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Mitigation of hydrogen hazards in water cooled power reactors

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FOREWORD

Hydrogen mitigation in water cooled power reactors has been an important area of study in the past two decades. In the 1990s, research activities to analyse and provisions to cope with the threat of hydrogen in a post-accident condition have focused mainly on the mitigation of hydrogen hazards in severe accidents.

The International Atomic Energy Agency and the Commission of the European Communities have been co-operating in an endeavour to update the state of the art of hydrogen research and the development of mitigation techniques since 1989. This report summarizes the actual status reached. Current concepts for hydrogen mitigation in the containment are outlined, with emphasis on measures which are already being implemented or which show promise for hydrogen mitigation in severe accidents.

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EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. Background

Past considerations of hydrogen generated in containment buildings have tended to focus attention on design basis accidents (DBAs) where the extent of the in-core metal–water reaction is limited at low values by the operation of the emergency core cooling systems (ECCS). The radiolysis of water in the core and in the containment sump, together with the possible corrosion of metals and paints in the containment, are all relatively slow processes. Therefore, in DBAs the time scale involved for the generation of hydrogen allows sufficient time for initiation of measures to control the amount of hydrogen in the containment atmosphere and to prevent any burning. Provisions have been made in most plants to keep the local hydrogen concentration below its flammability limit (4% of volume) by means of mixing devices and thermal recombiners.

Severe accidents, involving large scale core degradation and possibly even core concrete interactions, raise the possibility of hydrogen release rates greatly exceeding the capacity of conventional DBA hydrogen control measures. The accident at Three Mile Island illustrated the potential of unmitigated hydrogen accumulation to escalate the potential consequences of a severe accident.

In a severe accident scenario, local high hydrogen concentrations can be reached in a short time, leading to flammable gas mixtures in containment. Another possibility is that local high steam concentrations will initially create an inerted atmosphere and prevent burning for a limited time. While such temporary inerting provides additional time for mixing (dilution) of the hydrogen with containment air, depending on the quantity of hydrogen released, it prevents early intervention by deliberate ignition and sets up conditions for more severe combustion hazards after steam condensation eventually occurs, e.g., by spray initiation or the long term cooling down of the containment atmosphere.

As the foregoing example indicates, analysis of the hydrogen threat in post-accident containments is complex and highly plant- and scenario-specific. Many aspects must be considered in analysis of a hydrogen threat: accident sequences, hydrogen production rates, atmosphere thermalhydraulics, mixing processes, combustion phenomena, accident management strategies and mitigation hardware performance. Research activities on these topics have been continuing in several countries for the past two decades and are summarized in symposium proceedings and compilation documents [1.1–1.7].

A review document produced by IAEA/CEC [1.4] and the OECD workshop in 1996 [1.6] placed emphasis on the area of mitigation of hydrogen in severe accidents.

This report summarizes current concepts for hydrogen mitigation in containments, concentrating primarily on measures that are already being implemented or those that show promise in the near future for hydrogen mitigation in severe accidents.

1.2. Elements of hydrogen mitigation

Mitigation measures for hydrogen are presented in terms of a generic strategy embodying the defence in depth principle of reactor safety [1.8]. The strategy consists of safety objectives representing levels of defence. Common safety objectives, available countermeasures, engineered systems and their functions are listed in Table I and are described briefly below.

TABLE I. ELEMENTS OF A SAFETY STRATEGY AND MITIGATION MEASURES FOR HYDROGEN IN SEVERE ACCIDENTS

Objectives	Countermeasures or Engineered Systems	Functions
Preclude flammable mixtures by oxygen control	• Inerting the containment under normal operation (pre-inerting) • Post-accident inerting of containment by inert gas injection (post-inerting)	Dilute or replace the containment atmosphere with inert gas to maintain conditions outside the O_2 flammable limit (<5 vol %)
Preclude flammable mixtures by hydrogen control	• Mixing: – natural convection – engineered systems	Dilute H_2 with available containment air
	• Post-accident dilution (PAD) by local inert gas injection	Dilute H_2 and O_2
	• Recombiners (catalytic)	Remove H_2/O_2
Avoid unacceptable combustion pressures and temperatures	• Deliberate ignition	Burn by slow deflagration local volumes where flammable limits are exceeded
	• Post-accident dilution (PAD) by local inert gas injection	Suppress detonability in selected locations

The first objective is to preclude the occurrence of flammable gas mixtures. Various means may be relied upon to achieve this with varying degrees of cost, convenience and effectiveness. Here, the most effective measures are those that limit the available oxygen (inerting) and create a hydrogen-independent condition. Where inerting is not feasible, other measures can be invoked to manage the hydrogen accumulation in such a manner that flammability limits are not exceeded. Natural mixing and dilution of the hydrogen with containment air may be sufficient for many scenarios. Catalytic recombiners can add a mode of removal to supplement natural dilution and increase the prospect of maintaining non-flammable conditions. Diverse and independent measures are thus working for the goal of maintaining a non-flammable atmosphere.

The second objective, if flammability limits are exceeded anywhere, is to prevent continued penetration of the flammable range to more dangerous concentrations. Here, igniters provide a fast-acting means of intervention at near the limits of flammability.

Where continued penetration of the flammable range is not successfully intercepted, the objective is to minimize the volume of gases at flammable or detonable concentrations. This is may be achieved by preferential coverage of sensitive volumes with igniting devices, where used, to keep the potential combustible cloud size to some acceptable maximum. To this end, another proposition is a system that injects inert gas, locally, in the vicinity of the release or other trouble spots to reduce the detonability of the gases.

In the preceding discussion, it is evident that different countermeasures may be specific to a particular design and even to a particular phase of the accident. Also, different countermeasures may act synergistically, as well as provide diversity and some redundancy. For example, the hydrogen management measures that dilute or remove hydrogen (i.e., mixing and recombiners) contribute to lessening the potential consequences of a combustion event later in the accident.

As presented in Table I, the contemporary mitigation measures or engineered systems provide one of these two essential functions: either to *dilute* or to *remove* combustible gases. The systems can be further grouped as active (requiring system or operator action) and passive (not requiring system or operator action for some period of days following the accident). Table II summarizes mitigation measures in these terms.

Each of these systems is described in detail in the following sections. The descriptions are intended to address the practical aspects of effectiveness, implementation and proposed safety benefit, as well a noting any issues or incomplete knowledge surrounding the particular system. Concepts that are in use or are mature in concept demonstration are given proportionally greater attention.

TABLE II. THE ESSENTIAL FUNCTIONS AND MODE OF OPERATION OF HYDROGEN MITIGATION MEASURES

Function	Active	Passive
DILUTION	• Post-inerting • Post-accident dilution (PAD) • Mixing (forced)	• Pre-inerting • Mixing (natural)
REMOVAL	• Igniters (glow-plug) • Thermal recombiners	• Catalytic recombiners • Catalytic and battery-powered igniters

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2. EARLY HYDROGEN MANAGEMENT (BEFORE 1990)

During normal plant operation, hydrogen sources within most existing containment designs are essentially nil. Consequently hydrogen countermeasures are not considered necessary in this case. However, during an accident, hydrogen source terms within most existing containment designs may be significant, even for DBAs when the release rates are slow over long periods of time. To mitigate post-accident hydrogen, several approaches had been adapted for specific containment designs [2.1–2.10] and are listed in Table III.

TABLE III. STATUS OF HYDROGEN MANAGEMENT TECHNIQUES IN DIFFERENT TYPES OF CONTAINMENTS

Main types of containment	Provisions made for design basis accident (DBA)	Severe accident
PWR, large dry containment	Recombiners	None
PWR, ice condenser containment	Recombiners or mixing systems or both	Deliberate ignition
CANDU®, large dry, negative pressure		
– single unit	Mixing system	Mixing system
– multi-unit	Deliberate ignition and mixing system	Deliberate ignition and mixing system
BWR, US design Mark I	Pre-inerting and recombiners	Pre-inerting and recombiners
Mark II	Pre-inerting and recombiners	Pre-inerting and recombiners
Mark III	Recombiners	Deliberate ignition
Swedish design (similar to Mark III)	Pre-inerting	Pre-inerting and recombiners
German design	Pre-inerting, total or partial (wet well), and recombiners	Pre-inerting, total or partial (wet well), and recombiners

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For containment designs with relatively small dilution volumes, such as the BWR Mark I and Mark II, the preferred hydrogen mitigation option at that time involved pre-inerting and the use of conventional (thermal) recombiners to control radiolytic oxygen and to maintain inerting. Small containment volumes with no equipment to be maintained favour this radical solution of the hydrogen problem.

With larger containment volumes, pre-inerting becomes increasingly impractical because of the requirement for equipment maintenance. Therefore the mid-sized containment designs, such as the BWR Mark III and PWR ice-condenser, are equipped, in most countries, with conventional recombiners in addition to a deliberate ignition system. At that time, it was argued that the increased dilution capacity of the mid-sized containment designs will help to reduce hydrogen concentrations in the containment atmosphere. This argumentation is only valid for containment designs leading in the long term of an accident to stable homogeneous atmospheric conditions.

For both the small and mid-sized containment designs, the hydrogen counter-measures were often pre-determined by the local regulatory requirements. Where no such requirements were available, designers tended to adopt the standard practice utilized in similar containment designs.

For the large dry containment designs, Table III shows that the most commonly used hydrogen countermeasure was recombination by conventional recombiners (intended for DBA hydrogen). In multi-unit and some single-unit CANDU containments, mitigation is still provided by a combination of dilution by forced mixing and deliberate ignition. The appropriate choice of mitigation was always depending on the particular containment design and the calculated dynamics of the respective hydrogen source terms. In all cases, containment integrity was maintained by either precluding the formation of a flammable mixture composition, or by limiting the burn consequence to that associated with the ignition of near-flammability-limit mixture compositions (provided the containment structures can withstand the resulting thermal and mechanical loading).

In the WWER-440 and WWER-1000 containments, provisions for natural mixing and dilution with air available in the containment were made for accidental release of hydrogen and new countermeasures, such as igniters and recombiners, were considered.

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3. MITIGATION MEASURES FOR HYDROGEN IN SEVERE ACCIDENTS

3.1. Mixing

Dilution of the hydrogen with the containment air is the most readily available means of dealing with a broad range of hydrogen releases. For DBAs and all the most severe LOCA conditions, diluting hydrogen by mixing to below flammable concentrations with containment air is the principal means for short term hydrogen mitigation. Large dry containments have an inherent capacity to dilute several hundred kilograms of hydrogen to non-flammable concentrations. This capacity is considerable and, accompanied by credible mechanisms to achieve mixing, is credited in safety analyses.

Mixing may be achieved by:

- natural mechanisms (convection, diffusion), including containment designs that effectively utilize natural mechanisms;
- engineered systems that enhance or otherwise effectively utilize natural mechanisms (dampers, ice compartments, high point vents, sprays);
- engineered systems that actively produce desired mixing and distribution patterns (fans, coolers, ventilation systems).

Engineered systems may be used solely for mixing purposes, or they may have some other primary purpose. For example, sprays and coolers may be primarily required for steam condensation or fission-product control, but they can also effectively supplement mixing. Such systems may also be safety grade, with high availability and thus creditable for hydrogen.

If the quantities of hydrogen released exceed the diluting capacity of the containment air or if the rate of hydrogen release exceeds the capacity of mixing mechanisms, additional measures will be required to maintain a non-flammable atmosphere.

Although the mixing processes provide the context for the action of other subsequent mitigation measures, and analysis of mixing processes continues to be a key aspect of the hydrogen problem, mixing processes, per se, are not further addressed in this report. A recent state-of-the-art report by OECD experts provides a comprehensive reference on containment thermalhydraulics and hydrogen mixing [3.1].

3.2. Pre-inerting

3.2.1. Description

Where it is required to absolutely avoid any burning of hydrogen released in the nuclear reactor containment, it is necessary to generate an oxygen-depleted atmosphere in the containment before startup for normal plant operation. An inert gas (usually nitrogen for its greater chemical stability) is injected into the containment to substitute air (that is simultaneously let out to the ambient atmosphere) and to reduce the oxygen concentration below the level needed for hydrogen combustion (5% in volume for N_2–O_2 mixture) [3.2].

The important aspect for inerting is the ratio between oxygen and nitrogen; therefore, the changing composition of the gas mixture because of steam condensation is not a problem. Safety margins for oxygen concentration must account for the time delay necessary to monitor the oxygen distribution with a sampling system.

Of vital importance for normal operation, a combustion-inerted atmosphere is not breathable at normal pressure. For this reason, any need to do inspections, maintenance and repairs in a pre-inerted containment causes certain problems, such as,

- a lower margin of safety corresponding to the asphyxiation hazard for personnel and requirement for use of special breathing apparatus;
- a lower margin of safety, if de-inerting is made before shutdown or if the frequency of maintenance operations is reduced;
- a greater economical cost, particularly if de-inerting is made after shutdown and before entry to containment;

However, for small-volume containments where no equipment needs to be accessed, the advantages are generally seen to overcome the disadvantages of alternative measures.

Pre-inerting is required for small-volume containments where no equipment is to be used during normal operation: BWR plants with Mark I and Mark II types of containment, and modified versions of these BWR plants in Japan, Sweden and Germany (only Type 69) [3.3–3.7]. The following description of implementation experience of inerting systems is provided. Some additional detail is given because later descriptions for post-accident inertization schemes will require similar considerations.

3.2.2. Implementation conditions

Inerting is conducted by injecting gas into the containment and simultaneously directly to the atmosphere or through a gas treatment system (SBGTS) if the airborne letting out air radioactivity is too high. Injection flow rate is limited by the discharge flow rate because the containment pressure must remain almost constant. In the case of a direct discharge, the injection flow rate may even be three times greater than in case of discharge through the SBGTS (1500–4500 STP m^3/h in BWRs) [3.8–3.10]. The following description of implementation experience of inerting systems is provided.

If pre-inerting is conducted as an isothermal isobaric process in a perfectly mixed volume, the STP volume of inert gas, I, to be injected into a containment of volume V can be calculated by:

$$I = V \ln \frac{C_0}{C_f}$$

where C_0 (= 21% in air) and C_f is the initial and the final oxygen concentration in volume in the containment. Injection of liquid N_2 could perhaps cause stratification effects, which are very helpful to perform inerting with minimum effort (inert gas amount, time span), because only air could be vented. But fast vaporisation with injection of N_2 can generate unacceptable thermal shocks to equipment.

Evaporators are used to bring nitrogen from a liquid at 110 K, which is the standard method of storing large amounts of nitrogen, to a gas at 300 K. At 110 K, the nitrogen vapour pressure is 1.5 MPa, the specific volume of the saturated liquid is 0.045 10^{-3} m^3/mol and the saturated vapour is 0.452 10^{-3} m^3/mol; the heat of evaporation is 3848 J/mol. The heat capacity of the gas at constant pressure is 1.0 kJ/(kg K). Other properties are described in Section 3.3.1. In a BWR, the power needed to evaporate and heat nitrogen can reach 500 kW (according to the flow rate) and the total electrical power of the evaporators can reach 650 kW. The evaporators can also be air evaporators, which take the energy from the ambient air, but electrical heating is always necessary, to raise the gas temperature at the evaporator outlet, which is 10 to 50 K lower than the ambient value.

Control of these systems can be manual, except for the automatic stop of the nitrogen injection if the evaporator outlet temperature drops below a wanted value (260 K) or if the containment overpressure rises above 0.1 bar. Gas inlet and outlet must be far enough apart in the containment, to avoid by-pass.

Nitrogen injection is stopped when the oxygen concentration reaches the wanted value. Duration depends on the amount of nitrogen to be injected and on the flow rate. Safety authorities limit operation when oxygen concentration in containment is above specified values: USNRC requires no more than 24 h with power greater than 15%. Utilities are interested in reducing the pre-inerting and de-inerting times to limit economical costs. At present, for BWRs, duration of four to 24 h is allowed on the basis of design, safety requirements and radiation level in containment.

Nitrogen can be stored in situ as a liquid (30 to 50 m^3) in cryogenic tanks or supplied by trucks. Normally, the stored amount is enough for one pre-inerting process (15 000 to 25 000 STP m^3 for BWR Mark I and II). The tank pressure (and temperature) is maintained constant (13 to 15 bar) by releasing the nitrogen vapour (0.5 to 1%/d in mass).

The pre-inerting system also controls the oxygen concentration and the small containment overpressure (to avoid air entry) during normal operation. For these functions, smaller flow rates (10 to 150 STP m^3) and a smaller evaporator capacity are necessary.

The ventilation system (ten air exchanges per hour) provides mixing in containment, but the gas mixture composition could be non-uniform. Also for this reason, a safety margin is accounted for oxygen concentration (1 to 2.5% in comparison with a 5% flammability limit). The oxygen concentration can be measured from samples that were taken from the containment to measure hydrogen concentration.

When needed, de-inerting during normal conditions is usually conducted using the purging system, by injecting and letting out air directly to the atmosphere or through SBGTS.

At normal pressure entry to containment must be restricted for O_2 concentration below approximately 17 to 19% of O_2, if personnel do not use special breathing apparatus. Also in this case, safety margins should be able to account for non-uniform nitrogen distribution. Local safety authorities will evaluate whether entry to inerted containment can be allowed according to entry procedures, personnel training and reliability of breathing apparatus.

The most common and safe characteristics of the self-contained breathing apparatus (SCBA) are [3.11]:

- exhalation is vented to the atmosphere and not rebreathed (open circuit);
- the pressure inside the face piece, relative to the immediate environment, is positive during both inhalation and exhalation (positive pressure), for protection against inward leakage that could be caused by an improper face piece fit or a small tear in the breathing tube.

A normal SCBA has a minimum rated service life of 30 min, but longer duration SCBAs are on the market. An SCBA should not be used without thorough training and practice with the specific type of equipment available for use, under restricted movement, breathing and visibility conditions. Persons wearing SCBAs should not work alone and should be supervized.

Portable oxygen indicators (minimum weight of 80 g) can operate on different physical principles:

- Electrochemical types – The partial pressure of the oxygen in the atmosphere controls the rate of diffusion through a porous membrane and into an electrochemical cell with suitable electrolytes and electrodes. The oxygen enters into an electrochemical reaction, generating a current which in turn, reads the percentage of oxygen directly on a graduated scale.
- Paramagnetic types – The oxygen will displace other substances from strong magnetic fields, thus permitting its determination either by measuring the displacement force directly or by the effect of some other physical property, such as thermal loss.
- Infrared types – Infrared analysers employ simplified optical systems for spectrophotometry.

3.2.3. Demonstration of effectiveness

Because most system components will not have to be activated during accidents, they need only be certified by normal approval, listing, and certifying authorities who are responsible for industrial fire protection and safety equipment (such as German TÜV or Underwriters Laboratories or Factory Mutual). However, O_2 and H_2 instruments and wiring should be nuclear safety qualified, to operate during severe accidents.

At present, pre-inerting systems are employed in many plants, and have a large operating experience; the use of these systems is well proven.

3.2.4. Maintenance

During normal operation, valves, pipes, temperature and pressure measurements, cables, etc., can easily be inspected because they are outside the containment. Besides, equipment and stop valves can be tested.

Also, the sampling system used to measure oxygen is located outside the containment.

3.2.5. Long term inerting control (thermal recombiners)

The amount of oxygen inside a containment will increase during an accident because oxygen will be generated (for example, by radiolysis), but its volumetric concentration, which is the critical parameter for flammability, might even decrease because other incondensable gases (hydrogen, carbon monoxide and carbon dioxide) will be generated as well. However, systems should be installed to cope with the long term generation of oxygen in any type of accident. These systems may even be non-passive because they have to be activated days after the beginning of the accident.

Some more nitrogen could be injected if the rise in pressure is tolerable for the containment integrity or limitable by venting. Injection could become necessary so late that at least one of these two conditions could be satisfied. However, this measure does not resolve the problem of possible combustion in the venting or ventilation ducts.

Removal of oxygen and, later, also of hydrogen, could be conducted with recombiners or igniters. Recombiners seem better than igniters, because deflagration overpressure and the likelihood of transition to detonation rise more steeply with oxygen concentration in fuel-rich mixtures than with hydrogen concentration in lean mixtures.

At present the long term hydrogen control in some pre-inerted BWRs is provided by thermal recombiners outside containment. However, for an external position, contamination of the recombiner must be regarded together with the consequence of a high radiation field in case of a severe accident. In future, new passive catalytic recombiners (see Section 3.5) could be utilized inside containment.

The current system is designed to recombine a maximum of 1.4 10^{-3} STP m^3/s of oxygen with 2.8 10^{-3} STP m^3/s of hydrogen [3.12]. The inlet line ducts the process gas from the containment through a control valve and flowmeter to a special blower that circulates a total gaseous flow of 70 10^{-3} STP m^3/s. Gas flows through the heater pipe that spirals around the chamber where oxygen reacts with hydrogen. The heat, needed for increasing the gas temperature to the point where the hydrogen–oxygen reaction occurs spontaneously, is provided by the combustion and by electric heater elements.

The recombined gases flow from the reaction chamber to a water-spray gas cooler. Part of the effluent can be recirculated to provide a diluent, as necessary, and the remainder is returned to the containment. In fact, the maximum volumetric O_2 concentration must be 2% at the reaction chamber inlet to limit the combustion temperature, whereas the maximum concentration in the containment is 5%, which is the flammability limit. An automatic control of the electrical heater power and manual controls of the inlet flow and of the recirculation flow allow temperature to rise to a preset value of 980 K at the reaction chamber outlet, whichever is the thermodynamic condition of the inlet gas flow. Theoretical studies conducted on a similar but smaller type of thermal recombiner for PWRs suggest that thermal recombiners could even work properly with oxygen concentrations above the flammability limit [3.13] too. Their start-up is less than 1 to 1.5 h.

3.2.6. Other pre-accident measures

If limitations to the containment access cannot be tolerated (for example, in a very large containment), pre-inerting at atmospheric pressure is not practicable, but other measures can be taken during normal operation to create better conditions to mitigate the hydrogen problem.

Pre-inerting could be "partial", that is, limited at some zones of the containment (e.g., the wet well in BWRs), when these zones are particularly subjected to the "hydrogen risk", do not have equipment to be maintained and can easily be separated from the rest of the containment. Partial pre-inerting could also be interesting in view of a subsequent post-accident inerting.

Because the quality of air for breathing depends on the amount of oxygen per unit of volume, and flammability and the likelihood of detonation depend on the oxygen/inert ratio, the partial pressure of oxygen could be reduced to the air quality for breathing limit, from 0.21 bar to about 0.11 bar, and the containment could be pressurized with nitrogen up to about 2 bar, to avoid combustion, or 1.5 bar, to avoid detonation [3.14]. A pressurized containment would also involve economical costs, and advantages would not be significant if compared to post-inerting (Section 3.3) or to containment atmosphere dilution (Section 3.4). Moreover, if a lean fuel mixture should burn in a diluted pressurized atmosphere, the pressure after a deflagration could be higher, because the amount of reactants burnt per unit of volume could be the same. In fact, a parameter that affects the deflagration overpressure is rather the amount of reactants burnt per unit of volume than the volumetric concentration of the deficiency reactant.

Another solution involves using an engine that produces pollutant-free exhaust products and drives an exhauster; it could maintain an atmospheric pressure in containment, with O_2 and CO_2 at a partial pressure of 0.20 bar [3.15]. In this case, the containment atmosphere would be still breathable (O_2 partial pressure 0.16 bar), but detonation could not be attained [3.16, 3.17]. However, use of CO_2 for inertization is not favoured due to corrosion problems. Also, the CO_2 amount necessary to prevent dynamic loads cannot be evaluated with certainty, because the present knowledge is not enough to scale experimental data obtained in small volume on deflagration–detonation transition and detonation onset to the very large volumes of a nuclear reactor containment.

3.3. Post-inerting

3.3.1. Description

Post-inerting (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 [3.18, 3.19]. 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 pressurisation. Nitrogen and carbon dioxide have been considered as candidate non-combustible (diluent) gases. Use of the combustion-inhibiting gases such as Halon 1301 are not considered suitable for application in nuclear reactors as they may form corrosive or radioactive substances, which are hard to dispose of afterwards. In addition, the use of Halon has become quite restricted because of its pollutive effects.

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. The mixing could be achieved by a multipoint injection system together with forced or natural convection or both. To ensure the complete mixing of the diluent gas with the accidental atmosphere, careful investigations for specific containment designs are needed.

Some specific data for CO_2 and N_2 are listed in the Table IV. Carbon dioxide is more effective as a diluent than are other common gases, primarily because of high heat capacity.

TABLE IV. SOME SPECIFIC DATA FOR CARBON DIOXIDE (CO_2) AND NITROGEN (N_2)

Property	Dimension	CO_2	N_2
Molecular weight	kg/kmol	44.01	28.02
Gas constant	kJ/kg K	0.189	0.297
Normal density (at 0°C and 1 bar)	kg/m^3	1.977	1.25
Melting temperature	°C	–56.6 at 5.11 bar (triple point)	–210.5 at 1 bar
Melting enthalpy	kJ/kg	184	25.75
Saturation temperature (1 bar)	°C	–78.2 (sublimation)	–195.7 (boiling)
Critical temperature	°C	31.1	147.16
Critical pressure	bar	73.92	3.93
Specific heat (at 25°C, 1 bar)	kJ/kg K	0.846	1.038
Heat conductivity (at 25°C, 1 bar)	W/m K	0.016	0.026
Dynam. viscosity (at 25°C, 1 bar)	10^{-5}Ns/m^2	1.48	1.78

The advantages of CO_2 could be demonstrated by the following example: to inert a containment of 70 000 m^3 (starting condition: 20°C, 1 bar) with CO_2, approximately 190 t are needed, resulting in a total pressure of about 2.9 bar, whereas for N_2 those data are 230 t and 4.2 bar. The use of CO_2 will therefore delay a venting requirement, and inerting could be achieved earlier because less mass has to be injected into the containment atmosphere. It is obvious that because of this pressure, increasing post-inerting is not acceptable for specific containments when design values could be exceeded by such a measure or venting is required very early in the course of an accident [3.7].

To maintain the inerted condition for a long time, further accident management measures are required because of the hydrogen and oxygen production by sump water radiolysis; additional tons of oxygen could be produced in a few weeks. Thermal recombiners could be used, to control the oxygen content (see Section 3.5). In use of an external position, contamination of the recombiner must be considered. Repeated injection of inert gas, together with the use of a filtered venting system, could be another measure to keep the containment post-accident atmosphere inert. However, by the use of the venting system, radiological consequences for the vicinity of the plant have to be considered.

The storage of the gas at the site will always be in liquid form in tanks, which must be kept at low temperature (e.g., CO_2 –28°C; N_2 –162°C); there are large power requirements. These pressurized tanks (approximately 15 bar) must be placed outside the containment in a bunker.

For fire fighting and pre-inerting of BWRs, an evaporator is used to inject N_2 or CO_2 in a gaseous form. To achieve inerting of a containment with a volume of 70 000 m^3 in a short time (approximately 1 h) the power needed for the evaporator is about 20 MW; in this case, the piping diameter should be 300 mm for CO_2 and 500 mm for N_2 injection.

Injecting CO_2 or N_2 in a liquid form, the estimated required piping diameter is about 160 mm. In this case, a problem could be the creation of thermal shock loads on system components, which are relevant for safety and for other special accident management measures.

Until now, systems for post-inerting have not been applied in any nuclear power plant. Only a few theoretical investigations were done, concentrating on the possibility of such a measure [3.20, 3.21]. From the studies conducted, the following conclusions could be drawn:

- The effectiveness of a post-inerting measure is not questionable. Hydrogen combustion could be prevented by such a measure.
- As a candidate inert gas, CO_2, has some benefits in comparison with N_2.
- Timing of post-inerting is dependent on the accident sequences. Extended analyses may be required to develop a clear set of criteria to initiate post-inerting.
- Post-inerting leads to a considerable increase of pressure inside the containment, so that a venting system is required for most containment types. Early venting requires high capacity filter systems.
- The containment leakage will be increased by post-inerting because of the added contributions to containment pressure and added containment penetrations.
- Long term oxygen control measures are required to keep the system inerted.

Post-inerting thus offers the possibility of complete prevention of hydrogen combustion but has associated practical obstacles to implementation.

3.4. Post-accident dilution

Post-accident dilution (PAD) is a concept that attempts to gain some of the benefits of complete inertization but with a smaller amount of gas, injected strategically. Complete post-inertization, described in Section 3.3, carries considerable safety costs, in terms of containment pressurisation, 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 (for example, in strong containments with large dilution volumes), 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.

PAD 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.

Concepts for post-accident dilution of containment atmospheres have been analysed, [3.22, 3.23], but no practical implementation has been reported so far.

3.5. Catalytic recombination

3.5.1. Description

Catalytic recombiners use catalysts to oxidize (recombiner) the hydrogen and are operable outside the limits of flammability. There are two broad categories of catalytic recombiners:

- *Conventional catalytic recombiners* designed for DBA hydrogen, functioning in essentially the same way as thermal recombiners, operating mostly external to containment, delivering the containment atmosphere to heated catalysts with the use of powered gas pumps.
- *Passive recombiners,* which are situated inside the containment and use the heat of the oxidation reaction to produce flow through the unit by natural convection and thus do not require outside power or operator action.

This section deals exclusively with the latter, passive catalytic recombiners designed for use inside containment.

Passive autocatalytic recombiners (PARs) have been developed and have become commercially available hardware in the last decade [3.24–3.40]. 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 surfaces 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 structures to obtain the desired coverage of the containment volume and the desired overall capacity. The performance of recombiner units has been shown to be insensitive to the location within a particular room because of quite vigorous natural mixing produced by their operation. PAR capacities are ultimately subject to mass transfer limitations and may not keep up with high hydrogen release rates in small volumes, for example, as could exist in the immediate vicinity of the hydrogen release [3.41].

Catalytic recombiners are commercially available from vendors in Canada (AECL), Germany (Siemens, NIS), and Switzerland (Electrowatt). The essential principles of operation are similar but the catalyst materials differ quite significantly from one design to another. The hardware for Siemens and NIS has been commercially available since about 1992 and employs conventional industrial catalysts. The AECL and Electrowatt recombiners have been commercially available since 1996. Usually, these recombiners do not rely on external heating to become active, making them suited to containments with coolers, ice-condensers or dousing where it may be necessary for the recombiner to start under cool, condensing conditions and for long term hydrogen control, when containment atmosphere is cooled. Other aspects, such as extent of qualification testing, ease of sizing and interfacing to containment structures also differ between the commercial designs.

Tests of catalytic recombiners were carried out at the H_2PAR and Kali facilities in France; the Surtsey facility at Sandia National Laboratories, USA; the Large-Scale Vented Combustion Test Facility at the AECL Whiteshell Laboratories, Canada, and formerly at the Battelle Model Containment in Germany to demonstrate performance under atmospheres representative of severe accident environments.

As a result of consistently positive tests experience in different laboratories PARs are a quite well accepted safety measure to improve margins for hydrogen in any reactor design, including use for oxygen control in inerted BWR designs. PARs have already been implemented in plants in Belgium, Czech Republic, Germany, Hungary, Netherlands, Russian Federation, Slovakia, USA [3.42, 3.71] and installations in Canada, Finland, France, Spain and are intended soon [3.43–3.46].

3.5.2. Implementation conditions

Implementation of catalytic recombiners is essentially a matter of evaluating the capacity and qualification requirements for the particular plant together with the performance specifications and qualification file on the available hardware and completing a thermalhydraulics analysis of candidate placements.

Capacity

It has been estimated [3.37] that mass release rates of hydrogen in severe accidents in large power reactors are on the order of 100 to 500 kg/h (with peak values still higher [3.41]), depending on scenario and the type and size of reactor.

The capacity of natural convection recombiners (PARs) is given in terms of the inlet cross-section area (or the inlet flow area or the macroscopic catalyst area), for comparing and sizing catalytic recombiner units. Natural convection recombiners have been demonstrated to produce removal rates (in 4% H_2 at 1 bar) of 3–7 kg/h per m^2 inlet cross-section area, increasing about linearly with hydrogen concentration and initial pressure (or, better, only with hydrogen molar density) [3.41, 3.47, 3.48]. Large PWR designs are specifying between 10 m^2 and 30 m^2 of inlet cross-section area to meet capacity targets for severe-accident hydrogen terms [e.g. 3.41].

The installation of PARs is highly influenced by geometric and operational constraints (access to maintenance areas, accessibility of PARs for periodic surveillance, paths for convective flows, possible location of hydrogen release). Therefore, in addition to engineering judgements, detailed code calculations should be performed to confirm effectiveness of candidate PARs locations. In References [3.41, 3.42, 3.44, 3.49–3.52], the use of various containment codes has been reported for these purposes.

It should be noted that redundancy requirements could increase the capacity requirements. On the other hand, the available test data are for first-generation prototypes and scope may exist for further optimisation of catalyst performance or housing design to improve capacity. Simulation models are being developed towards this aim [3.49, 3.53, 3.54].

Resistance to fouling

Catalyst performance can be affected by chemical poisons, which bind to the active material in the catalyst. Examples of compounds known to poison noble metal catalysts include volatile compounds of lead, mercury, sulphur and iodine. The chemical make-up of the containment atmosphere during operation and during accidents needs to be closely considered for potential chemical poisons and a list provided for testing as part of the qualification procedure.

Catalyst performance may also be affected by dust, aerosols, condensing organics, etc., depositing on the catalyst surface. Such deposits, in sufficient quantities, will block access of the hydrogen to the active surfaces [3.72].

In both these aspects, prototype tests have produced encouraging results; resistance to most foreseeable atmospheric conditions have been demonstrated, and further work is on going. These tests are described in Section 3.5.3.

3.5.3. Demonstrations of concept and effectiveness

Experimental studies have been conducted on several catalyst formulations and self-starting response to the presence of hydrogen has been demonstrated under foreseeable thermalhydraulic condition in post-accident containments. Performance of catalysts materials in different configurations has been tested in terms of capacity, operating temperature resistance to flow, temperature range of operation. Studies have been done to demonstrate the resistance to selected poisons or fouling agents that could affect availability of the catalysts [3.73].

In the following, synopsizes of the development of catalytic recombiners at different laboratories in Germany, France, United States, Canada and Russia are given [3.48, 3.55–3.61].

Siemens-KWU

A catalytic recombiner consisting of thin stainless steel sheets coated by a material containing precious metal and arranged in housing has been developed and qualified by Siemens-KWU [3.31].

Inside the recombiner module, a row of parallel catalyst sheets is located at the lower end of a chimney. A deflector plate at the top of the shaft directs flow away from the wall or containment component to which the recombiner is attached.

The Siemens device is commercially available in several sizes and has been installed in some plants in Europe.

Gesellschaft für Reaktorsicherheit (GRS) and Electrowatt

GRS has developed unique catalyst formulations and conceptual recombiner designs for containment application [3.25, 3.33]. One example of the catalyst designs is a Pd-Ni-Cu alloy plasma injected onto stainless steel plates and enveloped by filters for protection from chemical fouling. In the proposed mode of operation, the plates are initially contained in a box to avoid contamination during normal operation and are automatically opened and unfolded in an accident. One advantage of an open design is that the plates intercept existing air streams and thus are not reliant solely on the natural convective flow generated by the recombination reaction.

Electrowatt has developed a GRS design to commercial stage, with the co-operation of KFA (Forschungszentrum Jülich GmbH) [3.39, 3.40]. This device, which is called KATAREK, was tested at the Kali facility in France.

NIS

Catalytic recombiners have been developed by NIS Company in Hanau, Germany [3.26, 3.32, 3.55] and tested at the Battelle Model Containment and SANDIA Laboratories. The NIS PAR module consists of a row with standard catalytic cartridges. The body of the module holds the catalyst cartridges in a vertical direction and guides the convective air flow. The PAR exit has a chimney with a free cross-sectional area equal to the cross-sectional area through the cartridges, for improving air circulation and enhancing hydrogen removal. The active elements are palladium-coated aluminium oxide spheres with hydrophobic treatment held between perforated steel plates. The elements are arranged in holders inside housing designed to optimize flow over the catalyst material. Development tests of performance with steam exposure, CO, I_2 and various firms (oil fires, cable fires) were conducted at 125°C, 3% H_2. The NIS device is commercially available.

AECL

Recombiners developed by AECL use special high performance catalysts originally developed for heavy-water manufacturing [3.59]. The catalyst comprises platinum and palladium crystallites on a zeolytic hydrophobic support bonded to a stainless steel mesh. The material is flexible and robust, manufactured in a variety of configurations and has been extensively tested for extreme environments. The AECL recombiner is the only recombiner that does not rely on heat from the accident to start in humid atmospheres — the AECL catalyst is fully active at 1% H_2 or O_2 in humid atmospheres at 25°C. Full-scale qualification testing for nuclear containment applications has been completed for conditions of accelerated thermal ageing, prolonged operation in hydrogen atmospheres, containment sprays, sump chemicals, radiation, fuel aerosols and possible chemical vapours. Testing has been carried out at AECL Whiteshell Laboratories in Canada and at the IPSN H2PAR Facility in France. The AECL Recombiners are commercially available and are currently being installed in plants in North America and Europe.

3.6. Deliberate ignition

3.6.1. Description

The purpose of a deliberate ignition system (DIS) 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 deleterious effects of combustion (i.e., combustion temperature and overpressures) increase with increasing penetration of the flammable range of compositions.

Rates of hydrogen release or steam condensation that exceed the capacity of mixing or recombination will lead to flammable gas mixtures. Once a flammable mixture is present, minimizing the consequences of a potential combustion becomes a priority. Deliberate ignition offers a means of managing this condition while limiting consequences to those consequences that are characteristic of slow deflagration (non-adiabatic, incomplete combustion and associated low overpressures). Moreover, with a distributed ignition system, there is opportunity for venting to non-flammable volumes adjacent to the region where combustion is initiated, further reducing combustion pressures realized in any particular compartment. There is the obvious risk that deflagration, initiated at one location, may propagate into a more sensitive region nearby (i.e., nearer to the release point of hydrogen) or vent to flammable adjacent volumes (known as jet ignition) and propagate more vigorously than expected [3.62, 3.63]. However, a detailed, station-specific analysis of mixing processes demonstrated combustion behaviours in complex geometries can result in igniter placements that minimize the risk of unacceptable combustion loads on local structures or equipment. Placement strategy, analysis methodology and environmental qualification of power supply are practical issues to be addressed in each DIS design.

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. Glow-plug igniters are continuously available and may be manually operated (on and off), automatic (on in response to LOCA signals) or semi-automatic (automatic on, operator disarm). They are easy to test and the consequences of inadvertent, premature or unnecessary actuation are nil.

The one serious disadvantage of glow-plug type igniters is the high power requirement (typically 150 to 200 W each), the concomitant reliance on outside power and the associated lengths of cables and containment penetrations to deliver the power. Reliance on outside power is a concern in some scenarios (i.e., station blackout) where igniter function may be interrupted.

Qualified glow-plug igniter hardware is commercially available from automotive (GM) or aerospace (TAYCO) companies.

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.

Spark igniters are well suited to battery power. Battery-powered spark igniters take full advantage of the inherent low-energy requirement of spark ignition to eliminate reliance on outside power altogether by using a self-contained power supply in the form of batteries. Commercially available units (Siemens), designed for nuclear containments, generate sparks at a frequency of several sparks per minute for about a week following an accident [3.31]. A special water-jacketed housing protects the electronics from thermal and mechanical loads. In the particular units available, triggering is achieved automatically by pressure or temperature signals produced by the accident. The set point for triggering needs to be low because pressure and temperature transients preceding hydrogen production can be quite small (i.e., Three Mile Island). Selection of a low set point, however, raises the possibility of unintended triggering, which would deplete the batteries and, unknown to the operator, render the igniter unavailable. Selection of a high set point raises the probability of the igniters not triggering when needed. It is possible to operate battery-powered igniters from the control room. Although this adds the cost of wiring to switches in the control room and associated containment penetrations, it retains the advantage of self-powered igniters and eliminates the problem of triggering a set point.

Although spark igniters are effective ignition sources, the low frequency of sparking, necessary to conserve battery power, makes them unavailable for intervals of close to 6 s. This interval should be considered in terms of the time scale of local combustible mixture formation (hydrogen release, mixing and steam condensation rates). 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. Gas composition in the vicinity of an igniter may change significantly in a few seconds.

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.

Catalytic igniters

Catalytic igniters employ the heat of H_2–O_2 reaction at a special catalytic element to produce surface ignition temperatures high enough to cause ignition. Catalytic igniters are self-actuating (in response to the presence of hydrogen), self-powered (using the enthalpy of the H_2–O_2 reaction) and continuously available. The catalytic igniter potentially combines the desirable characteristics of glow plugs (continuous, energetic source) and battery-powered spark igniters (self-powered, suitable for backfitting) without the disadvantages of set points and intermittent operation. Catalytic igniters have been manufactured and successfully tested under a range of conditions relevant to post-accident containment atmospheres.

Catalytic igniters are commercially available (Siemens). The catalytic elements are protected from the atmosphere by a metal housing that opens automatically in response to temperature or pressure transients associated with an accident. The problem of set points for actuation is similar to the problem of set points discussed for spark igniters, except that performance of the catalytic element is not necessarily impaired by premature or accidental opening. It may be that it is not necessary to isolate the element from the atmosphere at all, thus further simplifying its function.

The practical questions regarding catalytic igniter performance are related to the range of mixtures that can be ignited, the response time and their availability in terms of poisoning, fouling or mechanical damage. Catalytic igniters operate over a narrower range of mixture compositions (i.e., not as near to absolute limits of flammability) than the glow plug or spark igniters. 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. The response of the catalytic igniter to surrounding conditions is limited by the time required for gases to transit the element and produce heat for ignition. The existing formulations of catalyst have been successfully tested for most foreseeable conditions (resistance to water vapour, organic fumes, iodine, carbon monoxide, smoke and other potential fouling agents). However, the question of availability under all possible conditions is still open. In schemes where igniters are used in combination with catalytic recombiners, catalytic igniters introduce the possibility of both devices failing for a common reason.

3.6.2. Implementation conditions

The implementation of a deliberate ignition system involves practical aspects and analytical aspects. Practical aspects include electrical connections, power availability (for some igniter types, see preceding descriptions and Table V) and environmental and seismic qualification. Practical aspects of implementing DIS are of a station-specific engineering nature, and are not considered here in any further detail. Analytical aspects of implementing deliberate ignition are the predictive calculations of mixing and combustion behaviour that provide the basis for the numbers and locations of igniters. Reliable containment thermalhydraulic calculations for the release scenarios are essential to rationalize igniter placements and to produce the initial conditions for predictions of combustion behaviour subsequent to ignition [3.64].

The analytical requirements for optimum implementation of deliberate ignition are still a challenge to the state of knowledge today. Some new progress is being made in integrating containment and thermalhydraulics and advanced combustion models. Combined with engineering judgement, existing codes can provide a credible framework for implementation of igniters. Nonetheless, uncertainties in scenario, mixing and combustion predictions are inevitable. Generally, the approach is to compensate for these uncertainties, to some extent, by conservative numbers and redundant placements of ignition sources.

Igniter number and location

Effective placement of igniters aims to achieve the following:

- ignite flammable mixtures whenever and wherever they occur, to prevent further accumulation of H_2 or O_2 in the flammable range;
- limit the consequences of combustion to those consequences that are characteristic of slow deflagration (non-adiabatic incomplete combustion with associated low overpressures);
- avoid possibilities for high hydrogen accumulation in volumes between igniter locations;

TABLE V. COMPARISON OF CANDIDATE IGNITION TYPES FOR HYDROGEN CONTROL IN NUCLEAR CONTAINMENTS

Igniter type	Advantages	Disadvantages
Glow plug	• ignite over widest range of compositions • continuous availability • robust • operator controlled	• rely on AC power • high-power requirement • containment penetration
Spark	• battery powered, do not rely on AC power • easily backfitted, no connections required	• intermittent operation (in 5-s intervals) • not operator controlled • weaker ignition source than for glow-plug igniters • unavailable in long term • electromagnetic interference from spark • rely on triggering from LOCA signals
Catalytic	• self-powered, uses heat of H_2-O_2 reaction to produce ignition temperatures • easily back-fitted, no connections required	• operates over narrower range of compositions than do either spark or glow-plug igniters • response to changing conditions not instantaneous • potential for poisoning or fouling • rely on triggering from LOCA signals • combined with recombiners, subject to common cause failure

- take advantage of local pressure relief by venting to non-flammable volumes;
- avoid igniter placements that contribute to flame acceleration and “jet ignition”, phenomena (i.e., at dead-end of long rooms or linked volumes containing possible flammable mixtures); and
- avoid ignition locations that induce flow of H_2-rich, steam-inerted mixtures into adjacent compartments containing air.

Analysis is required to achieve these aims with a manageable number of igniters. For example, igniter placements 10 m apart, with 2 times redundancy results in a manageable number of igniters (100 to 150) to install in a large containment. If such uncertainties exist that igniter placement cannot demonstrably achieve these aims, the average distance between must be effectively shortened. Igniter spacing of 5 m, with 2 times redundancy requires 400 to

600 igniters, possibly an unmanageable number. Additional igniters compensate for predictive uncertainties only within that range where the required numbers of igniters are manageable.

Currently, igniters are installed as mitigation system in some plants as in single and multi-unit CANDU stations and PWRs with ice condenser containments [3.65–3.67].

3.7. Strategic combinations

3.7.1. Catalytic recombiners and igniters (dual concept)

A combination of deliberate ignition (Section 3.6) and catalytic recombination (Section 3.5), which is known as the 'dual concept', was developed and tested in Germany [3.31]. The test results indicated that such a combination should be effective in controlling the hydrogen concentration under inerted and non-inerted conditions inside a containment. In this case, it is recognized that recombiners cannot cope with the high hydrogen release rate early in the accident and therefore igniters are used for initiating combustion at the flammability limits and to prevent formation of rich mixtures.

For the use of a combination of recombiners and igniters, the following advantages exist [3.50, 3.68–3.70]:

- diversity in the system, local "backup" for recombiners or igniters;
- continuous H_2 reduction, already before that combustible gas mixtures have formed and under steam inerted conditions;
- in case of a limited release of H_2 (e.g., TMI accident) combustion could be prevented;
- in case of a sudden strong increase in H_2 release or steam condensation during accident progression, combustion starts from a lower level of H_2 concentration;
- for filtered venting less H_2 in the atmosphere because of continuous H_2 reduction by catalytic recombination; and
- long-term effectiveness of catalyst (radiolysis of sump water).

For both, the deliberate ignition and the dual concept, the layout and demonstration of their efficiency needs the use of appropriate thermalhydraulic computer codes, beside experimental results. Theoretical investigations are performed to determine the main convection flow paths of the gases inside the containment, relevant for the optimal location of catalytic devices and igniters, and for demonstrating the efficiency of such a system in different accident scenarios. It appears that current trends favour the installation of PARs backed up by igniters [3.46]. This concept is in use in existing reactors and is provided for advanced reactors as well [3.41].

3.7.2. 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, this strategy is limited in application only to relatively strong containments that can withstand deflagration pressures by a good margin.

Experimental tests show that carbon dioxide below 30% does not affect the recombiner efficiency but can greatly improve margins for strong flame acceleration and DDT. Large-scale experiments are needed to know the optimum CO_2 concentration to prevent flame acceleration in the large volumes of a nuclear reactor containment.

Application of post-accident dilution (PAD) system combined with recombiners or igniters is studied for multi-units WWER plants [3.23].

3.7.3. Forced mixing and deliberate ignition

The volume of air in large containments offers the potential to safely dilute several hundred kilograms of hydrogen. However, this potential may not be realized in the short term from natural-mixing mechanisms. Transient local pockets of high hydrogen concentrations and stratification may, inevitably, arise. Moreover, large numbers of igniters are required to cover all potential pockets where flammable mixtures may arise. Engineered mixing systems enables greater use to be made of the containment air to dilute the hydrogen, and prevent combustible mixtures for all but the worst hydrogen release scenarios. Where igniters are required, the homogenized atmosphere offers confidence that ignition at one location will not propagate to more sensitive regions elsewhere. Thus fewer igniters are required. With engineered mixing, the diluting capacity of containment air is more effectively utilized, and the number and placement of igniters is rationalized with greater confidence. Deflagration may be more complete and a higher peak pressure may occur, but its value is more easily predictable.

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4. CONCLUDING REMARKS

From the preceding sections, it is evident that a selection of measures for hydrogen mitigation is highly plant specific. Certain containment designs preclude the implementation of some measures and favour, or indeed necessitate, the implementation of other measures. Back fitting imposes certain other restrictions that are not imposed on designers of new containments.

Table VI summarizes the strengths and weaknesses of the various measures described in Section 3. Some of the strengths and weaknesses listed may be more or less significant, depending on the plant design.

Table VII reviews the alternative mitigation measures in terms of their function of either oxygen control or hydrogen control. This representation draws attention to the fundamental difference between the two approaches to controlling a combustion threat. Measures that control the limiting reactant (dilution or removal) achieve an immediate benefit of preventing flammability or reducing eventual combustion consequences in proportion to the extent of removal or dilution accomplished. Measures that control the excess reactant (inerting) are of an all-or-nothing nature. That is, a large intervention is required to render the excess reactant limiting in the combustion reaction. Oxygen control (in an initially air atmosphere) only becomes effective once oxygen concentration is reduced to below the rich flammability limit

In Section 3, some strategic combinations of measures are described that provide a sensible dual defence of diluting or removing hydrogen in most cases but also minimizing consequences in those cases where combustible mixtures cannot be avoided. For example, engineered mixing, catalytic recombination and CO_2 gas injection are effective means of maintaining a non-flammable condition for all but the most extreme rates and quantities of hydrogen release. And they also function to make combustion, if ever produced by deliberate or by unintentional ignition, more predictable and less energetic. Further, some measures are more suited to particular phases of the accident. For example, igniters are a last line of defence to prevent detonations under fast-developing local conditions but not an optimum choice for slow hydrogen releases or long term hydrogen control. Recombiners have mass-transfer limits in conditions of local high release rates but are highly effective for intermediate and long term hydrogen control. Diverse and independent measures are thus working for the goal of maintaining a non-flammable atmosphere, with measures to match the needs of each phase of the accident. Combinations of countermeasures are thus synergistic — and reliance on any one measure is reduced. In containment designs or subvolumes where the hydrogen threat is high, diverse and redundant systems for hydrogen control may provide cost-effective gains in safety margin.

To conclude, it is reiterated that the nature of the hydrogen threat to containment and the choice of measures to mitigate the hydrogen threat depend strongly on the containment design. There is not one single strategy or technique that is universally appropriate for all designs and accident scenarios, or even, for all phases of an accident in a particular design. Different measures may be more appropriate at different locations and at different times during an accident. A completed safety assessment for the particular plant is the only valid context for judging the adequacy of safety systems and accident management measures, including hydrogen countermeasures.

TABLE VI. SUMMARY OF STRENGTHS AND WEAKNESSES OF ALTERNATIVE HYDROGEN MITIGATION MEASURES

Hydrogen mitigation measure	Strengths	Weaknesses
Pre-inerting	– H_2 independent condition exits prior to accident – effectiveness well proven – passive; no operator action required – design not safety related – reduces corrosion problems during normal operation	– hazard of asphyxiation of personnel; not safety-oriented for normal operation – high cost of normal maintenance – affects duration and frequency of maintenance shutdowns – oxygen monitoring required – further measures required for long-term oxygen control
		– actions to be taken by the plant personnel early during the accident progression
Post-accident inerting	– create H_2 independent conditions before severe accident H_2 release starts – experiences for system layout exist from fire-fighting systems	– the criteria for the operator actions are accident-dependent (desirable to prevent post-inerting for DBAs) – containment pressure increase due to inert gas injection leads to early venting requirements, thus affecting the layout of the filtered vent-system

TABLE VI. (cont.)

Hydrogen mitigation measure	Strengths	Weaknesses
Post-accident inerting	– prevent detonations	– elevated pressure; higher leakage from the containment possible – after post-inerting, long-term actions have to be taken to keep the atmosphere inert (O_2 production by sump water radiolysis) – short-term mixing has to be realized by the system layout – in-use of fluidized gas injection; thermal shock loads to the equipment possible – serious consequences could result from accidental actuation during normal operation – may require additional containment penetrations – failure or untimely operator decisions during accidents lead to unmitigated containment threats – flammable gas mixtures are not prevented

TABLE VI. (cont.)

Hydrogen mitigation measure	Strengths	Weaknesses
Post-accident dilution	– increases the diluting capacity of containment air in proportion to amount of diluent added – reduces potential for local detonation and associated dynamic loads, missile generation, etc. if eventually combustion occurs	– no H_2/O_2 removal from the containment – long-term H_2/O_2 control still necessary – local loads and equipment damage still possible – actions have to be taken by the plant personnel during accident progression – actions depend on accident sequences (to exclude inert-gas injection in case of a DBA) – injected inert gas contributes to pressure build-up in the containment – the injection of fluidized gas could lead to damage to the equipment through thermal shock
Passive catalytic recombiners	– removal of H_2 and O_2 at non-flammable concentrations – self-starting in response H_2 (with available oxygen) – self-feeding by natural convection from heat of reaction	– mass transfer limited – some potential for fouling or chemical poisons

TABLE VI. (cont.)

Hydrogen mitigation measure	Strengths	Weaknesses
Passive catalytic recombiners	– supplement to natural mixing, homogenize stratified volumes – long-term H_2/O_2 control – qualified designs available from nuclear vendors – passive, do not require operator action or automation – qualified hardware available	– limited capacity; at high release rates, flammable mixtures may form locally.
Igniters	– fast-acting and high capacity removal of H_2/O_2 – proactive with respect to preventing strong deflagrations and detonations – some types of igniters are passive (catalytic igniters)	– power requirement (glow-plug) – selection of location and number requires complex analysis – operator action or trigger system required (glow-plug, spark) – H_2 distribution uncertainty contributes to uncertainty of consequences of combustion – survivability of essential equipment – threat of local pressure loads

TABLE VI. (cont.)

Hydrogen mitigation measure	Strengths	Weaknesses
Catalytic recombiners and igniters (dual concept)	– the system combines two lines of defence with diverse functional aspects – continuous reduction of H_2 below flammability limits, under steam-inerted conditions and after exceeding flammability limits – removal of H_2/O_2 prior to combustion lessens potential consequences of the combustion – long-term effectiveness – can be back-filled to existing containment	– detailed analysis needed to select the distribution of catalytic devices and igniters in the containment – local dynamic loads and missiles could not be excluded
Post-accident dilution (PAD) and catalytic recombination	– increases the diluting capacity of containment air in proportion to amount of diluent added – reduces threat of local dynamic loads and missiles (detonability) in short term, while recombiners remove hydrogen. – long-term effectiveness – removal of H_2 prior to an unintentional ignition	– actions have to be taken by the plant personnel during accident progression – such actions depend on accident sequences (in order to exclude inert gas injection in case of a DBA) – injection of inert gas contributes to pressure build-up in containment – the injection of fluidized gas could lead to damage to the equipment through thermal shock loads – some vulnerability to local blowdown forces for the catalytic recombiners

TABLE VI. (cont.)

Hydrogen mitigation measure	Strengths	Weaknesses
Containment atmosphere dilution by inert-gas injection and catalytic recombination		– elevated pressure level by inert-gas injection requires early venting and causes increase of leakage from containment
Engineered mixing and deliberate ignition	– same as deliberate ignition – control of H_2 distribution by engineered mixing – less uncertainty of combustion behaviour; ignition placement less critical – air movement improves completeness of combustion – optimizes dilution capacity of containment air volume – combines two lines of defence with diverse functional aspects	– vulnerable to station blackout interruption if requiring outside power – non-homogeneous hydrogen distribution, local loads, missile and equipment damage still possible

TABLE VII. MEASURES FOR SEVERE-ACCIDENT HYDROGEN MITIGATION

Oxygen control	Hydrogen control
First and only defence Effective prevention of combustion for all release scenarios but impractical to implement for many containment types pre-inerting* post-inerting* with early venting	First level of defence Practical to implement and effective prevention of combustion for most release scenarios catalytic recombiners engineered mixing post-CO_2 injection
	Second level of defence Practical to implement and effective mitigation of combustion consequences deliberate ignition post-CO_2 injection

* Still requires long-term O_2 control measures.

Strategic combinations of Level 1 and Level 2 measures

1. Catalytic recombiners and deliberate ignition,
2. engineered mixing and deliberate ignition,
3 post-CO_2 injection and deliberate ignition, and
4. catalytic recombiners and post-CO_2 injection (mitigated unintended ignition).

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