flow velocity in the long term test, along with the well-known characteristics of the facility, would prove useful for code validation, provided original detailed data can be made available.

Besides distribution tests, coupled thermohydraulic and aerosol tests were performed.VANAM M3 experiment was primarily an aerosol test, it also included thermohydraulic aspects and is, therefore, included here. The VANAM M3 test deals with containment thermohydraulics and aerosol behaviour with steam and aerosol release into the containment focusing on an unmitigated severe LWR accident with core meltdown. The containment and aerosol behaviour experiment, VANAM M3, was selected as an experimental comparison basis for ISP37. The main phenomena investigated are the thermal behaviour of a multi-compartment containment, e.g. pressure, temperature and the distribution and depletion of a soluble aerosol.

Through steam and aerosol injection lines (cavity R3 and pressurizer compartment R5), the atmospheric conditions were adjusted to attempt to simulate the selected severe accident sequence with pressurizer relief valve discharge. However, to compensate for the large leakage rate of the BMC Facility (>100% per day), air injections during several phases of the experiment led to reactor untypical conditions.

Nevertheless, this experiment provides data for the following processes:

- Long term natural convection;
- Changes in natural convection flows and amplitude caused by cooldown processes and different injection locations;
- Thermal stratification, atmospheric saturation, and superheating;
- Redistribution of non-condensable gases;
- Heat transfer at different elevations, local condensation effects;
- Sump temperature and depth;
- Dry and wet aerosol multicompartment distribution and depletion.

The experiment may be subdivided into six phases:

- 17 h facility heatup phase with steam injection into pressurizer compartment R5, keeping

- Pressure at a nominal value of 125 kPa;
- First NaOH aerosol release phase of 1 h into pressurizer compartment R5;
- 4.5 h dry aerosol depletion phase;
- Second aerosol release phase of 0.44 h into pressurizer compartment R5;
- 2 h mixing phase by steam injection into cavity R3 with wet aerosol depletion;
- 5 h wet depletion phase with steam injection into pressurizer compartment R5.

A comprehensive measurement system recorded the time histories of pressure, temperature distribution, humidity, sump level, atmospheric flow velocity, local aerosol concentration and depletion and aerosol size. In addition, from specific measurements, local wall heat transfer coefficients can be determined.

The VANAM M2 experiment [II-8, II-9] needs to be mentioned in addition to VANAM M3 because it differs in the compartment connections and the pressure level during the heat up phase. The data provided are for the same processes as in the block of tests M2*, M3 and M4. Test M3 differs in geometry:

The phases of test VANAM M2 are as follows:

- 6.5 h heatup to 250 kPa by injection of steam into pressurizer compartment R5,
- 0.5 h cooldown to 200 kPa without any injection,
- 6.5 h heatup by steam injection, pressure kept at 200 kPa;
- 50 min aerosol release phase coupled with hot air injection into pressurizer compartment R5;
- 4 h aerosol depletion and natural cool down phase;
- 2 h mixing phase by steam injection into pressurizer compartment R3 with wet aerosol depletion;
- 4 h steam injection into pressurizer compartment R5 with wet aerosol depletion.

Together, experiments VANAM M2 and M3 give a good opportunity to compare analytical models that describe the formation of convection loops with measured results.

The BMC Test F2 was used for a CEC thermohydraulic benchmark. The selected experiment, F2 provides data for a broad spectrum of ‘generic’ (not accident specific) thermohydraulic conditions.

Phase 1 of the experiment (0 to 48 h) addressed the long term heatup phase [II-13], and phases 2 to 4 (48 to 75 h) [II-11 – II-13] are of more interest in the context of this report because they provide detailed data for the following parameter, in a loop-type multicompartment configuration:

- Long term natural convection: onset and stagnation;
- Changes in natural convection flow direction and amplitude;
- Thermal stratification, atmospheric saturation and superheat;
- redistribution of non-condensable gases;
- Heat transfer at different elevations, local condensation effects;
- Sump temperature and depth.

Relevant experimental conclusions are summarized in Ref. [II-12]:

- Large scale mixing can be effected by natural convection, provided a suitable geometry of walls and openings and a steam or dry heat source in the lower part of such a geometry exists. Even if these conditions are fulfilled, stagnation periods without distinct convection can occur.
- Fluid injection can lead to either homogeneous or stable inhomogeneous conditions.
- Steam condensation on structures can – in the long term – result in very distinct local accumulation of air and other non-condensables (e.g. hydrogen).
- Depending on the density difference between injected and existing steam–air mixtures, and on the elevations of compartments and vent openings, the following behaviours were observed and are summarized: (1) A dense steam air mixture (i.e. with high air content), injected into a low-elevation compartment ‘fills up’ the injection compartment and the adjacent low-elevation compartments almost completely, whereas the lighter atmosphere is displaced upward. (2) A low-density mixture injected at the same site tends to immediately escape upward into higher-elevation compartments and to slowly entrain the original atmosphere from the injection compartment.
- Only zones participating in a large scale convection loop show an approximately uniform steam air distribution. In stagnation zones, separated by partitions or stratification phenomena, different compositions can develop, as observed in the annulus compartment, because of (1) the injection and ‘fill-up’ process, described above, or (2) air and gas accumulation resulting from steam condensation. (Former BMC tests demonstrated that this effect can even produce slight stratification in a single-volume geometry within a period of a few hours without steam injection, after a long homogenization phase.)

An interesting result regarding leakage flows is that steam component of leakage flow has to be neglected in the modelling of experiments because its energy is not released into the environment but into the containment wall.

II-4. VICTORIA gas mixing experiments—ice condenser containment circulation

The VICTORIA facility was constructed at the IVO Hydraulic Laboratory in Finland for studying ice containment thermohydraulics during SBLOCAs and severe accidents [II-14 – II-16]. An important goal was to support development of a new hydrogen management strategy for the Loviisa NPP (a WWER-440 reactor with ice condenser containment) in Finland.

The facility is a scale model of the Loviisa ice condenser containment, with a linear scaling factor of 1/15. The height of the vessel is thus 4.6 m and the diameter is 3.14 m.

The free volume of the vessel is approximately 21 m^3. The vessel was designed to withstand an overpressure of 2 bar(g) (1 bar = 100 kPa). The model and the Loviisa ice condenser containments are geometrically similar. Concrete structures of the containment are also made of concrete in the scale model. All the large steel equipment inside the containment – i.e. primary circuit piping, steam generators, pressurizer, and pressure vessel – is modeled as dummy elements in the model compartment. The Loviisa ice condenser containment is a double containment in which the pressure boundary of the containment is the free-standing cylindrical pressure vessel with a dome inside the secondary containment. In the experimental vessel, the secondary containment is the pressure boundary. The model containment was insulated from all sides to minimize heat losses to the environment.

One could select from six different release locations when simulating the energy and gas release into the lower compartment. Steam, water, and helium were released through a common adjustable nozzle. The ice condenser was built so that one of the ice condenser sections at a time could be moved into or out from the model. Ice condenser lower inlet, intermediate deck, and top deck doors and bypasses are modeled. The containment internal and external spray systems were also modeled.

The external spray system is the long term residual heat removal system in a severe accident, cooling the containment through the dome steel shell.

Temperatures were measured inside the vessel at about 300 points (in air space, structures and ice condensers). Relative humidities were measured at 10 different locations. Total pressure, pressure differences between compartments, and water level height were also measured.

Helium was used as a hydrogen simulant. Helium concentrations in the VICTORIA vessel were measured using a new technique, an instrument called SPARTA (spark transient analyzer). The method being applied in SPARTA is based on emission spectroscopy, where a high-voltage spark is created between two electrodes in a gas mixture. The instrument and its different modes of operation are described in detail in Ref. [II-17]. Some applications and sampling arrangements are described in Refs [II-18, II-19]. In most experiments, helium concentrations were measured at 10 different locations. Local vertical flow velocities were measured at the ice condenser outlets in the upper compartment with a fibre optic laser Doppler anemometer system.

The experimental programme consisted of three phases. In the first test phase in 1990–1992, ice condenser thermohydraulics and ice melting behaviour in SBLOCA scenarios were studied. The second test phase (1993) consisted of experiments for validation of containment dome external spraying heat transfer models. The third test phase, in 1994–1995, dealt with experiments designed to support hydrogen management strategy development for Loviisa (convective loop flow experiments and hydrogen distribution experiments). Of particular interest were the global convective flow patterns in the containment, as a consequence of forcing open the ice condenser doors during the experiment, and the helium transport and mixing under these flow conditions.

Findings from the third phase are discussed in Refs [II-20, II-21]. The experiments indicated that a global convective loop flow developed (with forced-open ice condenser doors), with one ice condenser in upflow and the other one in downflow, even with an initially symmetric ice configuration. This circulation loop tended to be quite effective in mixing the injected helium with volumes participating in the circulation. Mixing above the ice condenser outlet level in the upper compartment was seen to be very effective in all experiments. This well mixed region corresponded to about half of the upper compartment volume.

II-5. The TOSQAN test facility

II-5.1. Geometry

Description of the vessel

The TOSQAN enclosure is a cylindrical chamber of stainless steel and a sump [II-22]. The total internal volume (including the sump) is 7.0 m^3.

The whole wall is thermostatically controlled, being made of double shield of stainless steel, within which circulates the heat-transport fluid (mineral oil). The envelope is divided into two zones, in order to fix two different values of the wall temperature.

The top and bottom (including sump) parts of the vessel have the same temperature, called the ‘hot temperature’. On the middle zone, which constitutes the condensation zone, we impose a different temperature, called the ‘cold temperature’ or the temperature of the ‘cold wall’.

The windows

The enclosure is fitted with a total of 14 windows made each of 2 silica glasses (each is 35 mm thick), required for concentration and velocity measurements by laser diagnostics. Hot air flows inside each window to avoid condensation on its inner surface. A special coating has been put on each window to avoid light reflection. Two windows allow parallel to-wall measurements. The sump of TOSQAN also has two similar windows.

The air flows first in the lower windows and goes up in the others at a flow rate of 200 Nm^3/h. The inlet air temperature in the first window is 200 °C, and the outlet air temperature out of the last window is 100 °C. Most part of the energy added by this air flow goes out, because the temperature outside of the vessel is around 30 °C.

The inlets and outlets of the vessel

The injection tube comes from the side in the vessel, and after a 90° turn is directed towards the top of the vessel in the center of it. The injection tube enters in the vessel at height z = 1.55 m, and q = 45° on the south-west side. Its internal diameter is 41 mm. The tube is totally empty, and contains no particular device for velocity profile or turbulence. Its end is also simply cut perpendicularly to its axis. The steel thickness of the tube is 4.5 mm.

All gases are injected through this tube: steam, air, and helium. The condensed water is collected at the bottom of the condensing area, and flows in a small heated vessel connected to the TOSQAN vessel. Two exhaust pipes are connected to the vessel, at the top and the bottom. These are closed during the tests.

The leak rate of the vessel is less than 0.05 bar/hour at 6 bars pressure with around 80% steam 20% air gas mixture.

II-5.2. Processes of the facility

The windows are heated by a constant flow of inlet air.

All the injected gases, steam, air and helium, are heated before injection. The injection temperature, which depends on the gas and the pressure in the vessel, is measured just at the outlet of the pipe.

The steam is produced by a 100 KW boiler at 8 bars, and is injected into the vessel through a electrically heated pipe (from the boiler to the vessel). The steam flowrate is imposed through the aperture of a regulation valve on this line.

We impose two different oil temperatures (‘hot’ and ‘cold’), with constant flow rates.

The circumference of each part of the vessel is divided into 8 vertical identical and independent sectors, inside which the oil flows from bottom to top. In each sector the oil flows upwards in horizontal zigzags. The oil in the walls flows actually in elementary channels of rectangular section. This device insures the same temperature of the walls along the circumference at each height of the vessel. The wall temperature may vary with Z (vertical direction) only in one case: when the condensed mass flux is high (Qinj steam= 12 g/s), and only in the ‘cold’ wall, where in this case the oil temperature at the outlet of the cold wall is around 2°C higher than at the inlet of the cold wall.

II-6. The ThAI test facility

The ThAI Test facility is a downscaled containment test facility located at Eschborn, Germany. It is operated by Becker Technologies GmbH under the sponsorship of the German Federal Ministry of Economy and Labour (BMWA).

The main component of the facility is a cylindrical steel vessel 9.2 m high and 3.2 m in diameter. The total volume is 60 m^3. A sump is attached at the lower end.

The vessel space is compartmented by an open inner cylinder and a horizontal separation plane in the annular region with vent openings. The internal structures are removable. The outer cylindrical wall has cooling/heating jackets subdivided into three vertical sections. The entire vessel is thermally insulated.

The facility was designed to perform investigations of thermohydraulic processes in the atmosphere of a water reactor containment building during postulated accident transients. The behaviour of fission products (iodine and aerosols) can also be investigated. ThAI is an acronym for **Th**ermohydraulics, **I**odine and **A**erosols. The test vessel is located in a radiation control zone in order to permit experiments with radioactive iodine tracer material. The thickness of the vessel walls (e.g. 22 mm in the cylindrical part) provides a level of radiation shielding and at the same time an enhanced design pressure limit of 14 bar at 180°C temperature. This allows covering most thermohydraulic conditions that are expected to occur in a typical reactor containment.

ThAI can be characterized as a coupled-effects test facility. It allows investigating natural convection and atmosphere stratification, heat exchange with solid structures, heat conduction and storage in solid structures, as well as steam condensation on walls and in the atmosphere, and the transport of condensed water. The dynamics of the thermohydraulic processes is basically transient, the time evolution being governed by the thermal inertia of the heat exchanging structures. Thermohydraulic couplings of this kind are considered to dominate the transient evolution in the reactor containment as well.

The complexity of the ThAI experimental arrangement leads to complicated distributions of atmospheric flow and temperature. The instrumentation and the density of measurement transducers have been chosen to give information on the dominating features of these distributions. As compared to typical separate-effects experiments, instrumentation density is reduced locally. On the other hand, a total of 265 on-line measurement transducers are applied, giving a wealth of information relevant for validating numerical simulation models. So, the coupled-effects experiment does not include or replace separate-effects experiments but provides a complementary data set which is more directed towards coupling phenomena. It represents an important intermediate step between the separate-effects test and the prototypical conditions. Code validation could be done on each of these steps.

II-7. The PANDA test facility

PANDA is a large scale thermohydraulic test facility located at the Paul Scherrer Institut (PSI), Villigen, Switzerland. PANDA was initially designed for investigating LWR system behaviour and containment phenomena. The facility was first used to study passive decay heat removal system and containment response of the Simplified Boiling Water Reactor designed by General Electric. The scaling was 1:25 for volume, horizontal area, power (on decay heat level) and flow rates. Full vertical height is preserved and the same fluids were used. The complex containment compartments are simulated with interconnected cylindrical vessels. The multi-dimensionality is represented with two drywell vessels and two suppression chambers. PANDA has a modular structure, which is based on six pressure vessels with a total volume of 460 m^3. Four of the six pressure vessels have 4 m diameter and are arranged in two vertical columns. The two lower vessels simulating the wetwell have a volume of 120 m^3 each and are interconnected by two large lines. The lower line with about 1.4 m in diameter interconnects the suppression pools and the upper one with about 0.9 m diameter the wetwell gas space. These two WW vessels support the two other large vessels simulating the drywell, which have 90 m^3 volume each and are interconnected by a large line with about 0.9 m in diameter. The fifth pressure vessel with a volume of 17 m^3 simulates the gravity driven core cooling system pool and is placed between the two columns of large vessels, near their top. The sixth pressure vessel represents the RPV. In the lower part of the vessel electrical heater elements with 1.5 MW maximum power are installed. Riser and down comer are also modelled. The vessel has a diameter of 1.25 m and the height is about 19 m. Four rectangular-shaped, open pools four open pools with a total capacity of 60 m^3 are placed on top of the facility and are equipped with heat exchangers/condensers. The overall height of the facility is about 25 m and the maximum operating conditions are 10 bar for pressure and 200 °C for temperature. The vessels are interconnected with a number of lines that provide flexibility to configure the facility for a variety of large scale thermohydraulic experiments. The modular concept allows for example to adapt PANDA with a minimum of effort not only for integral containment system tests but also for multi-compartment three-dimensional separate effect investigations. In the past years PANDA has been used to investigate the integral system behaviour of three different LWR containments (SBWR, SWR1000 and ESBWR) with three different passive decay heat removal system concepts.

The facility instrumentation includes about 700 sensors to measure temperatures, pressures, pressure differences, liquid levels, flow rates, gas concentrations, fluid phases and electrical heater power.

Various auxiliary systems are available for establishing proper test initial and boundary conditions. Controlled systems allow for feeding/removing water, steam and gas (air or helium) to or from any vessel. In order to minimize heat losses the facility is well insulated: A layer of 200 mm rock-wool is applied on the pressure vessels (300 mm on the RPV) and 100 mm on the system lines and the pools. Characterization tests provided the actual heat loss data for the individual facility components.

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Annex III
COMBUSTION EXPERIMENT FACILITIES

Several experiments were performed to investigate the hydrogen combustion, better understand main dominating processes, and validate flame acceleration and DDT criteria in representative conditions and to contribute to the validation of dedicated computational tools. The list of main experiments is the following: (1) MUSCET Facility, (2) L. VIEW facility, (3) AECL Interconnected vessel facility, (4) The AECL large scale vented combustion test facility (LSVCTF), (5) The HTCF facility, (6) The Battelle Model Containment facility, (7) The DN-400 test Facility, (8) The PHDR facility, (9) The NUPEC Large scale Combustion Test facility and (10) The RUT test Facility.

III-1. MuSCET Facility (Technische Universität München – GERMANY)

The MUSCET Facility tests were performed at Technische Universität München (GERMANY) [III-1, III-2]. It includes an explosion tube equipped with a window section with an optical access for the application of optical measurement techniques (schlieren and laser-induced predissociation fluorescence for the investigation of the flame propagation and flame shape, laser Doppler velocimetry for the determination of the flow velocity of the expansion flow and the turbulence quantities). The objective of the tests was to examine the influence of several types of obstacles, typical for a reactor containment (tubes, grid-irons, and doors) on the flame propagation.

III-2. L.VIEW Facility (University of PISA – ITALY)

The L.VIEW Facility tests were performed at University of PISA (ITALY) [III-3, III-4]. This facility allows performing medium scaled deflagration tests with complete optical access from 2 directions simultaneously (from the front and the top side by means of a mirror placed above the test facility). The apparatus consists of a regular test section with the inner dimensions of 677 mm × 677 mm × 3200 mm, divided into 2 chambers, which simulate 2 connected rooms, e.g. by a door or a window. The first chamber has a length of 1050 mm and is separated from the second chamber by a wall with a central round orifice. The blockage ratio of the orifice can be varied from 96% up to 99.6% in order to investigate the influence of blockage ratios on the flame propagation. The second chamber is equipped with a weak rupture disk to the ambient atmosphere with the dimension 300 mm × 300 mm at the end flange.

The conventional instrumentation consists of 7 high-speed piezo-capacitive pressure transducers and 7 thermocouples. The visualization of the flame propagation is performed by means of a standard video camera with a frame rate of 25 Hz as well as a high-speed video camera with a maximum frame rate of 40000 Hz. In addition, the velocity of the expansion flow can be measured without inertia and non-intrusively for the horizontal and the vertical component with a two-component LDV system.

In the experiments, areas of direct ignition in the second chamber, ignition after a certain delay time, or even total flame extinction without ignition in the second chamber at all were observed, depending on the hydrogen concentration and the blockage ratio of the obstacle.

III-3. AECL interconnected vessels (AECL – CANADA)

The AECL Interconnected Vessels Facility Tests were performed at AECL, Whiteshell Laboratories (Canada) [III-5] with the objective to investigate the burning rate of near-flammability limit hydrogen air mixtures in a large scale facility. The experimental apparatus consists of a 6 m high and 1.5 m diameter cylindrical vessel (volume = 10.3 m^3) and a 2.3 m diameter sphere (volume = 6.3 m^3). These 2 vessels are joined together by a 2.7 m long pipe with an inside diameter of 0.45 m. The entire system is rated for a pressure of 10 MPa. To vary the size of the opening between the 2 vessels, orifices of different hole diameters (30 cm and 15 cm) were mounted between the pipe and the cylinder. In this facility the hydrogen concentration was independently varied from 6 to 20 vol.% in the sphere and 0 to 20 vol.% in the cylinder. The initial pressures in the vessels were atmospheric. The gas mixture in the sphere was ignited at the centre by an electric spark. The facility was equipped with a gas sampling and analysis system allowing gases from various locations in the 2 vessels to be sampled and analysed.

III-4. The Large scale Vented Combustion test facility (LSVCTF) – (AECL – CANADA)

The Large scale Vented Combustion test facility (LSVCTF) is located at the Whiteshell Laboratories in Pinawa, Manitoba (Canada) [III-6, III-7]. The facility is a 10 m long, 4 m wide, and 3 m high rectangular enclosure with an internal volume of 120 m^3. It is constructed of 1.25-cm thick steel plates welded to a rigid framework of steel I-beams. The entire structure is anchored to a 1 m thick concrete pad. Two roller mounted movable end walls are provided to open the vessel for internal modifications or to move in bulky experimental equipment, when needed. The combustion chamber, including the end walls, is electrically trace heated and heavily insulated to maintain temperatures in excess of 100°C for extended periods of time. The entire combustion chamber is enclosed in an insulated metal Quonset, which houses the gas analysis and hydraulic fan systems on one side and all the process piping on the other side. Venting occurs through openings in the end walls. The end walls are covered with removable rectangular steel plates bolted to the end-wall structure. Hydraulic fans in the combustion chamber are used for mixing and to generate turbulence during ignition and combustion. The test chamber is instrumented for pre test gas analysis, pressure transients, flame tracking, and vent velocity. The facility is located in a fenced area and is remotely operated.

The LSVCTF test facility has been used to perform a wide variety of experiments related to hydrogen combustion and recombination. Some of these are: (1) unobstructed vented combustion experiments in 30, 60, or 120 m^3 volumes to evaluate the effects of scale, (2) turbulent vented combustion experiments to study the effects of initial turbulence, (3) flame propagation studies between interconnected compartments, and (4) catalytic recombiner testing for hydrogen risk mitigation applications in large enclosures.

III-5. The HTCF facility (BNL – USA)

The High-Temperature Combustion Facility tests (HTCF) were performed at Brookhaven National Laboratory in order to study the influence of venting on the propagation of deflagration. The USNRC and the Japanese Nuclear Power Engineering Corporation, which is sponsored by the Ministry of International Trade and Industry (MITI), jointly funded the experiments. The HTCF detonation tube, which can be heated up to a maximum temperature of 700 K with a temperature uniformly of ±14 K, is 21.3 m long and is constructed from sections of stainless steel with an internal diameter of 273 mm. The test gases are mixed in a chamber fed with two pipes: one flowing air at room temperature and on the other a heated mixture of hydrogen and steam. The desired mixture composition is achieved by varying the individual constituent flow rates via choked venturis.

In the experiments investigating the DDT phenomenon, a flame is ignited and it subsequently accelerates as a result of turbulence generated in the induced flow ahead of it. For certain mixtures, this flame acceleration could lead to the initiation of a detonation wave. In order to promote flame acceleration, periodic orifice plates are installed down the length of the entire detonation tube. The orifice plates have an outer diameter of 273 mm (equivalent to the inner diameter of the tube), an inner diameter of 206 mm (BR=0.43), and have a spacing of one tube diameter.

For venting experiments, the main modification of the detonation vessel was the addition of four vent sections that were inserted between non-vented pipe sections. The total vent area per vent section is thus 4 times the detonation tube cross-section area (5.1% of the total vessel surface). The vent openings are initially closed by vent covers that are dislodged when the vessel pressure increases as a result of combustion. Main results showed that venting has a significant influence on both, the maximum flame speed and the transition to detonation. The influence of venting on the combustion phenomenon could be measured by the magnitude of change in the choking and the DDT limits from tests without venting to tests with venting.

III-6. The Battelle Model Containment Facility (Battelle – Germany)

The Battelle Model Containment Facility (Battelle – Germany) is one of the most comprehensive experimental programmes dedicated to combustion phenomena [III-8]. More than 100 combustion experiments were conducted in the BMC with the aim to study combustion under realistic severe accident conditions in a scaled-down volume. Tests are available from single-room arrangements with 40 m^3 up to five-room selections with about 200 m^3. In any case, a venting opening from the test section to the environment was included to restrict the combustion pressure rise to about 2 bar. The combustion phenomena studied in detail are ignition, slow combustion, acceleration, and jet ignition, as well as diluent impact (steam and CO_2) and obstacles. Generic obstacles such as cylinders and rows of pipes with different blockage ratios were investigated apart from jets through openings of different diameters. The experimental data can be used as data can be used to validate combustion models.

III-7. The DN-400 test Facility (Battelle – Germany)

The test facility DN-400 was built in Battelle (Germany) in order to examine scaling phenomena [III-9]. In this facility that has only 1 m^3 of volume, scaled identical obstacles were investigated and detailed measurements including turbulent fluctuations were conducted. The tests revealed a considerable scaling effect when the resulting flame speeds were compared with similar findings from the Battelle Model Containment. This strong effect of the test volume size on the combustion progress was identified to be mainly due to the much stronger wall effects and the missing buoyant influence in the early phase of combustion in the small facility and appeared to be challenging to applied combustion models.

III-8. The PHDR facility (FZK – Germany)

In order to study the scaling effect to larger volume parts of the outdated PHDR containment (FZK – Germany) was used for combustion experiments [III-10]. In this almost empty set of compartments with a volume of about 550 m^3, tests with gas compositions typical of severe accidents including steam as a diluent were conducted. The data obtained can be used to validate combustion models in comparison with the experiments from the Battelle Model Containment.

III-9. The NUPEC Large scale Combustion test facility (NUPEC – Japan)

The NUPEC Large scale Combustion Test facility was built at NUPEC (Japan) [III-11]. With a volume of about 270 m^3, it is rather big and is designed as a closed volume in contrast to the Battelle Model Containment and PHDR (vented combustion). With the numerous internal structures to represent large containment equipment such as steam generators and the connecting pipes between them, complex flame progress patterns can develop. This, together with the strong flame acceleration in the ring-like thick pipes (with internal orifices for additional flame acceleration), creates challenging situations to be simulated by combustion models.

III-10. The RUT Facility (Kurchatov Institute – Russian Federation)

The RUT Facility (Kurchatov Institute, Russian Federation) was designed to investigate flame acceleration phenomena and the transition to detonations of various hydrogen air–steam mixtures in a very large volume (480 m^3) and to provide experimental data for code validation [III-12]. RUT facility consists of a flame-acceleration section with periodic obstacles, followed by a ”canyon’. This facility is, therefore, very adequate for the scaling of experiments, performed in small scale explosion tubes.

The first part of the facility was a channel of 2.5 × 2.3 m cross-section and 34.6 m long; the second part was a canyon of 6 × 2.5 m cross-section and 10.5 m long, and the third one was a channel of 2.5 × 2.3 m cross-section and 20 m long. Twelve concrete obstacles were placed along the first channel with a spacing of 2.5 m (blockage ratios were 0.3 and 0.6).

In the framework of the HYCOM [III-13] project an extension of the experimental data base needed for the verification of newly developed analysis methods and codes to predict hydrogen combustion behaviour and corresponding loads on representative scale has been proposed. So, complementary experiments have been performed in the large scale test RUT facility in order to study the effect of mixture non-uniformity on behaviour of turbulent flames in multicompartment geometry under conditions and scale representative for severe accidents in NPP, ignition location, and end venting.

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ABBREVIATIONS

ACL	active cladding length
AECL	Atomic Energy of Canada Limited
AICC	adiabatic isochoric complete combustion
ASME	American Society of Mechanical Engineers
BDBA	beyond design basis accident
BWR	boiling water reactor
CANDU	Canadian deuterium uranium
CEA	Commissariat à l'Énergie Atomique
CFD	computational fluid dynamics
CSNI	Committee on the Safety of Nuclear Installations
DBA	design basis accident
DCH	direct containment heating
DDT	transition from deflagration to detonation
ECCS	emergency core cooling system
EDF	Electricité de France
EPR	european pressurized reactor
EPRI	Electric Power Research Institute
EU	European Union
EURATOM	European Atomic Energy Community
FZJ	Forschungszentrum Jeulich
FZK	Forschungszentrum Karlsruhe
GPR	Groupe Permanent des Réacteurs
GRS	Gesellschaft fuer Anlagen- und Reaktorsicherheit
HDR	decommissioned high-temperature reactor plant
IRSN	Institut de radioprotection et de sûreté nucléaire
ISP	international standard problem
LES	large eddy simulation
LOCA	loss of coolant accident
LWR	light water reactor
MCCI	molten core coolant interaction
NEA	Nuclear Energy Agency
NUPEC	Nuclear Power Engineering Corporation
OECD	Organisation for Economic Co-operation and Development
PAR	passive autocatalytic recombiner
PHWR	pressurized heavy water reactor
PSA	probabilistic safety assessment
PWR	pressurized water reactor
RBMK	high power boiling reactor with pressurized channels
RSK	Reaktorsicherheitskommission
USNRC	United States Nuclear Regulatory Commission
WWER	voda vodynoy energiticheskie reactor (water cooled, water moderated power reactor)
WOG	Westinghouse Owners Group

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