



SES6-CT-2004-502630

HySafe

“Safety of Hydrogen as an Energy Carrier”

Instrument: Network of Excellence
Thematic Priority: Sustainable Energy

Final Activity Report

Period covered: March 1st, 2004 to February 28th, 2009

Due date of deliverable: April 15, 2009
Actual submission date:

Start date of project: March 1st, 2004 (Duration: 5 years)

Dr.-Ing. Thomas Jordan
Forschungszentrum Karlsruhe GmbH

Version 0.1

Project co-funded by the European Commission within the Sixth Framework Programme (2002-2006)

Dissemination Level

PU Public
PP Restricted to other programme participants (including the Commission Services)
RE Restricted to a group specified by the consortium (including the Commission Services)
CO Confidential, only for members of the consortium (including the Commission Services)

Document History

| | | |
|------|------------|---|
| V0.1 | 12.03.2009 | First Draft Version |
| V0.2 | 14.03.2009 | Second draft |
| V1.0 | 30.06.2009 | Updated executive summary, corrected general part |
| V1.1 | 01.07.2009 | Inclusion of missing detailed descriptions |
| V1.2 | 10.07.2009 | Replacing executive summary and reformatting |

CONTENTS

| | |
|---|-----------|
| INTRODUCTION | 5 |
| 1 PROJECT OBJECTIVES AND MAJOR ACHIEVEMENTS | 22 |
| 1.1 OVERVIEW OF GENERAL NETWORK OBJECTIVES | 22 |
| 2 PROGRESS OF THE CLUSTER “BASIC RESEARCH” | 25 |
| 2.1 WORK PACKAGE WP2: INTEGRATION OF EXPERIMENTAL FACILITIES (IEF) | 25 |
| 2.1.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 25 |
| 2.1.2 <i>Achievements of the activity, the current state:</i> | 25 |
| 2.1.3 <i>Outlook for further research work:</i> | 26 |
| 2.1.4 <i>List of Deliverables for WP 2:</i> | 27 |
| 2.2 WORK PACKAGE WP6: NUMERICAL TOOLS | 27 |
| 2.3 WORK PACKAGE WP8: HYDROGEN RELEASE MIXING AND DISTRIBUTION | 31 |
| 2.3.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 31 |
| 2.3.2 <i>Achievements of the activity, the current state:</i> | 32 |
| 2.3.3 <i>Outlook for further research work:</i> | 33 |
| 2.3.4 <i>List of Deliverables:</i> | 33 |
| 2.3.5 <i>References</i> | 34 |
| 2.4 WORK PACKAGE WP9: HYDROGEN IGNITION AND (JET) FIRES | 34 |
| 2.5 WORK PACKAGE WP10: HYDROGEN EXPLOSIONS | 37 |
| 2.6 WORK PACKAGE WP18: MATERIAL COMPATIBILITY AND STRUCTURAL INTEGRITY | 41 |
| 2.6.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 41 |
| 2.6.2 <i>Achievements of the activity, the current state:</i> | 42 |
| 2.6.3 <i>Outlook for further research work:</i> | 46 |
| 2.6.4 <i>List of Deliverables for WP 18:</i> | 46 |
| 2.7 INTERNAL PROJECT IP1: INSHYDE (HYDROGEN RELEASES IN CONFINED AND PARTIALLY CONFINED SPACES) | 46 |
| 2.7.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 46 |
| 2.7.2 <i>Achievements of the activity, the current state:</i> | 47 |
| 2.7.3 <i>Outlook for further research work:</i> | 52 |
| 2.7.4 <i>List of Deliverables:</i> | 52 |
| 2.7.5 <i>References</i> | 53 |
| 2.8 INTERNAL PROJECT IP2: HYTUNNEL | 54 |
| 2.8.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 54 |
| 2.8.2 <i>Achievements of the activity, the current state:</i> | 56 |
| 2.8.3 <i>Outlook for further research work:</i> | 60 |
| 2.8.4 <i>List of Deliverables for IP 2:</i> | 60 |
| 3 PROGRESS OF THE CLUSTER “RISK MANAGEMENT” | 61 |
| 3.1 WORK PACKAGE WP5: HYDROGEN SAFETY INFORMATION SYSTEM – HYSAFE-IS | 61 |
| 3.1.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 61 |
| 3.1.2 <i>Achievements of the activity, the current state:</i> | 62 |
| 3.1.3 <i>Outlook for further research work:</i> | 62 |
| 3.1.4 <i>List of Deliverables for WP5:</i> | 62 |
| 3.2 WORK PACKAGE WP11: SAFETY MEASURES - PREVENTION AND MITIGATION | 63 |
| 3.2.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 63 |
| 3.2.2 <i>Achievements of the activity, the current state:</i> | 63 |
| 3.2.3 <i>Outlook for further research work:</i> | 65 |
| 3.2.4 <i>List of Deliverables for WP 11:</i> | 66 |
| 3.3 WORK PACKAGE WP12: RISK ASSESSMENT METHODOLOGY | 66 |
| 3.3.1 <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 66 |
| 3.3.2 <i>Achievements of the activity, the current state:</i> | 66 |
| 3.3.3 <i>Outlook for further research work:</i> | 67 |
| 3.3.4 <i>List of Deliverables for WP12 :</i> | 67 |

| | | |
|----------|---|---|
| 3.4 | WORK PACKAGE WP16: CONTRIBUTION TO STANDARDS AND LEGAL REQUIREMENTS | 68 |
| 3.4.1 | <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 68 |
| 3.4.2 | <i>Achievements of the activity, the current state:</i> | 68 |
| 3.4.3 | <i>Outlook for further research work:</i> | 69 |
| 3.4.4 | <i>List of Deliverables for WP 16:</i> | 69 |
| 3.5 | INTERNAL PROJECT IP3: HYQRA | 70 |
| 4 | PROGRESS OF THE CLUSTER “DISSEMINATION” | 72 |
| 4.1 | WORK PACKAGE WP1: BIENNIAL REPORT ON HYDROGEN SAFETY (BRHS) | 72 |
| 4.1.1 | <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 72 |
| 4.1.2 | <i>Achievements of the activity, the current state:</i> | 72 |
| 4.1.3 | <i>Outlook for further research work:</i> | 72 |
| 4.1.4 | <i>List of Deliverables for WP1:</i> | 73 |
| 4.2 | WORK PACKAGE WP14: INTERNATIONAL CONFERENCE ON HYDROGEN SAFETY (ICHS)..... | 73 |
| 4.2.1 | <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 73 |
| 4.2.2 | <i>Achievements of the activity, the current state:</i> | 73 |
| 4.2.3 | <i>Outlook for further research work:</i> | 74 |
| 4.2.4 | <i>List of Deliverables for WP 14:</i> | 74 |
| 4.3 | WORK PACKAGE WP15: E-ACADEMY OF HYDROGEN SAFETY | 74 |
| 4.3.1 | <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 75 |
| 4.3.2 | <i>Achievements of the activity, the current state:</i> | 75 |
| 4.3.3 | <i>Outlook for further education related work:</i> | 76 |
| 4.3.4 | <i>List of Deliverables for WP15:</i> | 77 |
| 5 | PROGRESS OF THE CLUSTER “MANAGEMENT” | 78 |
| 5.1 | WORK PACKAGE WP7: STRATEGIES | 78 |
| 5.1.1 | <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 78 |
| 5.1.2 | <i>Achievements of the activity, the current state:</i> | 78 |
| 5.2 | WORK PACKAGE WP17: OVERALL MANAGEMENT AND COORDINATION | 80 |
| 5.2.1 | <i>State of the art and knowledge gaps before 2004, and main objectives of this activity:</i> | 80 |
| 5.2.2 | <i>Achievements: Organisation</i> | Fehler! Textmarke nicht definiert. |
| 5.2.3 | <i>Achievements: Meetings</i> | Fehler! Textmarke nicht definiert. |
| 5.2.4 | <i>Achievements – Documents:</i> | Fehler! Textmarke nicht definiert. |
| 5.2.5 | <i>Achievements – Financials:</i> | Fehler! Textmarke nicht definiert. |
| 5.2.6 | <i>Achievements – Networking:</i> | Fehler! Textmarke nicht definiert. |
| 5.2.7 | <i>Achievements – Integration:</i> | Fehler! Textmarke nicht definiert. |

Part A - Executive Summary

Introduction

Still coined by the national schemes of old European policies also the European research suffered in many relevant areas from a high degree of fragmentation. For instance research activities in the field of hydrogen safety in Europe mainly originated from three areas: there were safety investigations for natural gas applications and studies of the automotive industries planning to introduce hydrogen driven fuel cells into the market. On the other hand, in the field of nuclear technology, hydrogen is a safety issue in severe accident and operational research for more than 20 years. The related research topics had different weights on national agendas and associated knowledge was dispersed, not compiled and partially even confidential.

To overcome this fragmentation, to support the needed integration and to focus related efforts the European Commission created a new instrument, the Networks of Excellence (NoE).

To facilitate the safe introduction of hydrogen as an energy carrier and to remove safety related obstacles, the NoE HySafe – Safety of Hydrogen as an Energy Carrier - was initiated and supported by the European Commission (EC).

There was a need to identify the partners' best expertise, potentially overlapping activities and possible gaps. Furthermore, in order to achieve a high standard in the quality of available relevant data, the know-how transfer between the partners needed to be enforced. The exchange of expertise and know-how between the partners is one of the keys to provide high quality and highly efficient experimental and theoretical research work. The objectives of the NoE HySafe were to

- strengthen, focus and integrate the fragmented research on hydrogen safety,
- form a self-sustained competitive scientific and industrial community,
- promote public awareness and trust in hydrogen technologies and
- develop an excellent safety culture.

The network, coordinated by the Forschungszentrum Karlsruhe, has 24 partners from 12 European countries including Russia and Canada. There are 12 partners from public research institutions, 7 industry partners, 5 universities and one governmental authority.

More than 120 scientists from these institutions have been nominated to contribute to the network. This number was the basis for the determination of the maximum EC grant, of 7 Mio Euro for 5 years. The total budget is 13 Mio Euro for this period.

The network activities formally started on March 1st, 2004. The NoE follow-up, the International Association for Hydrogen Safety HySafe (IA), was founded by a huge majority of the NoE consortium February 26th, 2009, in Brussels, Belgium. This non-profit association will continue the integration work and aim to maintain the network's successful activities like the international hydrogen safety conference, the website and databases, the handbooks etc.



Figure 1: The NoE HySafe logo

All network activities - 15 work packages and 3 internal projects - were arranged in four activity clusters. In line with the main objectives these clusters were the following: “Basic Research”, “Risk Management”, “Dissemination” and “Management”. The allocation of the activities in the clusters is depicted in the figure 1 below.

Table 1. NoE HySafe members (bold = IA founding members of the International Association)

| <i>Name of Institution</i> | <i>Abbrev.</i> | <i>Country</i> |
|--|----------------|----------------|
| Forschungszentrum Karlsruhe GmbH | FZK | DE |
| L'Air Liquide | AL | FR |
| Federal Institute for Materials Research and Testing | BAM | DE |
| BMW Forschung und Technik GmbH | BMW | DE |
| Building Research Establishment Ltd | BRE | UK |
| Commissariat à l'Energie Atomique | CEA | FR |
| Det Norske Veritas AS | DNV | NO |
| Fraunhofer-Gesellschaft ICT | Fh-ICT | DE |
| Forschungszentrum Jülich GmbH | FZJ | DE |
| GexCon AS | GexCon | NO |
| The United Kingdom's Health and Safety Laboratory | HSE/HSL | UK |
| Foundation INASMET | INASMET | ES |
| Inst. Nat. de l'Environnement industriel et des RISques | INERIS | FR |
| European Commission - JRC - Institute for Energy | JRC | NL |
| National Center for Scientific Research Demokritos | NCSR | EL |
| StatoilHydro ASA | SH | NO |
| DTU/Risø National Laboratory | DTU/Risø | DK |
| TNO | TNO | NL |
| University of Calgary | UC | CA |
| University of Pisa | UNIPI | IT |
| Universidad Politécnica de Madrid | UPM | ES |
| University of Ulster | UU | UK |
| VOLVO Technology Corporation | Volvo | SE |
| Warsaw University of Technology | WUT | PL |
| Russian Research Centre Kurchatov Institute | KI | RUS |

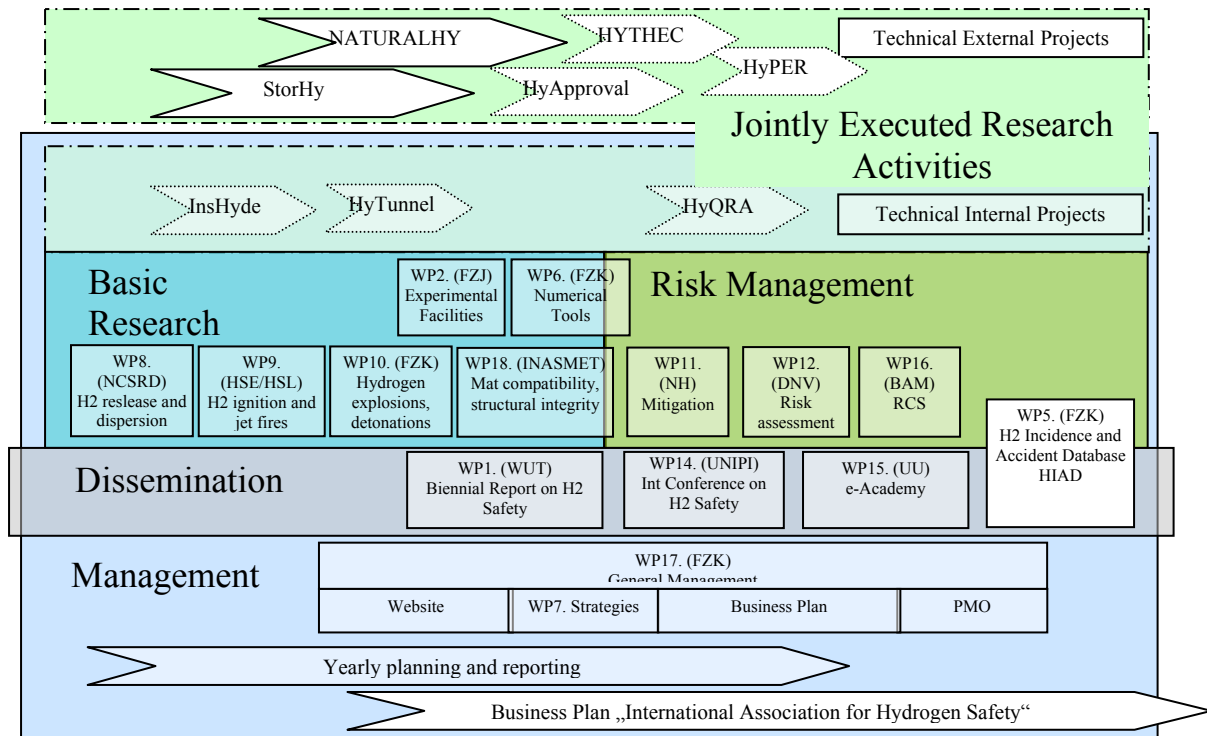


Figure 2: HySafe Activity Clusters

1 Results of Cluster “Basic Research”

The Cluster “Basic Research” consisted of the phenomena orientated work packages for hydrogen distribution, ignition and fires, explosions and material compatibilities. Additionally the two work packages integrating the hardware and software research tools and the internal projects InsHyde and HyTunnel were accommodated in this cluster.

1.1 Integration of the Experimental Facilities

In the first period of the project, a compilation of the experimental facilities [1] was provided to serve as a starting point for further activities. The final version of the IEF documentation including the updated IEF documents [29] contains a total of 109 technical descriptions of HySafe facilities operated by 15 partners. A web presentation [9] of all facilities is available through the HySafe website [42].

In order to ensure a common quality standard, a series of biannual workshops was initiated related to measurement techniques and experimental work. The general aim of the IEF workshops is to become acquainted with the partners’ activities, to share knowledge in the field of experimental work and to support jointly planned and performed experiments. A total of 8 well received workshops have been organised covering topics from measurement technologies to safety issues. Based on the information presented by the partners, a working document on best practice including the joint experimental knowledge of all partners with regard to experiments and instrumentation was created. Preserving the character of a working document, it was implemented in the IEF wiki page, which was set up in order to provide a communication platform. The series of workshops supports the

wiki-based working document on best practice intended to be a guide for experimental work in the field of hydrogen safety [43].

1.2 Numerical Tools

A series of single effect tests was identified to allow for model verification [16] and a large collection of Standard Benchmark Exercises Problems (SBEPs) was compiled, where the focus lied on the use of hydrogen in industry relevant scales [17, 19, 23, 34, 40]. In these more than 20 validation tests the physical and numerical adequacy of the models used in CFD simulations [5] was identified. The main phenomena addressed in these exercises were turbulent transport in particular in buoyant flows, hydrogen releases with small to strong inertial effects, effective flame velocities, transitional combustion phenomena etc. The participation in these SBEPs, quantified by the number of participants and codes was comparatively large, e.g. 12 partners with 10 different 3D CFD codes and one analytical 0D solver in SBEPV3.

The results of the SBEP exercises were compared and published regularly, in particular via the HySafe initiated conference ICHS [8,28].

The capabilities of this strong group was offered and in quite a few cases applied in external projects, e.g. HyApproval [44], HyPer etc.

1.3 Phenomena Orientated Work Packages (WP8 Mixing, WP9 Ignition and Fire, WP10 Explosion, WP18 Material Compatibilities)

The actual work of these expert groups was to collect, review and compile existing know-how in the related areas. Thus knowledge gaps were identified as a by-product. This collected know-how was mainly used in the internal projects InsHyde and HyTunnel but also applied in the other activities. A good example is the survey on ignition, deliverable D42 of WP9 which was used in the risk assessment work package as a basis for recommendations regarding selecting ignition models (deliverable D71 provided by WP12 and WP9 commonly). Other results of the phenomena oriented work packages – in particular WP10 - are presented in [22, 26, 32, 41] for instance, where new explosion tests delivered new insights in the transitional phenomena of flame acceleration and deflagration-detonation transition. The work package WP18 compiled information regarding high pressure high purity material compatibility [35] and regarding test procedures for nano-scaled storage materials in deliverable D112.

1.4 Internal Project “InsHyde”

In the first year of the NoE HySafe the “safety vote” defining the phenomena identification and ranking table (PIRT [4]) and an additional expert survey have pointed out that releases - even slow releases, with “small” release rates - of hydrogen in confined or partially confined geometries represent a serious risk, since combustible mixtures may form, which, if ignited, could lead to explosions and even to detonations. Thus, it revealed necessary to study different configurations of these non-catastrophic releases (position, release rate) and the accompanying sensor equipment and mitigation devices (ventilation or other ways of enhancing mixing, inertisation, active ignition or recombination). The InsHyde program has been initiated during in the 2nd year of the NoE and consisted of a broad experimental and computer simulation program.

Theoretical studies, literature surveys, sensor evaluations, a broad experimental program covering releases, mixing and combustion experiments and associated computer simulations helped to derive recommendations for the indoor usage of hydrogen. The key results of this internal project are summarised in [39].

There is an obvious link between confined environment and settings like residential garages or repair shops, where one has to prove that several kilograms of hydrogen can be stored safely. Here one has to account for imperfections either on the side of the vehicle or on the building itself. Therefore an application of the results of InsHyde to these scenarios was proposed in the HyGarage proposal.

Besides the InsHyde results already proved to be a valuable knowledge basis for other related projects like HyPer, where a handbook for the safe installation of small stationary hydrogen driven devices has been developed.

1.5 Internal project “HyTunnel”

The current tunnel regulations and standards identified relevant requirements and current practices in respect to the management of hazards and emergencies in the event of a fire were studied. Of particular relevance in Europe was the recently published EU Directive on minimum safety levels now required in the main road tunnels on the trans-European Road Network (*Directive 2004/54/EC*).

A review of modelling activity from the published literature related to hazard and risk assessment due to fires in tunnels was undertaken, particularly focusing on

- Hydrogen dispersion modelling studies in tunnel environment,
- Fire and explosion modelling studies, and
- Hydrogen release experiments relevant to tunnels.

This review included recent publications and international conferences including the HySafe conference ICHS organised 2005 in Pisa, Italy, and 2007 in San Sebastian, Spain.

Overall, the interaction of the ventilation system, tunnel geometry and hydrogen release is complicated, and recourse to numerical modelling is required. Some of the effects that ventilation inside a tunnel may have in respect to a release of hydrogen gas or on the smoke and heat from a fire (not necessarily a H₂ vehicle) can be summarised as follows:

- ✓ The supply of air may dilute the hydrogen such that it is below the flammability limit.
- ✓ The dispersed hydrogen may be transported safely out of the tunnel through either a portal or via an exhaust ventilation duct or shaft.
- ✓ The ventilation system may break down a stratified layer of flammable hydrogen gas mixture such that the resultant fully mixed gas is below the flammable limit.
- ✗ The released hydrogen may be transported such that the cloud of flammable gas mixture is extended well away from the point of release, either within the traffic space or along ventilation ducts or shafts.
- ✗ Hot smoke gases from a fire may get transported to neighbouring H₂ vehicles, exposing them to thermal hazard.
- ✗ Strong mechanical ventilation may create turbulence within the tunnel sufficient to affect the combustion regime (of hydrogen in particular) if ignition occurs.

The research of this work has led to some interesting findings. For example, some findings of the dispersion study are as follows:

- Horseshoe cross section tunnel indicates lower hazard than equivalent rectangular cross-section tunnel with regards to flammable cloud volume and its longitudinal and lateral spread
- Increasing height of the tunnel indicates safer conditions to tunnel users for buoyant releases of H₂
- Compressed gas H₂ (CGH₂) releases pose greater hazard than natural gas releases, but still not significant
- Increase of ventilation velocity decreases the cloud size and hence results in lower hazard;

However, CFD simulation results are not conclusive on the following aspects: level and extent of hazard with no ventilation versus ventilation and hazard posed by liquid hydrogen (LH₂) versus CGH₂ releases.

Further details, for instance also on the explosion research done in the frame of this activity, are included in the final report of the HyTunnel project [38].

2 Results of Cluster “Risk Management”

This cluster consisted of the work package for mitigation measures including sensors, the risk assessment work package, the regulation and standards work package and finally the work package dealing with the databases. The internal project for quantitative risk assessment HyQRA was successfully launched and provided a comparison of different approaches applied to the basic benchmark case, a prototypical refuelling station [33].

2.1 Hydrogen Incidents and Accidents Database (HIAD)

Before 2004 there was no database dedicated to hydrogen incidents or accidents. Therefore in the original plan for HySafe the development of such a database was included. Furthermore with an early information exchange with the US DOE it was tried to make the parallel efforts compatible for future data merging.

The HIAD database [18] is dedicated solely to incidents and accidents involving hydrogen. Due to the reluctant attitude of industry to share their data the database had to be designed to be based mainly on public information. The structure of the database was carefully designed and is documented in [2].

Agreements with other organisations providing databases (Mars, ARIA, VARO, Fireworld, ...) with at least some relevant entries have helped to develop the content of HIAD into 310 events which means that HIAD currently is the largest database for hydrogen incidents and accidents.

The data entry module was continuously improved and manuals for users were developed and updated. A Data Analysis Module has been developed and a HIAD Quality Assurance Expert Group (QAEG) was formed. In the last period of the official HySafe NoE, the QAEG approved the quality of 60 events.

The public database HIAD is maintained by the JRC, which as the EC body also runs other EC levelled databases on their ODIN server (see [45]).

2.2 Mitigation (WP11)

Similar as in the phenomenological work packages the main result of WP11 was to compile a survey of experimental facilities and numerical capabilities with regard to effect of mitigation measures. The results of this work have been reported in the deliverable D43/61. Also this activity mainly supported the internal projects with regard to sensor evaluation and consulting the participants in HyTunnel with regard to suitable mitigation technologies in tunnels. In close collaboration with WP12 and HyQRA WP11 delivered contributions to the InsHyde final report regarding risk reducing measures in garages, tunnels, refuelling stations etc.

2.3 Risk Assessment Methodology (WP12)

This activity prepared the basis for comparison of risk information and communication. The achievements are collected in [6] and [12]. Moreover, the issue of risk tolerance has got more attention both within HySafe and beyond. An important conclusion from our work is that risk criteria are never absolute, even where specific criteria are part of the legislation. Thus establishment of “basic” criteria is not considered a relevant, nor helpful objective.

Further, the basis for communication of risk has been established in [12], which is also an important step as most partners have been using different terminology and/or the terminology was not in accordance with European and ISO standards.

The work on explosive atmosphere hazardous zones has been based on the ATEX (“atmosphère explosible”) directive and underlying standards, in particular on the interpretation of the ATEX directive in Italian legislation, as this interpretation encompasses the use of risk assessment based evaluations for establishing the hazardous zones as an alternative to the standard templates. The work has resulted in a paper presented at the 2nd ICHS conference giving guidelines for ATEX hazardous zoning for a hydrogen applications as well as calculation examples for a hydrogen station. This paper is a part of [15].

The work on safety distances has resulted in a report [20] and the establishment of a benchmark base case (HySafe BBC) for testing of the methodology for safety distances and for quantitative risk assessment. The quantitative risk assessment has been carried out in HyQRA, while safety distance calculations have been carried out by several partners in WP12.

2.4 Regulation Codes and Standard (WP16)

This activity had the main function to serve as an information exchange platform for scientific groups and standards developing organisations [7].

The experts of WP 16 held a number of meetings during which they discussed matters of current interest in the international standardisation committees, mainly the ISO TC 197 and IEC TC 105. The WP16 group also participated in the development of a European regulation for the type approval of hydrogen road vehicles. The European Commission had invited experts to comment on a draft, and HySafe, represented by WP16, submitted such a comment which was approved by the group after intensive discussions.

As far as the effect on the international standard committees is concerned the general impression is that the weight of the European P members has increased. This is necessary because with India and China ISO TC 197 has now two new Asian members which will add considerable weight to the committee.

A long discussion about ways to improve the communication of involved parties is summarised in a milestone report. An internet forum was installed which makes it possible to exchange the relevant papers among the interested parties and to collect opinions on them. This is to prevent that a paper which poses problems for one partner is more or less automatically approved by the others simply because they do not know about these problems. This activity is still developing. Although targeting a concerted, scientifically based concerted voting from all European P members is too ambitious, certain coordination via HySafe became already obvious.

2.5 HyQRA

HyQRA is considered as the important bridging element between basic scientific work and industry relevant application. The aim with the activity is to develop a reference Quantitative Risk Assessment (QRA) methodology for hydrogen technologies applying, where necessary, simplified methods for acceptable answer times as required for engineering tools.

After the common definition of the HyQRA Benchmark Base Case (BBC) refuelling station scenario, including detailed geometry, piping and flow diagram, etc, all backed up by the associated HyApproval work, 8 HySafe members participated in the benchmarking exercise.

With the motivation of gradually better validated modelling of physics, in particular with modern CFD tools, numerous assumptions and analytical steps should be improved:

1. Optimal scenario selection
2. Methods/assumptions on leak probabilities
3. Ignition probability models (time dependent, S, I, C)
4. Acceptance criteria, structural response
5. Develop screening models (where appropriate)
6. Include fire modeling

The results are summarised in [33]. As quantitative risk assessment was also on the agenda of the IEA HIA Task 19 both groups cooperated closely on this key topic.

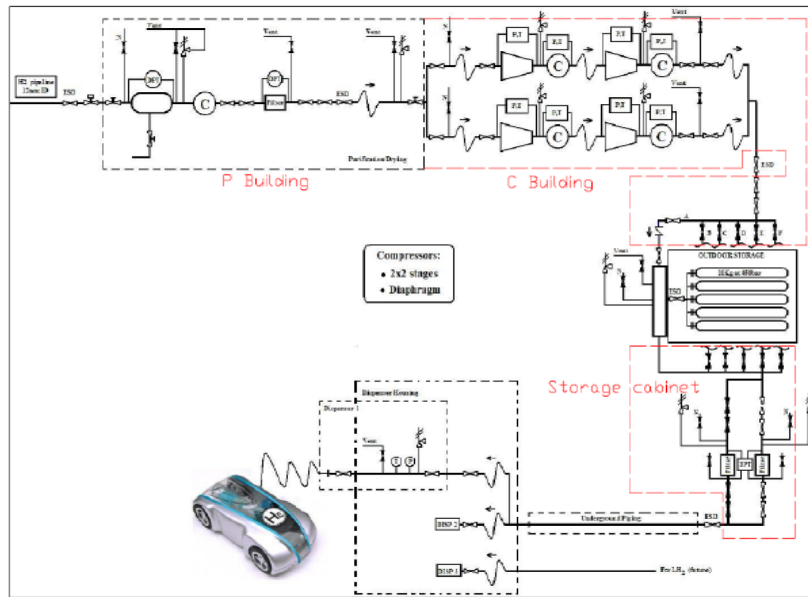


Figure 3: Piping and flow diagram of the benchmark base case “Hydrogen Refuelling Station”

3 Results of Cluster “Dissemination”

The cluster dissemination consists of the Biennial Report on Hydrogen Safety, the e-Academy and the International Conference on Hydrogen safety.

3.1 *Biennial Report on Hydrogen Safety (BRHS) [46,47]*

Based on the thematic structure proposed within the first activity period, the BRHS delivers periodically updated information on existing knowledge and progress on hydrogen safety issues. It should pull together existing scientific and technical information shared between members of the consortium and beyond when available [11]. It represents a unique reference to interested parties looking for comprehensive scientific information on different aspects of hydrogen safety, ranging from basic physical and chemical knowledge (dispersion, combustion) up to practical information related for instance to state of the art risk control measures or emergency response plans.

The first issue was developed with standard means like classical word processors and published as printable files on the HySafe website [46], the second issue was developed with modern Web 2.0 tools, in particular using a Wiki engine for collaborative editing [47]. The opportunities for paper printed versions are investigated currently.

3.2 *International Conference on Hydrogen Safety*

While safety is one topic among many in most conferences on hydrogen or fuel technology there was no dedicated hydrogen safety conference until the International Conference on Hydrogen Safety (ICHS) was first organised by HySafe September 8 to 10, 2005 in Pisa, Italy. The proceedings (deliverable D31) are available online [8, 48].

The 2nd ICHS was organised in September 11 to 13, 2007, in San Sebastian, Spain. About 250 international participants from different stakeholder groups, like industry, SDOs,

government, authorities and research groups openly communicated results of their research work and participated in intense discussions. Central topics were the applicability of CFD for certification procedures and the status of quantitative risk assessment. The proceedings (deliverable D95) were also published on the conference website [28, 49] after a reasonable time span.

A special issue of the “International Journal of Hydrogen Energy” has been published with 16 selected papers of the 1st ICHS (International Journal of Hydrogen Energy, 32, 2007). Also for the 2nd ICHS a similar special issue of the “International Journal of Hydrogen Energy” is going to be published.

The first two events showed a high degree of integration between several international projects, since HyFleet::CUTE (EU), StorHy (EU), NaturalHy (EU), HyPer (EU), Ardenty (J) and Canadian Hydrogen Safety Program (CDN) were partners in the event organization; also a broad participation of international bodies as ISO, IEA, HELP and H2 Code and Systems for Hydrogen Safety was reached. The first two conferences were held in association with IPHE, as they hosted the IPHE RC&S workshop.



Figure 4: The 3rd International Conference on Hydrogen Safety organised by HySafe

For the 3rd ICHS besides the IPHE recognition also the involvement of and support by the US DOE and the IEA has been successfully negotiated. Meetings of expert groups and educational or training courses like the European Summer School for Hydrogen Safety are arranged in combination with this conference.

The ICHS conference series have been successful both for the public, with more than 700 participants coming from about 25 different countries of the whole world, and for the scientific program with about 220 memories. The 2nd ICHS showed a great number of participants who have already been in the 1st ICHS, thus highlighting the success of the ICHS series in term of continuity and also a great interest in disseminating the hydrogen safety problems/results in the international community.

The again promising number of abstracts arrived for the 3rd ICHS (130 from 18 countries) indicates that with this HySafe activity a demand of the community has been met.

3.3 e-Academy- Education and Training

There were no coordinated educational and training activities in Europe in the area of hydrogen safety before March 2004, when the European e-Academy of Hydrogen Safety commenced its activities within the framework of the HySafe consortium. Before the start of the HySafe project, there were no activities to develop dedicated higher educational programmes in the world, including absence of a key element for establishing of any specific educational program - a curriculum. The HySafe e-Academy filled this gap with extraordinary success.

The International Curriculum on Hydrogen Safety Engineering [36] regularly updated with contribution of more than 60 experts throughout the globe has been further developed and filled with content with the help of new higher education courses and modules:

- PgCert/PgDip/MSc course in Hydrogen Safety Engineering by UU.
- CPD course *Safe Production, Transportation and Use of Hydrogen as a Fuel* by WUT.
- Module *Hydrogen Safety* in the context of the existing course *Renewable Energy* by UNIPI.
- Module *Safety in Hydrogen Vehicles* by UPM.

The world's first postgraduate course in Hydrogen Safety Engineering (PgCert in HSE commenced in January 2007, full MSc course in HSE commences in January 2009 at the University of Ulster [50]) and the European Summer School on Hydrogen Safety (FP6 Marie Curie Actions HyCourse project, 2006-2010 [51]) have been established. The latter is organised under the auspices of HySafe and in collaboration with US DOE. HySafe partners and international experts delivered contributions to:

- 1st ESSHS (15-24 August 2006, Belfast): 86 participant from 23 countries;
- 2nd ESSHS (30 July – 8 August 2007, Belfast): 79 from 31 countries;
- 3rd ESSHS (21-30 July 2008, Belfast): 87 participants from 30 countries;
- 4th ESSHS (planned for 6-15 September 2009, Ajaccio, Corsica).

The International Short Course Series “Progress in Hydrogen Safety” [52] for joint delivery of educational/training in the state-of-the-art of hydrogen safety have been set up

- Short course No.1: “Hydrogen and fuel cell technologies: Safety Issues”, 29 September - 3 October 2008, Belfast, United Kingdom;
- Short course No.2: “Hydrogen regulations, codes and standards”, 26 - 30 January 2009, Belfast, United Kingdom;
- Short course No.3: “Safety of hydrogen fuelled vehicles” (programme to follow), 27 April - 1 May 2009, Belfast, United Kingdom;
- Short course No.4: “The hydrogen and fuel cell infrastructure” (programme to follow), 15 - 19 June, Ajaccio, Corsica, France.

A pool of specialists from both academic and non-academic institutions able to deliver teaching on hydrogen safety engineering at the highest level by introduction of latest research results into the educational process has been created by the above activities. These experts have been also involved in the joint supervision of research students. In this context a list of consolidated topics for research students at the organisations of the HySafe partnership has been developed [53].

FP6 Marie Curie Actions have been used to acquire funding for four of these topics. A grant (contract No. MEST-CT-2005-020245, HySAFEST project: *Early Stage Training in*

Fundamentals of Hydrogen Safety) has been awarded to complement HySafe activities in this area. Additionally, three Work-in-Progress workshop/sessions for young researchers in hydrogen safety have been organised (see [54,55,56]).

A database of organisations working in the hydrogen industry with currently more than 6000 entries was built up to form a market of potential trainees and to disseminate the results from mutual activities of the network [31]. Finally two further databases were created: a database with references to peer reviewed journal papers on hydrogen safety, published by HySafe partners [57] and an Alumni Database [58].

4 Results of Cluster “Management”

This cluster is responsible for the general strategies and the day-to-day management of the network. The coordinator was responsible for the communication internally and externally and provided support for administrative, financial and legal issues.

4.1 Management (WP17)

The coordinator supported by the project management office (PMO) and by the coordination committee (CC) set-up and developed further the network’s organisational structure. With the concept of work package clusters a new management layer was introduced to ease the management of the large number of activities. An advisor and supporter group and a diversity committee were established and later a special expert group on the material issues (WP18) was introduced.

The coordinator also arranged the extension of the network by the Russian partner Kurchatov Institute successfully applying to the EC INCO call FP6-2006-TTC-TU.

Communication means, in particular the networks website, the regular newsletter and telephone conferences, were set-up and maintained. Meeting schedules and decision procedures were improved and captured in the management handbook.

For the website [42] a special CMS system with a sophisticated access and visibility control has been programmed to provide online staff administration, meeting planning, easy file uploading and other features to support all network activities including the dissemination efforts. For example a Wiki system has been integrated in the website to support the editing of common reports and a newsgroup forum was established to support the discussions on new standards and regulations in particular.

The website maintains currently about 2000 documents, including the 120 deliverables, milestone reports, internal and external scientific publications, presentations. Intentionally the majority of the deliverables are public; the most important 41 of them are listed in the references [1]-[41].

With the EC reporting and reviewing activities were coordinated and the due delivery of project results was controlled in meetings and in direct contact with responsible authors. The coordinator and other members of the CC represented and presented the network at more than 60 external events, like conferences workshops etc with oral presentations or posters. Among these the yearly European Technical Review meetings, the Hannover Fair, the IEA HIA Task 19 expert meetings and the yearly US NHA conference have to be

highlighted. Additionally, several questionnaires, radio and even TV interviews were provided to inform about the network's activities.

4.2 Strategies (WP7)

In an initial effort the network supported by external experts set up a phenomena identification and ranking table (PIRT) for the internal road mapping and definition of research headlines. This work package also organised the yearly activity planning in the joint programs of activities and the revision of the network's orientation.

New dedicated project proposals for EC FP6 and national programs were coordinated or at least supported via WP7. Some examples for this vital activity are the preparations of the HyGuide, IgnHyd, InsHyde, HyTunnel, HyPer, HyQRA, HySchool, HyGlobe, HySafest, HyFrac, HyNano and HyGarage proposals. A few of them succeeded as externally or internally funded projects, others were at least partially treated as internal sub-tasks. The coordinator and 8 further partners represented the HySafe consortium in the important HyFIT project proposal, responding to the EC INFRA call. Although in a first response no support from EC was indicated the partners are still striving to re-submit a revised version to the H2&FC JTI.

Other external projects like HyApproval or HYTHEC for instance were supported by safety peer reviews of their key documents or by safety workshops arranged by HySafe. To provide a unique assessment framework for the safety performance of EC supported projects a "Safety Action Plan" was drafted. It was based on a similar obligatory reporting scheme which is applied in US DOE supported projects.

4.3 International Association for Hydrogen Safety (IA) HySafe

A vision and mission statement and a strategy plan for the NoE follow-up were developed by a special task force. The mission of IA HySafe is to be the international focal point for hydrogen safety research, education and training.



Figure 5. The IA HySafe logo

The statutes for this legal body were developed to comply with the Belgium law concerning the "Association Internationale Sans But Lucratif" (AISBL), an international not-for-profit association. The decision to choose this legal form for the continuation was based on an internal survey and consultations with other NoEs.

The founding membership was restricted to NoE members to resolve issues regarding intellectual property protection in an easier way. On 26 February 2009 the association was founded by 17 of the 24 HySafe members (see Table 1). Immediately after the founding five new applications for membership also from industry have been filed in.

However, the association is open for any interested party complying with the requirements laid down in the statutes. A membership fee structure, keeping the association open to as many as possible relevant members, has been set up.

5 SUMMARY OF KEY RESULTS

It should be reminded and emphasised here, that the actual objective of a network of excellence is integration. So besides the technical achievements, which have been already detailed above, the success of the network has been continuously measured by qualifiers like common project work, common publications, sharing of knowledge, tools and even staff, etc. These qualities are difficult to quantify and sometimes even do not fit conventional scientific work schemes. However, the following shortlist tries to summarise the actual key success of HySafe in the light of integration.

The NoE HySafe, consisting of industry, education and research oriented partners,

- **commonly** defined the **state-of-the-art** regarding modelling of hydrogen behaviour, safety related risk management and technologies,
- **agreed on methodologies for the identification** and jointly identified the most **critical scenarios and phenomena** related to the use of hydrogen as an energy carrier,
- developed further **the common understanding** of the behaviour and proper handling of hydrogen in particular in partially confined areas,
- set up an open, integrated scientific and industrial community with an extensive **communication framework for scientific information exchange** and educational purposes, and
- finally provided with the **founding of the International Association for Hydrogen Safety** the suitable legal backbone for the further networking, i.e. continuation of the successful NoE activities, and thereby preserves the initial investment of all NoE partners including the EC.

6 Outlook

The international focus for hydrogen safety will be further developed within IA HySafe. The geographical scope, the networking activities of the NoE, in particular the conference, the education and training, the research coordination, the benchmarking and the maintenance and further development of related documentation will be developed further. It is foreseen that IA HySafe's most important operational vehicles could become the website and the hydrogen safety information system HySafe-IS. As a consequence, it is of vital importance that the Association develop plans for maintenance, i.e. how to keep the contents of HySafe-IS up-to-date and assess whether it holds all relevant information related to hydrogen safety. This involves both operational field data (non-accident) and the further development of HIAD.

Although already in the NoE phase some critical safety issues could be resolved as described above, from a scientific or technical perspective still many issues have to be addressed. Only to mention a few here:

- Properties and behaviour of cold hydrogen from liquid releases
- Release strategies related to accidental scenarios, i.e. scientifically grounded requirements to location of and operational parameters for pressure relief devices

- Further the understanding of ignition phenomena to allow suitable modelling
- Impinging and wall attached jets and jet fires with the associated heat transfer to set conditions for safe blowdown
- Safety sensor development
- Transitional combustion phenomena in realistic conditions (low temperatures, congestion, non-uniform mixtures...) and the impact on mitigation measures, for example flame acceleration and deflagration-detonation-transition in the presence of water sprays
- Formulation of requirements for permitting the use of hydrogen vehicles (cars and commercial vehicles) in confined spaces
- Increase the understanding of hydrogen behaviour in confined spaces, with focus on vehicle applications and indoor use of portable hydrogen technologies
- Develop further appropriate safety engineering methodology like a reference quantitative risk assessment methodology and apply it to garage, tunnel scenarios etc
- Development of a reliable reference simulation tool for combustion open to the research community
- Composite storage and vehicle safety testing strategies
- Hydrogen pipeline field tests

On a European level, development of a strong link to the JTI demonstration projects might be possible via a close cooperation with the EC Joint Research Centre Petten. The real international dimension will be further developed by the existent close contacts to the US DOE, to the Canadian research network, to the Japanese JARI, and to the relevant groups at IEA HIA and the IPHE and by hopefully many international members.

7 References

([1]-[41] and other deliverables are available from <http://www.hysafe.net/deliverable>)

- [1] HySafe Deliverable D9, Report on compiled facility descriptions, WP2, FZJ
- [2] HySafe Deliverable D22, Specification and definition of HIAD, WP5, DNV
- [3] HySafe Deliverable D23, Status report on compilation of results of SBEPs, WP3, UPM
- [4] HySafe Deliverable D24, Report on phenomena / scenario ranking, WP4, CEA
- [5] HySafe Deliverable D25, CFD models in the simulations of the problems related to H2 safety, WP6, FZK
- [6] HySafe Deliverable D26, Summary on HySafe Risk Assessment methodologies/approaches, WP12, DNV
- [7] HySafe Deliverable D27, Sub-task 16.3 List of authorities, WP16, INERIS
- [8] HySafe Deliverable D31, Proceedings of the first ICHS, WP14, UNIPI
- [9] HySafe Deliverable D33, Website presentation of the facilities, WP2, FZJ
- [10] HySafe Deliverable D34, Available information including existing standards for bonfire tests of H2 tank structures, WP9, BAM
- [11] HySafe Deliverable D41, Database of Literature on Hydrogen Safety, WP1, INERIS
- [12] HySafe Deliverable D44, Established definitions and classifications of incidences and accidents, WP12, DNV

- [13] HySafe Deliverable D51, 2nd Status report on code validation applicability based on SBEP results , WP3, FZK
- [14] HySafe Deliverable D54, Report on sensor evaluation, WP11, INERIS
- [15] HySafe Deliverable D64, Report on hazard zone methodology for hydrogen including calculation examples, WP12, NH
- [16] HySafe Deliverable D66, Report on CFD code validation (SBEP), WP6, GexCon
- [17] HySafe Deliverable D75, List of Basic Test Problems, WP6, FZK
- [18] HySafe Deliverable D80, The 1st "HySafe Hydrogen Accident Statistical Report" , WP5, DNV
- [19] HySafe Deliverable D81, Specifications of the set of SBEPs for the 4th period, WP6, FZK
- [20] HySafe Deliverable D84, Report on internal safety distances, WP12, DNV
- [21] HySafe Deliverable D85, Report on the Updating of the PIRT, WP7, CEA
- [22] HySafe Deliverable D87, Report on results of experiments, WP10, FZK
- [23] HySafe Deliverable D88, Compilation report on SBEPs results of the 4th period, WP6, FZK
- [24] HySafe Deliverable D89, HyTunnel Activity Report, IP.2, BRE
- [25] HySafe Deliverable D90, Business Plan EU Institute for Hydrogen Safety 'HySafe', WP7, FZK
- [26] HySafe Deliverable D91, Report on results of FA/DDT experiments, WP10, FZK
- [27] HySafe Deliverable D92, Proposal for the Safety Action Plan (identical with D86), WP7, FZK
- [28] HySafe Deliverable D95, Proceedings of the 2nd ICHS, WP14, UNIPI
- [29] HySafe Deliverable D96, Updated IEF documents, WP2, FZJ
- [30] HySafe Deliverable D97, Updated on existing know-how in the field of Material Compatibility, WP18, INASMET
- [31] HySafe Deliverable D99, Database of organisations working in hydrogen industry, WP15, UNIPI
- [32] HySafe Deliverable D102, Preparation and performance of the 2nd phase explosion experiments, WP10, FZK
- [33] HySafe Deliverable D106, HyQRA-Report on use of simplified methods for QRA, IP.3, GexCon
- [34] HySafe Deliverable D107, Specifications of the set of SBEPs for the 5th period, WP6, FZK
- [35] HySafe Deliverable D108, HyFrac-Report , WP18, AL
- [36] HySafe Deliverable D109, International Curriculum on Hydrogen Safety, WP15, UU
- [37] HySafe Deliverable D110, BRHS (2nd issue), WP1, WUT
- [38] HySafe Deliverable D111, HyTunnel-Final Report, IP.2, BRE
- [39] HySafe Deliverable D113, Guidance for using hydrogen in confined spaces - InsHyde final report, IP.1, NCSR
- [40] HySafe Deliverable D115, SBEP data base, WP6, FZK
- [41] HySafe Deliverable D116, Report on the results of the experiments, WP10, FZK
- [42] <http://www.hysafe.net>
- [43] <http://www.hysafe.net/wiki/WP2/IEF>
- [44] <http://www.hyapproval.org>
- [45] <https://odin.jrc.ec.europa.eu/engineering-databases.html>
- [46] <http://www.hysafe.net/BRHS>
- [47] <http://www.hysafe.net/wiki/BRHS/BRHS> (to be published)
- [48] <http://conference.ing.unipi.it/ichs2005/ICHS-Papers/index.htm>
- [49] <http://conference.ing.unipi.it/ichs/index.php?id=122>

- [50] <http://www.hysafe.org/MScHSE>
- [51] <http://www.engj.ulst.ac.uk/esshs/hycourse/>
- [52] <http://www.engj.ulst.ac.uk/esshs/iscsphs/>
- [53] <http://www.hysafe.org/ConsTopics>
- [54] <http://www.hysafe.org/WIPSep2007>
- [55] <http://www.engj.ulst.ac.uk/esshs/2ndesshs/2ndesshsprogramme.php>
- [56] <http://www.hysafe.org/WIPJuly2008>
- [57] <http://www.hysafe.org/PublHySafe>
- [58] <http://www.hysafe.org/AlumniDB>

Part B – Detailed Final Activity Report

8 Project objectives and major achievements

8.1 Overview of general network objectives

The introduction and commercialisation of hydrogen as an energy carrier of the future makes great demands on all aspects of safety. Technologies and applications allowing the use of hydrogen should provide at least the same level of safety, reliability, and comfort as today's fossil energy carriers.

The HySafe network has been focused on safety issues relevant to improve and co-ordinate the knowledge and understanding of hydrogen safety and to support the safe and efficient introduction and commercialisation of hydrogen as an energy carrier of the future, including the related hydrogen applications. Thus HySafe will contribute to the safe transition to a more sustainable development in Europe.

Hydrogen safety issues were subject to numerous research efforts. However, there have been still a number of knowledge gaps with significant deficiencies in terms of safe technical solutions, including mitigation techniques, and in the availability and scope of widely accepted and harmonised standards and methodologies, together with associated regulatory issues. Development of a robust and reliable framework to assess the safety of hydrogen technologies and applications, and to harmonise testing procedures and quality assurance standards was and is therefore necessary.

The main objective of the HySafe network was to strengthen, integrate and focus fragmented research efforts to provide a basis that will allow removal of safety-related barriers to the implementation of hydrogen as an energy carrier. In this way the network should contribute to promoting public awareness and trust in hydrogen technology within Europe by providing a basis for communicating the risks associated with hydrogen. Before "HySafe" there was some existing co-operation in the field, but much of the research output especially if financed by industry partners is not necessarily easy to obtain. Substantial benefits were expected from identifying and using existing information and from preventing duplication of work.

There are certain historical differences in the methodologies and approaches for addressing safety issues. This concerns differences in probabilistic and deterministic approaches in safety studies and differences in the approaches of industry, research organisations, and public authorities. Development of a common understanding and common approaches provided a benefit for all partners involved, as they gained access to improved methodologies based on the input and experience from others. Finally this will also help to facilitate the safe introduction of hydrogen technologies and applications.

The network developed an integrated, sustainable, competitive, scientific and industrial community capable of jointly addressing the challenges presented by the development of an excellent safety culture not only across Europe but worldwide. One critical element in this direction has been the founding of the International Association for Hydrogen Safety "HySafe", the legal body and long-lasting integrated follow-up to the Network of Excellence.

In detail, the objectives of the HySafe network included:

- To contribute to a common understanding and common approaches for addressing hydrogen safety issues:
 - a common approach for ranking the importance of relevant physical phenomena, hazards and scenarios should be developed;
 - identification, assessment and prioritisation of all relevant hazards through developing the current risk assessment methodologies, and establishing clearer links between related safety issues;
 - establishment of a hydrogen incident and accident database, which should provide a common basis for hydrogen risk management and studies to quantify the risks associated with hydrogen applications.
- To integrate experience and knowledge within industrial organisations familiar with hydrogen processing technology and research organisations with facilities for experimental research and exploitation of results in numerical prediction tools;
- To integrate and harmonise the fragmented research base by:
 - creation of a set of specialised complementary research facilities that should allow optimisation of the necessary experimental efforts to address hydrogen safety issues;
 - identification of a set of specialised complementary models and codes that can be used for numerical safety studies; their ranges of applicability will be specified;
 - harmonising development of safety and risk assessment methods;
 - integrating and optimising national financial resources allocated to hydrogen safety;
 - integration of human resources;
 - promotion of fundamental research necessary to address hydrogen safety issues.
- To provide contributions based on safety and risk studies to EU-legal requirements, standards, codes of practice and guidelines by:
 - pre-normative research in identified critical areas;
 - providing scientific information and updating the European mirror committee members of the international standardisation groups;
 - development and implementation of a performance-based approach to hydrogen safety engineering;
 - use of results from detailed safety and risk assessment studies for different hydrogen applications as input to development of legal requirements, standards and codes of practice;
 - extracting net outcomes from safety and risk assessment studies, e.g. deterministic safety distances;
 - development and validation of hydrogen accident prevention and mitigation techniques.
- To contribute into education and training on hydrogen safety issues in order to provide an improved technical culture for handling hydrogen as an energy carrier by:
 - organizing short training courses and lecture courses;
 - organizing education and training on hydrogen safety, including on-line mode (e-Academy);
 - establishing a website with up-to-date information on Hydrogen Safety;
 - establishing the International Conference on Hydrogen Safety;
 - publishing the Biennial Report on Hydrogen Safety.

The network links to the state-of-the-art in the field of hydrogen safety are manifold. Evidently, as the experts in this field are gathered in HySafe there is a natural link to external activities and the updating is simply reached by the personnel representation, communication and reporting. The network partners from universities and from the public

research centre form the human basis of this state-of-the-art, at least with regard to the European developments. The state-of-the-art is strongly connected to what has been published and applied. For the publication the disseminating activities, like the ICHS, the BRHS including the Handbook for Hydrogen Safety and the educational efforts are suitable communication channels.

Most of the consortium partners, especially the industry partners, have delegated members in the national and international standardization and regulatory bodies, allowing transferring the knowledge behind the state-of-the-art from scientific to normative grounds. The state-of-the-art has been manifested in the work of the IPHE recognised HySafe network. The outcome has been compiled with the help of the dissemination activities like the international conference, the biennial report and this yearly activity report.

To account for developments which take place outside the EU the network has built up links with the key institutions and persons, conducting complementary research related to hydrogen safety. The most prominent example is the intense cooperation with the IEA HIA Task 19 group, again with a broad participation of HySafe partners. Besides the still European centred HySafe subgroup participating in this international information exchange the other highly active nations in the fields of hydrogen developments like North America, Japan, Russia and China openly report on their current activities there. The Network Advisory Council offered another means for this external collaboration and updating concerning the state-of-the-art; a similar group could be established in the HySafe IA via the honour members. Another element in the external networking was the involvement in the IPHE, where HySafe - as one of the first acknowledged IPHE projects – gained broad world-wide visibility.

Other very practical updating opportunities have been realised via the Hydrogen Safety Summer School, successfully implemented by the partner UU and the active participation in and short courses offered for other international conferences like the WHEC or EHEC. The educational events continuously fill the iteratively updated curriculum with fresh and high quality content.

9 Progress of the Cluster “Basic Research”

9.1 Work Package WP2: *Integration of Experimental Facilities (IEF)*

Lead Contractor: FZJ

Contractors involved: BAM, CEA, Fh-ICT, FZK, GexCon, HSL, INASMET, INERIS, JRC, KI, TNO, UNIPI, WUT; Active supporter: ET

9.1.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

With regard to the goals of the HySafe Network, research facilities are needed for the experimental investigation of relevant phenomena, for testing devices and safety concepts as well as for the generation of validation data for the various numerical codes and models. The integrating activity ‘Integration of Experimental Facilities (IEF)’ should provide basic support for jointly performed experimental work within HySafe. IEF represents a long lasting effort for reaching sustainable integration of the partners’ experimental research capacities and expertise, even beyond the NoE phase.

Experimental activities in the field of hydrogen safety in Europe mainly originate from two areas: On the one hand, hydrogen safety research has developed from safety investigations for natural gas applications. On the other hand, in the field of nuclear technology, hydrogen is a safety issue in severe accident research since more than 20 years. In the frame of HySafe, partners from both research fields contribute with their specific expertise. Initially, these partners own and operate numerous test facilities for diverse research tasks reaching from material research in laboratory scale to full scale explosion areas. Consequently, there was a need to identify the partners’ best expertise, potentially overlapping activities but also possible gaps. Furthermore, in order to achieve a high standard in the quality of experimental data, the know-how transfer between the partners needed to be enforced. The exchange of expertise and know-how between the partners is one of the keys to provide high quality experimental work.

9.1.2 Achievements of the activity, the current state:

The strategy for reaching the objectives consisted of two parts. On the one hand, a documentation of the experimental capacities has been prepared and analysed. On the other hand, a close communication base has been established by means of biannual workshops on experimental issues.

IEF documentation

In the first period of the project, a compilation of the experimental facilities [1,2] was provided to serve as a starting point for further activities. At that time, the document contained the descriptions of 78 facilities taking into account information on particular

features and measurement capabilities in order to identify specific expertise as well as aspects concerning possible integration activities.

In order to identify the best expertise of the partners, the work in the second period focused on the categorisation of the experimental facilities [5] and on the compilation of instrumentation [4]. Liquid hydrogen applications were identified as major gap in knowledge among the partners. ET EnergieTechnologie joined the work package as active supporter in the third period in order to fill this gap. Together with the new Russian partner KI, both new partners were included in the set of IEF documents.

The final version of the IEF documentation [7] including the updated IEF documents [2,4,5] contains a total of 109 technical descriptions of HySafe facilities operated by 15 partners. A web presentation [3] of all facilities is available through the HySafe website.

All these documents have been continuously enhanced and extended in order to account for progress in knowledge and technical possibilities. Externally, a link to IEA Task 19 has been established through which technical information on the HySafe facilities will be included in IEA databases related to experimental data and facilities.

IEF workshops

In order to ensure a common quality standard, a series of biannual workshops was started in the second period covering topics related to measurement techniques and experimental work. The general aim of the IEF workshops was to become acquainted with the partners' activities, to share knowledge in the field of experimental work and to support jointly planned and performed experiments. In this respect, these workshops served for improving and maintaining the quality of experimental work and support the integration process as well. The workshops include presentations by the partners related to the subject of the workshop, visits of experimental facilities, and presentations and discussions on planned and performed experiments. The output includes a CD compilation of the presentations and recommendations for forthcoming experiments.

A total of 8 well received workshops have been organised covering topics from measurement technologies to safety issues. Based on the information presented by the partners, a working document on best practice [6] including the joint experimental knowledge of all partners with regard to experiments and instrumentation was created. Preserving the character of a working document, it was implemented in the IEF wiki page, which was set up in order to provide a communication platform. The series of workshops supports the wiki-based working document on best practice intended to be a guide for experimental work in the field of hydrogen safety.

9.1.3 Outlook for further research work:

The IEF activity has proven to be of high interest for those partners involved in experimental activities. Consequently, the communication platform based on regular IEF workshops and IEF wiki page established can be expected to be continued and enhanced in the frame of the IA HySafe. The IEF documentation may serve as a starting point for future reference.

The regular exchange of knowledge revealed several measurement tasks in experiments on hydrogen safety which are challenging and need considerable efforts and knowledge in

order to produce reliable results. Jointly performed studies have been started in order to assure and enhance the quality of future experimental work. These studies performed by a small group of partners give first indications how future common projects could be performed within the IA HySafe.

9.1.4 List of Deliverables for WP 2:

- [1] D05. Report on unified format for descriptions of experimental facilities
- [2] D09. Report on compiled facility descriptions
- [3] D33. Website presentation of the facilities
- [4] D35. Compilation of instrumentation
- [5] D45. Report on facilities classification
- [6] D70. Working document on best practice
- [7] D96. Updated IEF documents

9.2 Work Package WP6: Numerical Tools

Lead Contractor: FZK

Contractors involved: BRE, CEA, DNV, FZJ, FZK, GexCon, HSE/HSL, JRC, NCSR, TNO, UC, UPM, UU, WUT, KI

9.2.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

In the community working in the area of safety analysis based on CFD simulations a large number of CFD codes was used including both “in house” and commercial codes. However, numerous examples indicated that the predictions of such codes can exhibit significant variations. Among the reasons for this unacceptable spread in numerical predictions, an inadequate application of even well known and widely used numerical models can play a key role. Other reasons can be found in the utilisation of obsolete or generally restricted models, and often in the application of models outside their validity range. Verification and validation procedures are frequently disordered and non-systematic. Therefore, the necessity of methodology of CFD application was apparent. An integration of the expertise of NoE partners in the frame of a ‘CFD club’ activity gave a vast potential to eliminate such problems and to bring CFD simulation to a higher level of quality.

The objective of ‘CFD club’ was to promote development and to provide an appropriate application of the CFD methods related to the thematic structure of the network. This activity was intended to organise an effective exchange of information concerning the models and the codes and to promote joint research activities aimed at the code and model development.

It was planned that the network participants will select and provide experimental results for formulation of Standard Benchmark Exercise Problems (hereinafter *HySafe – SBEP*). First, the existing data relevant to the thematic structure of the network will be identified. Second, the gaps addressed in the joint research programme will be used for formulation of

the standard problems. The participants will use their computer codes for simulation of the standard problems. Regular exchange of the results will be made. The standard problems and exchange of the results will allow improving the code models. The club will create a collection of exercises consisting of theoretical and experimental cases having conceptual importance in the course of codes' verification and validation.

9.2.2 Achievements of the activity, the current state:

During the NoE five years period the main actions addressed the following directions:

- Identification of the phenomena, which have major importance for H2 safety and have to be reproduced in CFD simulations, on the basis of the expertise of the work package participants along the results of PIRT activity (WP4);
- Synthesis analysis of the existing models and codes of the partners was performed. The partners have prepared an extended analytical review of the existing and potential models, their assets and limitations, their ability for the description of the project specific problems; recommendations on model applications for different phenomena.
- Creation of the database of the theoretical and experimental Standard Benchmark Exercise Problems candidates;
- Participation in simulation of the chosen SBEPs and in the subsequent analysis; identification of the knowledge gaps and their elimination;
- Participation in applied simulations, formulated as pre-test and post-test simulations aimed to provide possible assistance to the experimental work packages and/or Internal Projects;
- Activity in the frames of establishment of extended role of CFD in (Q)RA;

At the early stage considerable efforts were made for the identification of the major phenomena, which should be investigated thoroughly in the course of the work package activities. In the subsequent work package operation the most strength was concentrated on such topics, which allowed identifying knowledge gaps and to large extent cover them:

- turbulence modelling in the mixing processes after intensive H2 injections typical for the industrial accident scenarios;
- jet modelling, including dispersion and distribution phase together with
- jet combustion,
- large-scale detonation modelling;
- vented combustion;
- large-scale combustions in confined and semi-confined geometries (such as tunnels, etc), (Q)RA simulation exercises imitating circumstances of possible H2 accidents.

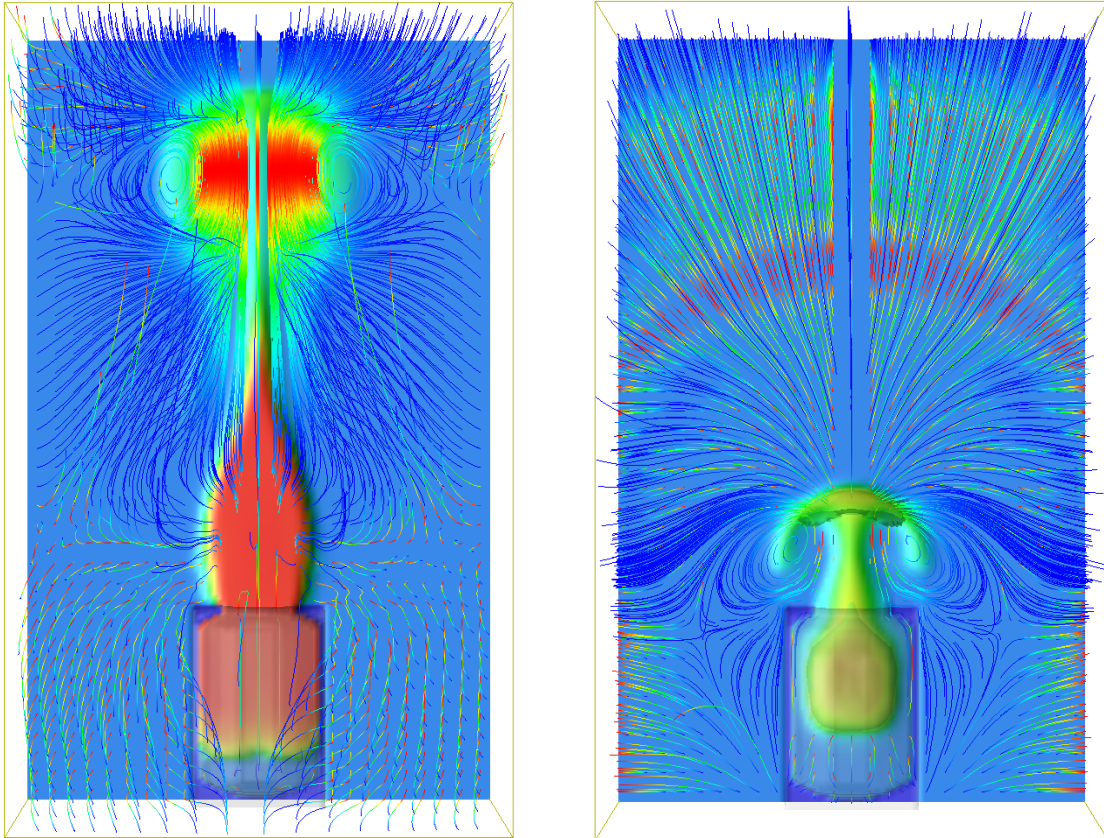


Figure 1. Simulation of the SBEP dedicated to vented combustion.

An extensive document, the deliverable D25, was created covering the results of the phenomena ranking and including comprehensive description of the partners' codes and approaches.

The SBEP candidate database was created by the consistent input of most partners. The database includes now 33 entries with the description of experiments. All chosen experiments are open for public access since they were either extracted from the open literature or belong to participants who were able to grant access to the relevant information.

From the SBEP candidate database 21 experiments were taken for the simulations. Most partners took active part in the modelling activity and subsequent presentation of the results and their discussions. As a result of these actions eleven publications (including journal articles and conference presentations) were prepared; two invited lectures were prepared as an overview of the work package work.

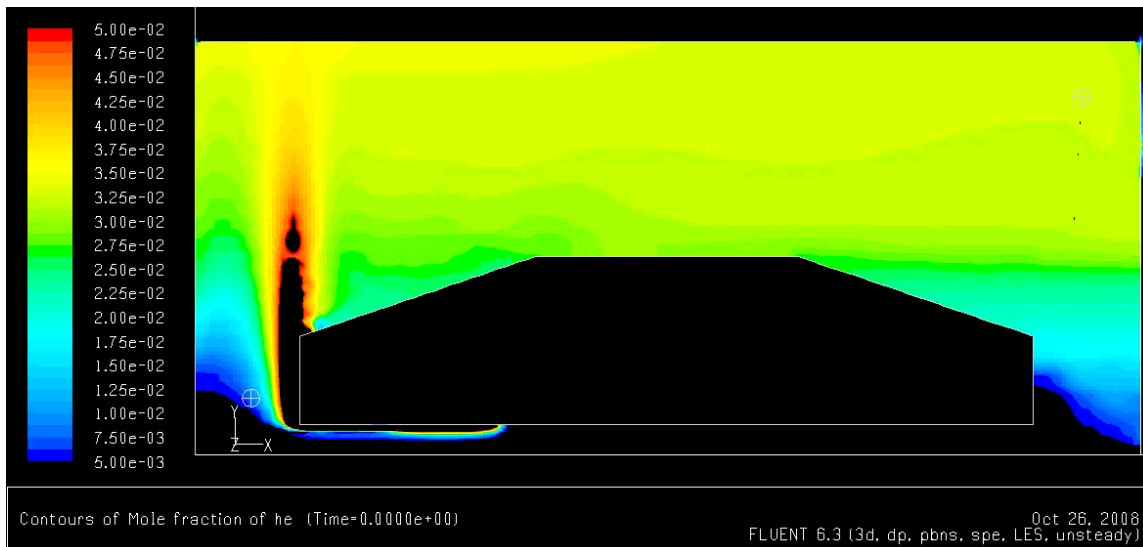


Figure 2. Simulation of the SBEP dedicated to the hydrogen distribution in the private garage.

Since the main form of the ‘CFD club’ activity is public discussions and debates, one of the main indicators of achievements is a number of the partner meetings. During the reporting period there were 14 special meetings organised. All partners actively participated in SBEP simulations and discussions of simulation results during these meetings.

Many partners were active in the field of applied simulations: many simulations were performed as 1) pre-test activity in the frames of Internal Projects InsHyde and HyTunnel; 2) support for the RA work package WP12 and 3) independent confirmation of EC Projects HyApproval and HyPer conclusions.

All the deliverables were nominated having a public access.

9.2.3 Outlook for further research work:

The mission of HySafe IA is to facilitate the development and dissemination of hydrogen safety knowledge. This includes maintaining and further developing infrastructure for hydrogen safety research and promoting coordinated research in the field of hydrogen safety.

Therefore, a committee in the IA dedicated to identifying and closing knowledge gaps in both modelling and experimental fields is required. This new committee can take advantage of the knowledge accumulated within work packages 2 and in 6 of HySafe NoE implementing the following subjects:

- Further valorisation of the benchmark database built during HySafe. This database is an essential tool for monitoring progress in modelling capabilities of the members, for evaluating CFD codes and modelling practices, and will serve as a support for education and training. The corresponding actions are the maintenance of the database with updated results and its adaptation for the defined objectives.
- Continuation of benchmarking activities (SBEPs) focused on dispersion and combustion of hydrogen. As a start, it is suggested to concentrate on a limited number of new SBEPs, for example two per year, and at the same time encourage participation of a large number of partners.

- Harmonization of the modelling and experimental research activities performed by the partners.
- Dissemination of results through the international conference (link to the conference committee).
- Providing the basis for scientific education (link to the education committee).
- Identifying knowledge gaps through systematic analysis of limitations of various modelling approaches with regards to experimental evidences.

9.2.4 List of Deliverables for WP06:

- [1] D10 Specifications for initial set of SBEP
- [2] D19 SBEP on hydrogen mixing and distribution
- [3] D20 SBEP on hydrogen fires or explosions
- [4] D23 Status report on compilation of results of SBEPs
- [5] D25. Report on CFD models in the simulations of the problems related to H2 safety.
- [6] D36 Specifications of the set of SBEPs for the 2nd period (WP3.1 + WP3.2, WP3.3, WP3.4 & WP3.5)
- [7] D46 Compilation report on SBEPs results of the 2nd period
- [8] D51 Second Status report on code validation and applicability based on the results of SBEPs
- [9] D53. Report on sub-task 2&3
- [10] D57 Specifications of the set of SBEPs for the 3rd period (WP3.1 + WP3.2, WP3.3, WP3.4 & WP3.5)
- [11] D66. Report on CFD code validation (SBEP)
- [12] D69 Compilation report on SBEPs results of the 3rd period
- [13] D73 Report of simulations performed for external projects and for other risk assessments
- [14] D75 List of Basic Test Problems
- [15] D81 Specifications of the set of SBEPs for the 4th period
- [16] D88 Compilation report on SBEPs results of the 4th period
- [17] D107 [Specifications of the set of SBEPs for the 5th period](#)
- [18] D114 Compilation report on SBEPs results of the 5th period
- [19] D115 SBEP data base

9.3 Work Package WP8: *Hydrogen Release Mixing and Distribution*

Coordination: NCSR
 Partners: CEA, FZK, DNV, INERIS, TNO, GexCon, FZJ, UU, HSE-HSL, FH-ICT, STATOIL-HYDRO

9.3.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

The WP8 main objectives were:

- To perform new experiments on H2 release related to future H2 applications.
- To perform CFD calculations in support of the new experiments.

- To support the HySafe network activities and other EC-funded H2 projects by providing input on hydrogen release, mixing and distribution phenomena.

Review of previous work (D01)

A review of previous experimental and computational work on hydrogen release and dispersion has been performed (D01).

9.3.2 Achievements of the activity, the current state:

Hydrogen dispersion experiments by INERIS

The short and long term evolution of the hydrogen/air mixing of a low momentum release inside an unventilated space at constant pressure has been studied experimentally by Lacomme et al. (2007) [1]. The experiments were performed inside a garage like gallery of dimensions 7.2x3.78x2.88 m, using hydrogen and helium for hydrogen mass flow ranging from 0.2 g/s to 1 g/s (vol. flow from 2.3 to 11.5 l/s) for 240 s release time. Diameter of orifice varied from 5 to 20 mm. The release was vertically upwards from the horizontal centre of the facility, 0.265m above the ground. Hydrogen concentration was measured at 12 positions along the jet axis and laterally displaced to it for a period of 90 min. The experiments showed that a horizontally almost homogenous and vertically stratified layer of hydrogen/air mixture developed fast close to the ceiling. Vertical concentration profiles (see Figure 3) show that hydrogen concentrations are rather homogenous in the formed layer near the ceiling. The higher the layer concentration the more the slope of the profile increases. With increase of the release flow rate the concentration gradient between the hydrogen layer and the ground increases. During the release phase, concentration in the layer is mainly correlated with the flow rate. This layer did not change significantly during the period after the end of release (diffusion phase). For test INERIS-6C (1g/s and 20mm orifice) the flammable hydrogen/air mixture occupied approximately half the height of the facility. For the 0.2g/s release the concentration did not exceed the LFL. Homogeneous conditions were reached four hours after the release. The performed helium tests showed a strong similarity with hydrogen.

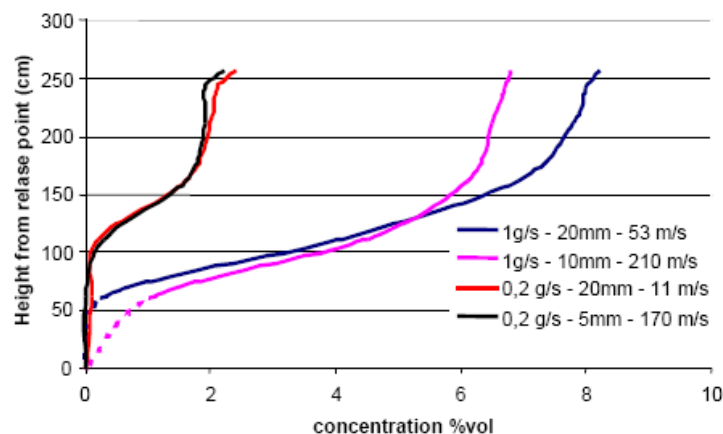


Figure 3: Vertical concentration profile at end of release for various release rates, according to Lacomme et al. (2007)

Helium dispersion experiments by CEA (D65)

Helium dispersion experiments were performed by CEA [2] in a full scale newly built realistic GARAGE facility. The work was partly funded by HySafe and the French project DRIVE [3]. The GARAGE interior dimensions were 5.76 m (length) x 2.96 m (width) x

2.42 m (height). Results were presented for test cases performed in the free volume of GARAGE without any ventilation. Tests 1 and 2 were performed with a flow rate of 688 NL/min (2 g/s helium) using the same nozzle diameter of 20.7 mm and varying the release duration from 121 to 500 s respectively. Tests 3 and 4 were performed with a flow rate of 18 NL/min (0.05 g/s helium) using the same release duration 3740 s and varying the nozzle diameter from 5 to 29.7 mm respectively. In this series helium concentration during and after injection phase was measured at 64 monitoring points. For the given aspect ratio of the GARAGE and test conditions, no overturning of flow takes place and stratified layers are formed inside the geometry. The analysis of results clearly showed that for the leaks inside the unventilated GARAGE, the risk induced is most strongly affected by the total volume of the gas released rather than the flow rate. For the test cases with similar initial conditions peak concentration levels increases with an increase in the injected volume. Test cases with similar injected gas volumes but different initial conditions, show almost identical peak concentration levels at the end of injection phase. However, variations in flow rates influence the mixing behaviour inside the GARAGE that in turn changes the decay rates of gas concentrations. Test cases with higher injected volumes of gas represent the worse condition and it takes longer time to reduce the concentration levels below lower flammability limit of hydrogen.

CFD pre-test calculations (D67)

Pre-test calculations have been performed to support the experimental work (INERIS-6C [4] and FZK/PRO-SCIENCE tests [5]). These are described in D67. This deliverable also includes a description of the calculations performed by GexCon for the HyTunnel internal project.

Scaling issues (D68, D65)

Scaling issues are important when performing experiments. Scaling issues including similarity between helium and hydrogen have been analyzed by partners FZK and NCSR. A comparison between hydrogen test INERIS-6C and helium test CEA-1 performed by CEA showed good agreement (D65).

9.3.3 Outlook for further research work:

The consortium suggests funding of further experimental work in order to:

- Increase our understanding on gaseous hydrogen dispersion behaviour especially for confined spaces
- Increase our understanding of hydrogen dispersion behaviour for liquefied hydrogen releases

9.3.4 List of Deliverables:

| Deliverable No | Title | Access status | Contributing Partners |
|----------------|--|---------------|--|
| 01 | Review of Existing Experimental Hydrogen-Helium Release & Dispersion Data For Standard Benchmark Exercise Problems | PP | <u>NCSR</u> , UU, CEA, FZK, INERIS, FZJ, GexCon, STATOIL-HYDRO, DNV, TNO, HSL-HSE, BAM, Fh-ICT |
| 13 | Report on Proposals for | PP | <u>CEA, INERIS, NCSR</u> , FZK, |

| | | | |
|----|--|----|---|
| | tests/other activities – H2 Release | | DNV, STATOIL-HYDRO, TNO, GexCon, FZJ, UU, HSL |
| 65 | Experimental results on helium release inside a full scale GARAGE set-up | PP | <u>CEA</u> , INERIS |
| 67 | Report on CFD Calculations Report on scaling methodology. | PP | <u>GexCon</u> , UU, NCSR |
| 68 | Scaling of Gas Distribution, Mixing Processes | PP | <u>FZK</u> , NCSR |

9.3.5 References

- [1] J.M. Lacomme, Y. Dagba, D. Jamois, L. Perrette, Ch. Proust, Large-Scale Hydrogen Release In An Isothermal Confined Area, Second International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007
- [2] Gupta, S., Brinster, J., Studer, E., Tkatschenko, I., Hydrogen related risks within a private garage: concentration measurements in a realistic full scale experimental facility, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007
- [3] Perrette L, Paillere H, Joncquet G. (2006). Presentation of French national project DRIVE : Experimental data for the evaluation of hydrogen risks onboard vehicles, the validation of numerical tools and the edition of guidelines. Proceedings of WHEC 16, 13-16 June, Lyon, France.
- [4] A.G. Venetsanos, E. Papanikolaou, M. Delichatsios, J. Garcia, O.R. Hansen, M. Heitsch, A. Huser, W. Jahn, T. Jordan, J-M. Lacomme, H.S. Ledin, D. Makarov, P. Middha, E. Studer, A.V. Tchouvelev, A. Teodorczyk, F. Verbecke, M.M. van der Voort, An Inter-Comparison Exercise On the Capabilities of CFD Models to Predict the Short and Long Term Distribution and Mixing of Hydrogen in a Garage, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007
- [5] P. Middha, O.R. Hansen, J. Grune, A. Kotchourko, Validation of CFD calculations against ignited impinging jet experiments, 2nd International Conference on Hydrogen Safety, San Sebastian Spain, 11-13 September, 2007

9.4 Work Package WP9: *Hydrogen ignition and (jet) fires*

Lead Contractor: HSL
 Contractors involved: BAM, BRE, DNV, Fh-ICT, HSE/HSL, INERIS, JRC, Risø, TNO, UU, WUT, NH, BMW, VOLVO

9.4.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

The original objectives of WP9 were:

- Support the network activities by providing input on hydrogen ignition and fire hazards for various release scenarios.

- To further understanding of H₂ ignition and especially issues relating to “spontaneous ignition” of pressurised releases and ignition of liquid releases.
- Produce base data on the extent and heat flux from hydrogen fires/flames from credible leak scenarios in real situations.
- Behaviour of hydrogen storage tanks and peripheral components to ambient fires.

In 2003/4 there was little knowledge regarding the issues addressed above. In particular, while there was considerable anecdotal evidence regarding spontaneous ignition, and some shock tube work, there had been no real demonstration of the phenomena relating to realistic plant scenarios. This was clearly an area that needed further investigation.

The knowledge regarding flames was more complete than that for spontaneous ignition, with some information available, but still large gaps in knowledge.

The information on storage tanks behaviour was different in the sense that this was a new commercially sensitive area where information was being produced but was not readily available for commercial reasons.

What was clear for the first two areas was that to fulfil these objectives, experimental testing would be required to provide the data required.

9.4.2 Achievements of the activity, the current state:

Spontaneous Ignition

- i. It is now clear that there is a much better understanding of this issue with a number of groups now having done experimental and modelling work on this issue. It is probably fair to say that much of this activity was catalysed to some degree by the debate of this topic within HySafe and publication of a review paper back in 2005 (1).
- ii. Largely on the back of the investigation of this issue, HSL were able to partly justify national funding to develop a unique 1000 bar hydrogen storage and release facility (2) on its site at Buxton where work is currently underway (again using national funding) to investigate this phenomena and produce guidance on its control (paper in preparation for ICHS3). This work is also coordinated at an international level with US partners (Sandia National Laboratories) and Princeton University through IEA HIA Task 19. and papers prepared for ICHS3. In addition there is also a further collaboration with the HyFire project on the modelling of these phenomena.

Hydrogen Jet Fires

Again through the debate within HySafe the issue of hydrogen jet fires was highlighted, and particularly the lack of data in relation to flame size, visibility and thermal hazard. This debate was wider than this through interaction with IEA HIA Task 19. From the debate the gaps in knowledge have and are been addressed through following:

- i. Activity within HySafe strengthened justification for development of 1000 bar facility at HSL to address this issue.
- ii. Debate and activities within HySafe fed directly into linked HyPer project and experimental work carried out as part of this project to address at flame/jet extent and effects of barriers and jets connecting to surfaces, again coordinating with the US through IEA HIA Task 19 leading to the involvement of Sandia National Laboratories as US funded partner to this project. This work has all been reported through the HyPer project and a number of publications are being produced through ICHS3 and the Hazards Conference in Manchester, Autumn 2009 (see [2,3,4,5]).
- iii. Currently an additional experimental and modelling program underway linking through IEA HIA Task 19 involving StatoilHydro, Shell and Andrei V. Tchouvelev funded by Natural Resources Canada to look at hydrogen venting and the current standards.

9.4.3 Outlook for further research work:

The work regarding hydrogen venting continues. In addition, the unique facility at HSL, the skills and expertise developed within HySafe, and the strong links to US etc create a good situation to deal with any future related issues. This should clearly form part of IA HySafe activities.

9.4.4 List of Deliverables for WP9

D2 Report on data for SBEP - H2 ignition and fires [WP9 HSE/HSL](#) PP
 D72 Report describing pre-normative input to guidelines regarding design of hydrogen application to redu [WP9 HSE/HSL](#) PP
 D34 Report on available information including existing standards for bonfire tests of H2 tank structures [WP9 BAM](#) Report PU
 D14 Report on Proposals for tests / other activities - H2 ignition and fires [WP9 HSE/HSL](#) Report PP
 D32 Review of WP9 subtasks [WP9 HSE/HSL](#) 4 Report PP 14
 D71 Report describing ignition model to be used in risk assessment studies [WP9 DNV](#) 4 Report PP 30
 D42 Report including analysis of collected information for IgnHyd [WP9 HSE/HSL](#) 4 Report PP 20

9.4.5 References

- [1] ASTBURY, G.R., HAWKSWORTH, S.J., (2005) Spontaneous ignition of hydrogen leaks: A review of postulated mechanisms. International Conference on Hydrogen Safety, 8-10 September 2005, Congress Palace Pisa Italy & republished in International Journal of Hydrogen Energy Volume 32, Issue 13, September 2007, Pages 2178-2185
- [2] WILLOUGHBY, D.B. ROYLE, M.(2009) The interaction of hydrogen jet releases with walls and barriers, submitted to ICH3
- [3] HAWKSWORTH, S., SPAGNI, D., NEWSHOLME, G. (2006) Residential and Small Stationary Hydrogen Energy Systems: Risks and Opportunities. Proceedings of VGR Conference on Risk Assessment and Management in Civil and Industrial Settlements, Palace de Congress, Pisa, Italy, 17-19 October, Paper 700220.pdf

- [4] ROYLE, M., WILLOUGHBY, D.B., (2009) Consequences of catastrophic releases of ignited and unignited hydrogen jet releases, submitted ICHS3
- [5] S. BRENNAN, A. BENGOUER, M. CARCASSI, G. CERCHIARA, G. EVANS, A. FRIEDRICH, O. GENTILHOMME, W. HOUF, A. KOTCHURKO, N. KOTCHOURKO, S. KUDRIAKOV, D. MAKAROV, V. MOLKOV, E. PAPANIKOLAOU, C. PITRE, M. ROYLE, R. SCHEFER, G. STERN, A. VENETSANOS, A. VESER, D. WILLOUGHBY, J. YANEZ (2009) Hydrogen And Fuel Cell Stationary Applications: Key Findings, submitted Of Modelling And Experimental Work In The HyPer Project, submitted ICHS3.
- [6] S. BRENNAN, A. BENGOUER, M. CARCASSI, G. CERCHIARA, G. EVANS, A. FRIEDRICH, O. GENTILHOMME, W. HOUF, A. KOTCHURKO, N. KOTCHOURKO, S. KUDRIAKOV, D. MAKAROV, V. MOLKOV, E. PAPANIKOLAOU, C. PITRE, M. ROYLE, R. SCHEFER, G. STERN, A. VENETSANOS, A. VESER, D. WILLOUGHBY, J. YANEZ (2009), Towards Minimising Hazards In Hydrogen And Fuel Cell Stationary Applications: Key Findings Of Modelling And Experimental Work In The HYPER Project, Submitted Hazards XXI conference, Manchester Autumn 2009.

9.5 Work Package WP10: Hydrogen Explosions

Lead Contractor: FZK

Contractors involved: FZK, Fh-ICT, GexCon, INERIS, HSE/HSL, NCSR D, TNO, UC, UNIPI, WUT, UU, KI

9.5.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

For the evaluation of hazards associated with hydrogen fires and explosions it is necessary to determine the level of consequences that can be expected in various accidents. A characterisation of consequences in terms of pressure and thermal loading will serve as one of the important inputs for the overall risk evaluation. At the same time the level of consequences could provide an immediate deterministic outcome on safety distances, effectiveness of different mitigation techniques, if probabilistic risk assessment approaches are unacceptable.

If ignition of hydrogen mixtures is possible, the main hazards to be evaluated include thermal effects, pressure effects and effects of missiles generated by hydrogen explosions. It is not clear yet which hydrogen production methods, storage media, and/or distribution means will be widely utilised in the future. There are, however, solutions that are proposed and discussed. These solutions were taken as the basis for the list of scenarios considered in the WP4 (PIRT studies) and in the frames of WP10 work independently.

The properties of hydrogen are considerably different from conventional fuels. Hydrogen is expected to be less dangerous in terms of thermal and fire hazards, but it may be responsible for stronger pressure effects under certain conditions. It has been known that weak ignition in mixtures of hydrogen with air can easily result in intensive flame acceleration, development of fast supersonic combustion regimes, and, under certain

conditions, in deflagration-to-detonation transition. Pressure loads associated with fast combustion modes and detonations can be very severe.

The geometrical options for gaseous explosions defined by various hydrogen applications include the following cases that are to be addressed in the study of H₂ explosions:

- confined explosion;
- semi-confined or vented explosions;
- unconfined explosions.

Before and still in considerable degree now it is not easy to predict hydrogen combustion behaviour and corresponding pressure and thermal loads from explosions of stratified hydrogen clouds typical for H₂ releases in confined and semi-confined geometries (tunnels, parking, garages, etc.). Venting of hydrogen explosion in complex geometries and/or non-uniform mixtures represents another problem case that should be additionally investigated. Predictions of the hydrogen combustion behaviour in cases with venting are required to investigate efficiency of venting as a mitigating measure aiming at reduction of consequences of the accidents with hydrogen. The problem of deficiency of the experimental database and lack of model capabilities can be identified for the cases of unconfined explosions in obstructed areas (refuelling stations, etc.).

Thus the objectives of the work package were formulated as follows:

- Develop methodology for evaluation of hydrogen explosion phenomena;
- Scan existing experimental database on hydrogen fires and ignition;
- Support the network activities by providing input on hydrogen explosion hazards, for various release scenarios, including formulation of the priority directions of the investigations and performance of the experiments.

9.5.2 Achievements of the activity, the current state:

At the early stage of the work package work all partners worked to prepare a review of available experimental data. Sources of information included the scientific literature, previous EC-hydrogen-related projects (EIHP, EIHP2, etc) as well as the own data of partners, who were willing to share their data within the network. These data were reviewed and agreed upon at the WP10 coordination meeting. Selected data were examined and submitted to WP3 (later integrated in WP6) constituting the basis of experimental database of SBEP candidates (deliverable D3).

Following this period the partners concentrated on formulation of proposals for future experimental work on hydrogen explosions and submission to project consortium. An analysis of requirements for the future experiments was made by HSE/HSL and INERIS. On the partners work package meeting the general approach for the essential future development was formulated. The proposals on future experiments which can be performed on their own test sites were formulated by WUT and FZK. Contributions to internal projects InsHyde and HyTunnel were drafted.

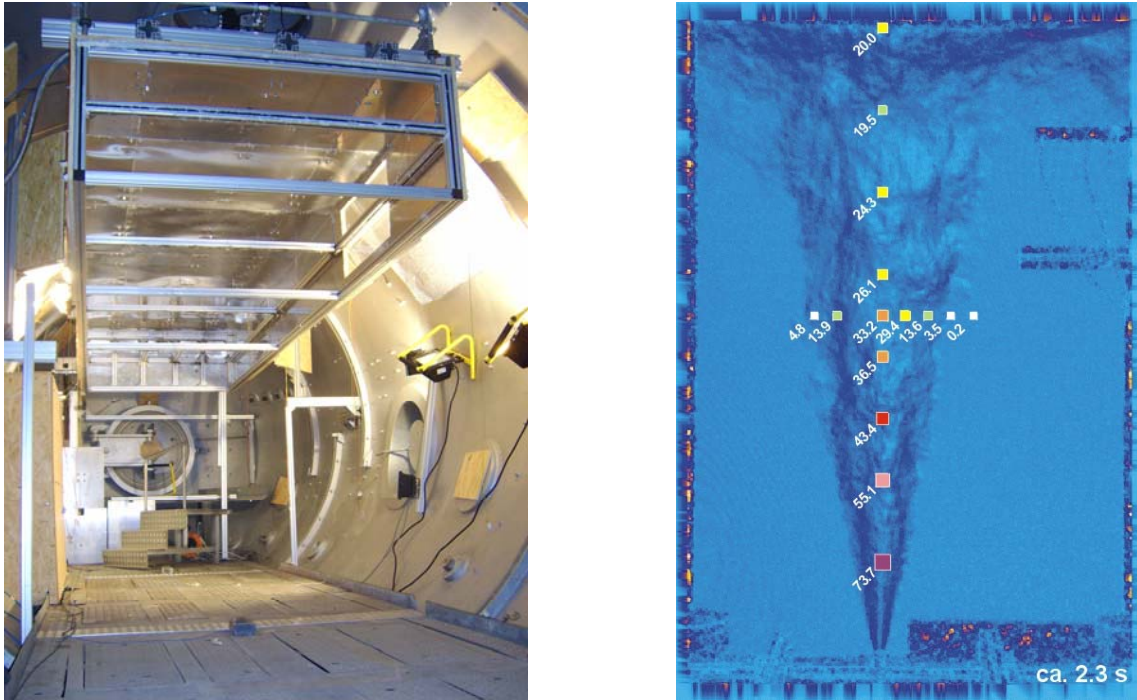


Figure 4. Outline of the experimental facility in the tests for internal project HyTunnel (left) and visualization of the jet obtained in the course of the carrying out of the first phase of the InsHyde internal project (right) .

The experiments planned in the frames of the InsHyde project were completed. Pre-test calculations provided by GexCon were used at the stage of experiment preparation and analysis. The obtained data provided information on realistic - while conservative - expected regimes of combustion and maximum expected pressure loads for the hydrogen small-scale accident scenarios typical for H₂-driven vehicle workshops. These data were not available before and therefore fill the knowledge gap existing before. On the basis of the obtained information further activities are planned.

In the frames of the work package activity two meetings devoted to support of HyTunnel internal project were organized. During the first meeting the broad discussions allowed to finalize the set of experiments on FA and DDT which has to be performed. The planned experiments were prepared and carried out. On the second meeting the main results with preliminary analysis were reported. On both meetings additionally the applied simulations, which have to be performed, were discussed intensively.

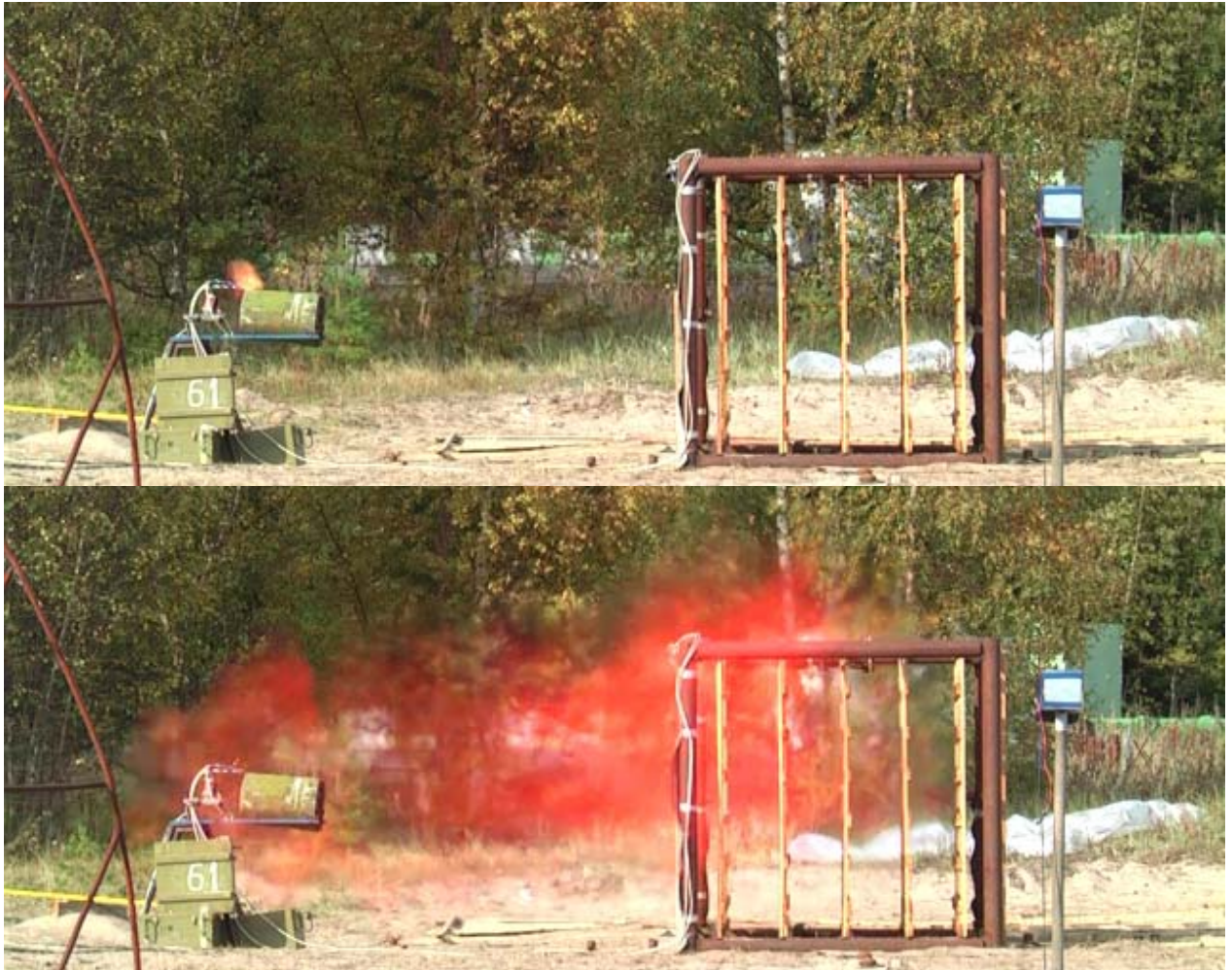


Figure 5. Large-scale combustion tests performed in second phase experiments work.

The results of the ‘HyTunnel’ experiments provided a brand new data on the possibility of strong flame acceleration and DDT in semi-open geometrical environment, which are typical for many accident scenarios expected for hydrogen-related industry. These results have introductory character and allows, from one side, to make already certain conclusions about expected regimes of combustion for such geometrical conditions for given H₂-air mixtures and, from other side, to formulate exhaustive proposals for further experimental activities.

The experiments planned as second phase of hydrogen explosion in semi-confined geometries were completed. The obtained data provided information on large-scale realistic expected regimes of combustion and maximum expected pressure loads for the hydrogen accident scenarios in configuration with horizontal propagation of intensive jets in obstructed geometries. The obtained data allowed obtain valuable information on the possibility of strong explosion effects for intensive jets in such configurations. These data were not available before and thus fill the before-existing knowledge gap. On the basis of the obtained information further activities can be recommended.

In the frames of the work package activity multiple discussions during preparation and performance phase were carried out. The planned experiments were prepared and carried out. Obtained results were analyzed and published and are partially in preparation for the presentation at 3rd ICHS conference.

9.5.3 Outlook for further research work:

The work on hydrogen explosions has to be continued in particular to address non-homogeneous distributions and the behaviour of cold premixed clouds generated by liquid spills. Another issue is the impact of sprays on the combustion phenomena. Although some first principal investigations have been started information with practical relevance is lacking.

It is hoped that the major part of this open issues can be addressed in project work co-funded by public sources. The International Association for Hydrogen Safety, IA HySafe, might take a role in this future activity acting as coordinator.

9.5.4 List of Deliverables for WP10:

- [1] D3 Report on data for SBEP – explosions
- [2] D15 Report on Proposals for tests / other activities – explosions
- [3] D63 Report on preparation and conduction of experiments
- [4] D87 Report on results of experiments
- [5] D91 Report on results of FA/DDT experiments
- [6] D102 Report on the preparation and performance of the second phase explosion experiments
- [7] D116 Report on the results of the experiments

9.6 *Work Package WP18: Material Compatibility and Structural Integrity*

Lead Contractor: INASMET
 Contractors involved: AL, BAM, BMW, DNV, Fh-ICT, FZK, SH, DTU/Risø, HSE/HSL, INERIS, KI, UNIPI, UPM

9.6.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

In a “hydrogen economy” scenario, large scale production, storage, transportation and use of hydrogen become necessary. Hydrogen components and systems involve a wide variety of materials, metallic and non-metallic. Each material that is involved should be carefully evaluated for its use in the design, operating and emergency conditions to which it will be exposed. The selection of a material that is suitable for use in hydrogen system involves several factors as – of course - the compatibility with hydrogen itself (with concerns such as hydrogen embrittlement, hydrogen attack, hydriding, porosity, permeation and diffusion). Thus, some considerations, tests etc. are involved in the choice of a material to be used in a hydrogen system. This knowledge actually exists in the scientific and specialised industry communities but it is quite dispersed and not properly focused to the “hydrogen economy” scenario.

In the case of the Hydrogen storage some solid materials are considered a promising way from the safety point of view. Hydrides, some nano-structured carbon based materials, hollow glass microspheres and others are potential candidates. These materials have some

special behaviour in reactions with the surrounding atmosphere and there are some risks associated.

The general aim of this work programme has been the critical assessment of the existing knowledge and the determination of critical gaps in the field of study.

In summary the main objectives have been:

- To consolidate existing know-how in the field of material compatibility.
- To identify gaps in the understanding of engineering material.
- To support internal and external projects by recommending existing infrastructure and providing profound knowledge to all involved parties.
- To increase the fundamental understanding of the safety issues regarding solid-state hydrogen storage materials: especially release and reaction kinetics of light metal or alloyed storage media.

9.6.2 Achievements of the activity, the current state:

Main achievements of the work package have consisted of the identification of tests, standards as key in the assessment of the suitability of a material for its use in hydrogen components and systems. A variety of experiments like fatigue, corrosion, bonfire, permeation, rupture...as well as the approval of pressure relief devices, benign behaviour of system components to failure have to be performed in order to prove the system's eligibility for different hydrogen applications, as for example the automotive one.. Partners in HySafe with materials testing capabilities are Air Liquide, BAM, CEA, DNV, Fh-ICT, FZJ, FZK, GexCon, HSL, INASMET, INERIS, KI, DTU/Risø and StatoilHydro. ET and INTA, that have been supporters of NoE HySafe, have also some capabilities. In addition, several organizations outside the HySafe consortium, have been identified as capable of performing such tests. These are included in the Table below.

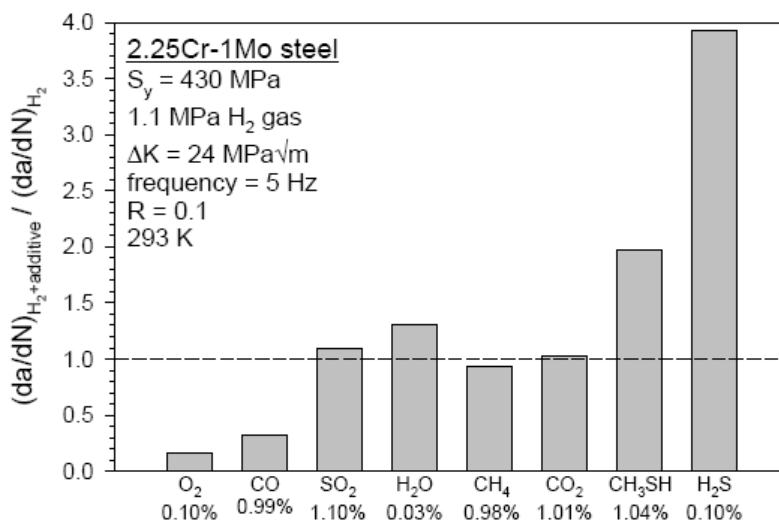
| Organization | Country | Field of activity | Web |
|---|---------|--|--|
| Anachem Laboratories | U.S.A. | Hydrogen embrittlement and hydrogen pick-up testing. | www.anachemlabs.com |
| Bodycote Testing, Inc. | U.S.A. | Hydrogen embrittlement testing (ASTM F519) of components that have been plated. | mtusa.bodycote.com |
| ET EnergieTechnologie | Germany | Hydrogen embrittlement testing (1000bar, 300°C), Hydrogen permeation testing (800bar – CGH2; 20K – LH2) | www.et-energietechnologie.de |
| InterCorr International | U.S.A. | Stress corrosion cracking, sulphide stress cracking and hydrogen induced cracking testing. | www.intercorr.com |
| Institut de la Recherche sur l'Hydrogène. (IRH) Université du Québec à Trois Rivières | Canada | General research in Hydrogen Safety. Materials for hydrogen storage. | irh.uqtr.ca |
| Japan Petroleum Energy Centre. Hydrogen Technology Group. | Japan | Risk Management Approaches to the Japanese Regulations of Hydrogen Supply Stations Metallic Materials. Capabilities. 500 bar | www.pecj.or.jp |
| Kennedy Space Center | U.S.A. | Corrosion research and material evaluation in corrosive environments (hydrogen | www.corrosion.ksc.nasa.gov |

| | | | | |
|---|--------|--|---|-------------------------------------|
| | | | embrittlement, hydrogen blistering, stress corrosion cracking). | gov |
| Metallurgical Consultants | U.S.A. | | Hydrogen embrittlement testing. | www.materi alsengineer.c om |
| Motor Vehicle Fire Research Institute | U.S.A. | | Motor Vehicle Fire Research Institute (MVFRI) is an independent, nonprofit, applied engineering and physical sciences organization specializing in automobile fire safety research. Stress corrosion cracking, environment induced cracking, hydrogen diffusion etc. Techniques: constant load; SSRT; constant displacement (4-pt bend, C-ring); fracture mechanics (constant load, rising load or rising displacement); hydrogen permeation. Environments: predominantly aqueous, up to 200 °C at open circuit or under applied potential and including H ₂ S; low to moderate pressure H ₂ gas a possibility but 20 years since last studies in H ₂ gas Modelling: H ₂ permeation and crack-tip H. Standards: ISO 7539 Parts as appropriate (including H ₂ permeation standard); NACE standards as appropriate. | www.mvfri. org |
| National Physical Laboratory NPL | U.K. | | Ultrasonic inspection for detection of hydrogen damage in power plant boiler tubes. | www.npl.co. uk |
| NDE Associates, Inc. | U.S.A. | | Hydrogen pipelines | www.nde.co m |
| National Institute of Standards and Technology (NIST) | U.S.A. | | Hydrogen embrittlement testing. | www.omega researchinc.c om |
| Omega Research | U.S.A. | | General testing facilities. 350 / 700 bar Hydrogen dispenser. Specialized facility dedicated to evaluating the performance of high pressure components under various temperatures and environments. A hydrogen/CNG safe room is also available. | www.omega researchinc.c om |
| Powertech | Canada | | Hydrogen Vehicle Center. Designed specifically as a hydrogen-safe facility to accommodate the simultaneous servicing of up to six hydrogen vehicles. Specialized testing including vehicle fires, gunfire tests, cylinder bonfires and various impact and crush tests. | www.powert ech.bc.ca |
| Praxair | U.S.A. | | General purpose testing facilities. | www.praxair .com |
| Sandia National Laboratories | U.S.A. | | General purpose testing facilities. Metal Hydride Center of Excellence. | www.ca.san dia.gov/hydr ogen/ |
| Savannah River National Laboratory | U.S.A. | | Fundamental safety testing and analysis of hydrogen storage materials & systems | srl.n.doe.gov |

Solid Sate H Storage Materials

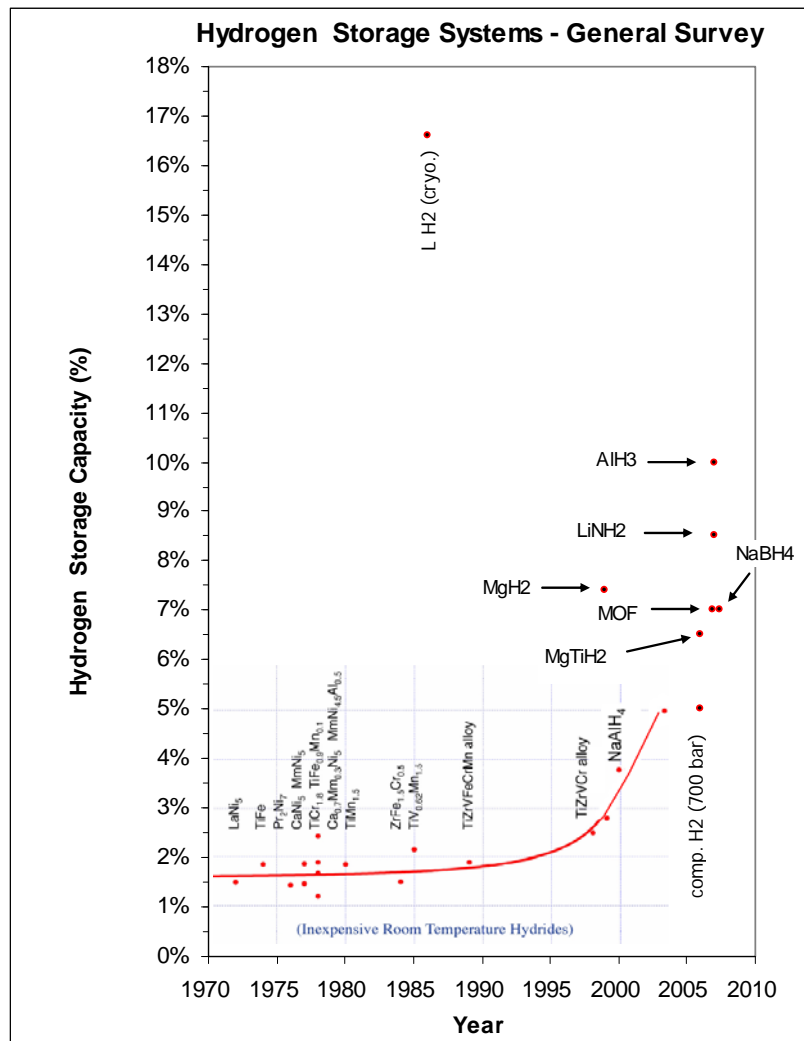
| | | | |
|---|--------|--|--------------------|
| Surtronics, Inc. | U.S.A. | Thermal stress relief of hydrogen embrittlement process to parts that have been plated. | www.surtronics.com |
| The Hendrix Group | U.S.A. | Corrosion and hydrogen embrittlement testing. Temperature controlled mechanical test facility in hydrogen at 1000 bar. | www.hghouston.com |
| TWI | U.K. | Tensile/low cycle fatigue/fracture toughness. Up to 1000bar hydrogen. T -150 to +85°C Could also use methane/hydrogen mixtures. Could perform ISO11114-4 tests. | www.twi.co.uk |
| United States Environmental Protection Agency | U.S.A. | Hydrogen Fuelling Station. Hydrogen vehicle Testing facilities | www.epa.gov |
| United Technologies Research Center | U.S.A. | General purpose testing facilities | www.utrc.com |
| University of Calgary | Canada | R&D, training etc. in: Hydrogen embrittlement, stress corrosion cracking, sulphide stress cracking. | www.ucalgary.ca |
| University of Missouri | U.S.A. | Analysis of composite hydrogen storage cylinders under transient thermal loads Polymers | www.missouri.edu |

Several literature sources have reported the effects on hydrogen embrittlement (HE) of gaseous impurities. It is known that higher levels of hydrogen purity lead to higher embrittling effects on steels, but it may also be valuable for high pressure storage purposes to know what gases act as inhibitors to HE. The effect of impurities on materials behaviour has been studied in this work package. Gas impurities can inhibit, accelerate, or have no effect upon hydrogen embrittlement. O₂ and SO₂ act as inhibitors, CH₄ and N₂ as gases with no effect, and H₂S and CO₂ are known to be accelerators of HE (see Figure below).



On the field of nanomaterials for hydrogen storage, main achievements have been the definition of the relevant materials for this application, the collection of existing standardized test methods to investigate reaction kinetics of hazardous release and

oxidation kinetics, as well as evaluation models and the definition of the set of criteria for suitability and approaches to estimate hazards from experimental data.



The main risks which directly arise from the use of such hydrides or metals concern the involvement of the following aspects:

- The solids are highly porous or nano-structured to expose high surface areas to easy hydrogen access but also to easy air access on accidents.
- The metals are in a pure state on hydrogen release and highly sensitive to oxidation in case of contact to air.
- The temperatures are elevated on operation in relation to oxidation reactions of metals, even they are considered moderate.
- In addition gaseous hydrogen is present

This means that an accident with a rupture of the container or feeding lines might enable air to get into contact with the residual metals of the hydride decomposition or desorption; in addition, elevated temperatures might enhance effects (AlH₃ ~ 400 K).

Air/oxygen gets access to the pure metals and also in cases of only passivation reactions - thin protecting oxide layers (for Al ~ 2 – 4 nm) - would initiate violent conversion of the nano-, or nano-structures materials. 10-30% of metals might be oxidised at high reaction

rates releasing heats of oxidation leading to catastrophic explosions if not protected by adequate mitigation measures:

- Thermal explosion of container and the subsequent distribution
- Explosion of released metal of nano-size in air
- Even Deflagration Detonation Transitions (DDT) might be possible if well distributed nano-particles ignite.

9.6.3 Outlook for further research work:

The International Association for Hydrogen Safety, IA HySafe, might take a role in this future activity acting as coordinator for the materials testing services provided by the companies related in the Table above and further studies concerning safety of materials for hydrogen storage

9.6.4 List of Deliverables for WP 18:

- [1] D 77. Report on existing know-how in the field of Material Compatibility (INASMET)
 [2] D 97. Updated report on existing know-how in the field of Material Compatibility (INASMET)
 [3] D101. HyFrac - Report on existing know-how and recommendations (AL) (*)
 [4] D108. HyFrac - Report on experimental programme (AL) (*)
 [5] D112. HyNano- Report on recommended test protocols (Fh-ICT)
 (*) Deliverables D101 and D108 have been merged and issued in a single one D101-108

9.7 *Internal Project IPI: InsHyde (Hydrogen Releases in Confined and Partially Confined Spaces)*

Coordination: NCSR
 Partners: CEA, FZK, DNV, INASMET, INERIS, TNO, GexCon, FZJ, UU, HSE-HSL, Fh-ICT, BRE, JRC, UNIPI, VOLVO, WUT, AL, BMW, UPM, StatoilHydro, UC, DTU/Risø
 Duration: 3 years (2005-2008)
 Website: <http://www.hysafe.net/InsHyde>

9.7.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

In the first year of HySafe the “safety vote” of the PIRT exercise and the expert survey have pointed out that releases (even slow releases, with “small” release rates) of hydrogen in confined or partially confined geometries represent a serious risk, since combustible mixtures may form, which, if ignited, could lead to explosions and even to detonations. Thus, it is necessary to study different configurations of release (position, release rate) and the accompanying sensor equipment and mitigation devices (ventilation or other ways of enhancing mixing, inertisation, active ignition or recombination). The InsHyde program has been initiated during the 2nd JPA of HySafe to address this need.

The InsHyde project main objectives were:

- To investigate realistic (ATEX related) indoor leaks and ultimately to provide recommendations for the safe use / storage of indoor hydrogen systems
- To pull together work packages proposals and existing research projects toward a common goal and a useful contribution to the society for the safe implementation of hydrogen technologies.

9.7.2 Achievements of the activity, the current state:

InsHyde activities were divided into the following 10 subtasks:

- IP1.1 Review (lead, DNV)
- IP1.2 Gas Detection experiments (lead JRC)
- IP1.3 Theoretical study of permeation (lead VOLVO)
- IP1.4 Dispersion experiments (lead CEA)
- IP1.5 Explosion experiments (lead FZK)
- IP1.6 Ignition (lead HSL/HSE)
- IP1.7 CFD modelling (lead GexCon)
- IP1.8 Scaling methodology (lead FZK)
- IP1.9 Recommendations and Conclusions (lead INERIS)
- IP1.10 Dissemination (lead INERIS)

Hydrogen detectors performance evaluation and inter-laboratory calibration tests by JRC, INERIS and BAM (D54)

The gas detection experiments performed in subtask IP1.2 had the scope to experimentally assess the performance of gas detectors, to prepare their use in the context of dispersion experiments and to contribute to D113.

Two different experimental programs were performed: an inter-laboratory comparison on calibration-type tests on selected sensor types carried out by JRC and BAM, and a test program based on IEC 61779-1 & 4 for hydrogen sensors, to assess the performance of some commercially available hydrogen detectors, carried out by JRC and INERIS.

Nine different detectors or sensors were tested from different manufacturers. This sample includes both electrochemical and catalytic technologies. The basic tests consisted in the acquisition of calibration curves and in measuring the response and recovery time during an instantaneous variation of the hydrogen concentrations. Sensors performance has been assessed by studying the signal response to variation in environmental temperature, humidity and pressure. In addition, sensors' cross-sensitivity has been investigated in the case of carbon monoxide.

Tests have shown that the electrochemical technology allows to detect H₂ concentration lower than in the case of catalytic technology, whose detection threshold is more around 500 ppm (between 1 and 2 % of H₂ lower flammability limit LFL).

A new "continuous calibration" concept has been tested, consisting in the continuous recording of the sensor response upon a progressive increase/decrease of hydrogen content in the test gas. The results compare well with those obtained by the standardised technique. The response time (t₉₀) of catalytic detectors, with a gas test concentration of 50 % of H₂ LFL (middle of the scale), was less than 10 seconds. Response time was moderately

influenced by temperature. Humidity had a greater impact on response time. Increased humidity leads to higher response time value. CO sensitivity results high by catalytic combustion sensors (approximately 1/3 of that to hydrogen). The effect is approximately independent from the presence or the absence of hydrogen in the test atmosphere (tested hydrogen range has been 0 to 1% in air). Also humidity variations cause a deviation of the sensor reading, though of a more limited amount than in the CO case. Quantitative assessment if the humidity effect is hindered by discrepancies in the results of the two laboratories. The “continuous calibration” concept cannot be used in this case. In comparison to the humidity and cross-sensitivity effects, temperature and pressure variation induce a more limited signal deviation.

Further performance based investigations using different hydrogen sensors and detectors are necessary to cover the many different possible contexts of use.

Study of permeation by VOLVO, NCSR, UU, BRE and CEA (D74)

Permeation issues were studied using various approaches, theoretical, computational and experimental.

NCSR investigated the time and space evolution of the hydrogen distribution in confined settings, due to permeation from compressed gaseous hydrogen bus or car storage systems, using the three dimensional CFD dispersion code ADREA-HF. The main goal was to examine whether hydrogen is distributed homogeneously within the given facility or whether stratified conditions are developed, under certain conditions. The nominal hydrogen flow rate considered was 1.087 NL/min, based on a SAE proposal for type 4 storage cylinders at end of life and max material temperature and a bus facility volume of 681m³. The release was assumed to be directed upwards from a 0.15m diameter hole located at the middle part of the bus cylinders casing. Ventilation rates up to 0.03 ACH (air exchanges per hour) were considered. Simulated time periods extended up to 20 days. The CFD simulations by NCSR showed that fully homogeneous conditions exist for low enough ventilation rates, while stratified conditions prevail for higher ventilation rates. Regarding flow structure it was found that the vertical concentration profiles can be considered as the superposition of the concentration at the floor (driven by laminar diffusion) plus a concentration difference between floor and ceiling (driven by buoyancy forces). In all cases considered this concentration difference was found less than 0.5%. ADREA-HF was also validated against experiments performed by CEA at the GARAGE facility, using helium, with good agreement between predicted concentrations and experimental data.

Hydrogen dispersion experiments by INERIS

The short and long term evolution of the hydrogen/air mixing of a low momentum release inside an unventilated space at constant pressure has been studied experimentally by Lacombe et al. (2007) [1]. The experiments were performed inside a garage like gallery of dimensions 7.2x3.78x2.88 m, using hydrogen and helium for hydrogen mass flow ranging from 0.2 g/s to 1 g/s (vol. flow from 2.3 to 11.5 l/s) for 240 s release time. Diameter of orifice varied from 5 to 20 mm. The release was vertically upwards from the horizontal centre of the facility, 0.265m above the ground. Hydrogen concentration was measured at 12 positions along the jet axis and laterally displaced to it for a period of 90 min. The experiments showed that a horizontally almost homogenous and vertically stratified layer of hydrogen/air mixture developed fast close to the ceiling. Vertical concentration profiles (see Figure 3) show that hydrogen concentrations are rather homogenous in the formed layer near the ceiling. The higher the layer concentration the more the slope of the profile increases. With increase of the release flow rate the concentration gradient between the

hydrogen layer and the ground increases. During the release phase, concentration in the layer is mainly correlated with the flow rate. This layer did not change significantly during the period after the end of release (diffusion phase). For test INERIS-6C (1g/s and 20mm orifice) the flammable hydrogen/air mixture occupied approximately half the height of the facility. For the 0.2g/s release the concentration did not exceed the LFL. Homogeneous conditions were reached four hours after the release. The performed helium tests showed a strong similarity with hydrogen.

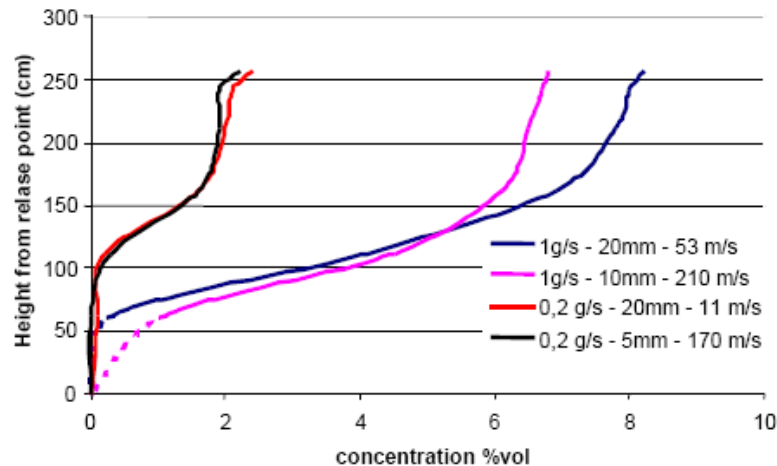


Figure 6: Vertical concentration profile at end of release for various release rates, according to Lacome et al. (2007)

Helium dispersion experiments by CEA (D65)

Helium dispersion experiments were performed by CEA [2] in a full scale newly built realistic GARAGE facility. The work was partly funded by HySafe and the French project DRIVE [3]. The GARAGE interior dimensions were 5.76 m (length) x 2.96 m (width) x 2.42 m (height). Results were presented for test cases performed in the free volume of GARAGE without any ventilation. Tests 1 and 2 were performed with a flow rate of 688 NL/min (2 g/s helium) using the same nozzle diameter of 20.7 mm and varying the release duration from 121 to 500 s respectively. Tests 3 and 4 were performed with a flow rate of 18 NL/min (0.05 g/s helium) using the same release duration 3740 s and varying the nozzle diameter from 5 to 29.7 mm respectively. In this series helium concentration during and after injection phase was measured at 64 monitoring points. For the given aspect ratio of the GARAGE and test conditions, no overturning of flow takes place and stratified layers are formed inside the geometry. The analysis of results clearly showed that for the leaks inside the unventilated GARAGE, the risk induced is most strongly affected by the total volume of the gas released rather than the flow rate. For the test cases with similar initial conditions peak concentration levels increases with an increase in the injected volume. Test cases with similar injected gas volumes but different initial conditions, show almost identical peak concentration levels at the end of injection phase. However, variations in flow rates influence the mixing behaviour inside the GARAGE that in turn changes the decay rates of gas concentrations. Test cases with higher injected volumes of gas represent the worse condition and takes longer time to reduce the concentration levels below lower flammability limit of hydrogen.

Hydrogen combustion experiments by FZK/PRO-SCIENCE (D63)

Hydrogen distribution and combustion experiments were performed during May 2006 by supporter Pro-Science and FZK [4]. In the scenarios analyzed, a limited amount of hydrogen, possibly enclosed in the pipes and the engine of a faulty hydrogen powered

vehicle, is accidentally released. The study investigated the hazard potential of this limited amount of hydrogen when it is released into an almost open geometry with no additional venting, travelling upwards as free jet until it either reaches a horizontal plate, is accumulated in a hood above the release or penetrates a porous system on its way upwards. Hydrogen release scenarios of up to 10 g hydrogen through one of three different nozzles with release times from 1 to 70 s into a low confined ambience were investigated. In 33 experiments the concentration distribution and the shape of the free jet H₂ cloud was determined via concentration measurements. The hydrogen concentrations measured in vertical direction along the axis of the jet can be described by mathematical functions, the measured horizontal hydrogen concentration profiles of the jet exhibit the shape of Gaussian distribution functions. Furthermore the possibility of an accumulation of the released hydrogen in a hood above the jet was investigated. Additionally the experiments concerning the hydrogen distribution behaviour were supplemented by Background-Oriented-Schlieren (BOS) photography.

In 81 combustion experiments pressure and sound level measurements were performed for the scenarios described. The ignition of the released hydrogen was initiated in positions along the axis of the release, where concentrations of about 30 Vol.-% H₂ (about stoichiometric concentration) were determined in the distribution experiments. Due to the ignition of the undisturbed free jet a maximum overpressure of 11.1 mbar was detected by the pressure gauge in the closest distance (0.403 m) to the ignition source, with a maximum sound level of 121 dB(A) in a distance of three meters from the ignition (experiment PIF03). In the experiments where a hydrogen accumulation in a hood above the release was investigated, a maximum overpressure of 53.2 mbar was measured by the pressure gauge at the highest position inside the hood in a distance of 0.78 m to the ignition, with a maximum sound level that exceeded the measuring range of the sound level meter (130 dB(A)) in a distance of three meters from the ignition (experiment PIF08).

In the experiments, where grid net layer structures were used as flame acceleration devices to simulate porous materials in the vicinity of the hydrogen source, a maximum overpressure of 9176 mbar was recorded by the pressure sensor in the closest distance (0.345 m) to the ignition, while a maximum overpressure of 410 mbar was measured by the pressure sensor in the largest distance of 1.945 m to the ignition (experiment PIC22). In this experiment no sound level measurements were performed to protect the sound level meter.

Hydrogen combustion experiments by KI

The distribution and combustion of large high pressure jet releases of hydrogen both into free space and into congested area have been experimentally investigated by Kurchatov Institute. More than one hundred experiments were performed at the “Vargos” testing site. Released hydrogen mass varied from 0.1Kg to 1.0Kg with average ejection rate of 200 g/s. Various congestion levels were examined. The influence of additional small congested area was investigated. Different geometrical conditions were modelled and different combustion regimes were obtained.

Main conclusions from the experiments are:

- Spontaneous autoignition of mixture during ejection was not observed.
- For hydrogen release amount more than 400g in uncongested area no ignition was observed because the hydrogen concentration in a point of ignition is lower than flammability limit.

- In a case of congested area (blockage ratios 0.3 and 0.54) ignition and slow combustion took place in all experiments. The maximum overpressure in these experiments was lower than 60 mbar.
- In experiments with additional congestion maximum overpressure reaches 400 mbar.
- During experiments a special geometry was identified that results in fast deflagration with overpressure more than 10 atm.

CFD validation and inter-comparison (D66, D67, D46)

Test INERIS-6C was used for extensive CFD validation [5]. Blind and post calculations were performed. Participation in the benchmark exercise was large: 12 organizations, two of which were non-HySafe partners, with 10 different CFD codes applying 8 different turbulence models, including an analytical solution. In contrast to earlier CFD validation [6] some partners' blind calculations overestimated the mixing of hydrogen with air and predicted transition to homogeneous conditions in the enclosure much faster than the experimental evidence. This behaviour was attributed to poor discretization accuracy options selected by the CFD users. Improved discretization characteristics (higher order convective schemes, increased vertical grid resolution and smaller time steps) showed to improve the predictions in comparison with the experiments.

Hydrogen dispersion experiments, performed by GexCon outside of HySafe, in a small scale compartmented naturally ventilated enclosure, were used for CFD validation and inter-comparison [7]. GexCon performed blind CFD simulations of the release and ignition scenarios of the FZK/PRO-SCIENCE combustion experiments discussed above [8]. Besides CFD validation the simulations aimed at assisting the planning of the experiments. The simulated results were found to correlate reasonably well with experimental data, both in terms of the gas concentrations and overpressures subsequent to ignition. Nevertheless, the experimental set-up can be considered to be small-scale and less severe than many accidents and real-life situations. Future large-scale data of this type will be very valuable to confirm ability to predict large-scale accident scenarios.

Initial guidance for using hydrogen in confined spaces. Results from InsHyde (D113)

This report aims at gathering the knowledge learned during the InsHyde project, as well on a theoretical point of view as on a practical point of view. It focuses on the use of hydrogen in confined spaces and the necessary safety measures to be taken. It does not aim at gathering all the documents issued by InsHyde and HySafe on this subject but to give an overview of each topic. References to detailed documents, available via HySafe, are made in each chapter so that the reader may deepen the subject of interest for him or her. To be fully complete, this report makes references to existing standards and best practices.

In the first chapter, the physical properties of hydrogen are briefly summarized. In the second chapter, focus is given on the risk control measures to be applied for a safe use of hydrogen indoor. This chapter aims at improving the safety of existing systems and at designing a safe system in an integrated way. In chapter 3 focus is given on the behaviour of hydrogen in potentially accidental situations and this means release, dispersion and of course ignition and explosion. In the fourth chapter a short overview of risk assessment methodology is given and some examples of what has been done amongst HySafe partners to design safe experiments with hydrogen. At last, all the procedures followed by HySafe partners to design and perform safe experiments with hydrogen (dispersion, ignition, explosion, etc...) are gathered in the annex.

Submission of proposals

A proposal regarding an FP7 collaborative project entitled “HyGarage” has been submitted to EC call Energy 1.3.1 (May 2007). The proposal involved 14 partners for 3 years. The proposal was rejected with total evaluation score 12.5 over 15.0. Main goals were set as following:

- To review existing safety requirements across Europe for use of private or commercial vehicles in garage, workshop and parking environments
- To validate the existing safety requirements for use of hydrogen powered vehicles using experiments, CFD and risk assessment methodology and propose changes if necessary
- To produce guidance documents one for each environment and communicate these documents to related stakeholders (building authorities, fire service, automotive industry, ...)
- To increase our understanding of hydrogen behaviour in confined and semi-confined spaces and to fill gaps in the knowledge base
- To provide the basis (e.g. formulated in technical requirements and specifications) on which automotive industry, facility operators, insurers and authorities/ governments (e.g. by developing related legal requirements like EU directives or in the future possibly also GTR for hydrogen related infrastructures) can consistently judge - qualitatively and quantitatively – on the risk associated with operating and parking hydrogen vehicles in garage facilities

9.7.3 Outlook for further research work:

The consortium strongly suggests funding of further pre-normative work in order to:

- Formulate the requirements for permitting the use of hydrogen vehicles (cars and commercial vehicles) in confined spaces
- Increase our understanding on hydrogen behaviour in confined spaces

This work should be jointly undertaken by research, industry and regulatory bodies.

9.7.4 List of Deliverables:

| Deliverable No | Title | Access status | Contributing Partners |
|----------------|---|---------------|--|
| 38 | Report on CFD-experimental matrix design for internal project InsHyde | RE | <u>NCSRD</u> , CEA, INERIS, JRC, BAM, FZK, GexCon |
| 46 | Compilation report on SBEP results of the 2nd JPA period and Initial Evaluation of results | PP | <u>NCSRD</u> , CEA, DNV, FZK, FZJ, GexCon, HSL-HSE, UPM, UU, WUT, INERIS, AVT, GRS |
| 54 | Sub-task IP1.2 Gas detection experiments | PU | <u>JRC</u> , BAM, INERIS |
| 63 | Report on preparation and conduction of experiments. FZK distribution and combustion experiments: H2 release and subsequent ignition in low-confinement | CO | <u>FZK</u> , PRO-SCIENCE |

| | | | |
|-----|--|----|---|
| | enclosures | | |
| 65 | Experimental results on helium release inside a full scale GARAGE set-up | PP | <u>CEA</u> , INERIS |
| 66 | Report on CFD code validation | PP | <u>GexCon</u> , UU, NCSR, FZK, INERIS, FZJ, GexCon, JRC, DNV, HSL-HSE |
| 67 | Report on CFD Calculations | PP | <u>GexCon</u> , UU, NCSR |
| 68 | Report on scaling methodology. Scaling of Gas Distribution, Mixing Processes | PP | <u>FZK</u> , NCSR |
| 72 | IgnHyd Report on Pre-Normative Input to Guidelines Regarding Hydrogen Ignition | PP | <u>HSL-HSE</u> |
| 74 | Report On Permeation | PP | <u>VOLVO</u> , UU, NCSR, CEA, BRE |
| 113 | Initial guidance for using hydrogen in confined spaces. Results from InsHyde | PU | <u>NCSR</u> , INERIS, BMW, BRE, FH-ICT, FZJ, FZK, GexCon, HSL, INASMET, INERIS, JRC, KI, NCSR, STATOIL/HYDRO, UNIPI, UU |

9.7.5 References

- [1] J.M. Lacome, Y. Dagba, D. Jamois, L. Perrette, Ch. Proust, Large-Scale Hydrogen Release In An Isothermal Confined Area, Second International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007
- [2] Gupta, S., Brinster, J., Studer, E., Tkatschenko, I., Hydrogen related risks within a private garage: concentration measurements in a realistic full scale experimental facility, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007
- [3] Perrette L, Paillere H, Joncquet G. (2006). Presentation of French national project DRIVE : Experimental data for the evaluation of hydrogen risks onboard vehicles, the validation of numerical tools and the edition of guidelines. Proceedings of WHEC 16, 13-16 June, Lyon, France.
- [4] A. Friedrich, J. Grune, N. Kotchourko, A. Kotchourko, K. Sempert, G. Stern, M. Kuznetsov, Experimental study of jet-formed hydrogen-air mixtures and pressure loads from their deflagrations in low confined surroundings, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 Sept. 2007
- [5] A.G. Venetsanos, E. Papanikolaou, M. Delichatsios, J. Garcia, O.R. Hansen, M. Heitsch, A. Huser, W. Jahn, T. Jordan, J-M. Lacome, H.S. Ledin, D. Makarov, P. Middha, E. Studer, A.V. Tchouvelev, A. Teodorczyk, F. Verbecke, M.M. van der Voort, An Inter-Comparison Exercise On the Capabilities of CFD Models to Predict the Short and Long Term Distribution and Mixing of Hydrogen in a Garage, 2nd International Conference on Hydrogen Safety, San Sebastian, Spain, 11-13 September, 2007
- [6] Gallego E., Migoya E., Martin-Valdepenas J.M., Crespo A., Garcia J., Venetsanos A.G., Papanikolaou E., Kumar S., Studer E., Dagba Y., Jordan T., Jahn W., Oiset S., Makarov D., An Inter-comparison Exercise on the Capabilities of CFD Models to Predict Distribution and Mixing of H2 in a Closed Vessel, Int. J. Hydrogen Energy, 32, No 13, 2007, pp. 2235-2245.

- [7] T. Jordan, J. García, O. Hansen, A. Huser, S. Ledin, P. Middha, V. Molkov, J. Travis, A. Venetsanos, F. Verbecke, J. Xiao, Results of the HySafe CFD Validation Benchmark SBEPV5, 2nd International Conference on Hydrogen Safety, San Sebastian Spain, 11-13 September, 2007
- [8] P. Middha, O.R. Hansen, J. Grune, A. Kotchourko, Validation of CFD calculations against ignited impinging jet experiments, 2nd International Conference on Hydrogen Safety, San Sebastian Spain, 11-13 September, 2007
- [9] Papanikolaou E.A. and Venetsanos A.G., CFD simulations of hydrogen release and dispersion inside the storage room of a hydrogen refuelling station using the ADREA-HF code, 2nd International Conference on Hydrogen Safety, San Sebastian Spain, 11-13 September, 2007
- [10] Venetsanos A.G., Papanikolaou E., Delichatsios M., Garcia J., Hansen O.R., Heitsch M., Huser A., Jahn W., Jordan T., Lacomme J-M., Ledin H.S., Makarov D., Middha P., Studer E., Tchouvelev A.V., Teodorczyk A., Verbecke F., Van der Voort M.M., An Inter-Comparison Exercise On the Capabilities of CFD Models to Predict the Short and Long Term Distribution and Mixing of Hydrogen in a Garage, Accepted IJHE, January 2009

9.8 Internal Project IP2: HyTunnel

Lead Contractor: BRE

Contractors involved: BMW, BRE, FZK, GexCon, HSL, NCSR, UPM, UU, Volvo, WUT

9.8.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

As part of the drive towards a cleaner environment and alternative energy sources, the automotive industry is researching and developing technology to allow vehicles to run on hydrogen.

Two technologies have emerged in respect to powering hydrogen vehicles, described briefly below.

- Hydrogen fuel cell vehicles

In a hydrogen fuel-cell the stored hydrogen reacts with oxygen (from the air) to produce water and electricity, the latter of which is used to power the electric motor. Hydrogen is stored as a compressed gas in cylinders under high pressure, typically at 35 MPa or 70 MPa, in order to provide sufficient quantities of the fuel.

The fuel cell approach is being more widely pursued compared to that of the hydrogen internal combustion engine. A number of motor manufacturers are developing hydrogen fuel cell cars. Fuel cell buses are also being developed, and have been introduced in various cities around the world.

- Hydrogen internal combustion vehicles

Here the hydrogen is burned in an internal combustion engine in basically the same way as traditional gasoline fuelled cars. Whilst the idea has been around for a long time, the technology is currently being pursued only to a limited degree compared to fuel cell vehicles (see below). BMW has recently launched a limited number of its Hydrogen 7 car which is a bi-fuel vehicle can switch between hydrogen and gasoline. When in hydrogen mode, hydrogen is injected directly into the car's air intake manifold.

The hydrogen fuel is stored as liquid rather than as compressed gas. To remain as a liquid, the hydrogen must be super-cooled to cryogenic temperatures of at least -253°C .

It has been suggested that hydrogen vehicles will emerge as a leading contender to replace today's internal combustion engine powered vehicles. Whilst in reality this vision may not materialise, or not be realised for some years, the safety issues surrounding the use of hydrogen vehicles inside tunnels need to be addressed now.

From the perspective of fire and general hazard control, tunnel designs and operational procedures need to address one or more of the following issues:

- Construction materials. This addresses the resistance of the tunnel walls and lining materials to fire gases and radiation fluxes. Resistance of concrete to spalling has been of particular interest in recent years, and a number of developments in respect to improved performance have been reported, e.g. addition of fibres into the concrete mix. The structural integrity of tunnel construction is usually designed for and tested in terms of exposure to a specified time-temperature curve, representing the exposure conditions to be expected for the design scenario. The construction may also consider the resistance to the effects of explosion.
- Detection and surveillance. In normal operation, detection of vehicle emissions, e.g. CO, may be incorporated in the tunnel design. Additional ventilation can then be provided to alleviate conditions inside the tunnel. Heat detection is used principally to detect a fire event. Video surveillance, including in the infrared, may be used to detect the presence of smoke, and coupled with appropriate image processing technology may be able to automatically detect the onset of a fire.
- Ventilation and smoke control. In the context of HyTunnel, the issue that arguably requires most immediate attention is the tunnel ventilation, both in normal and emergency modes. It is the tunnel air distribution, both from the tunnel ventilation systems and the influence of traffic and environmental conditions that will determine the distribution of hydrogen if there is a release inside the tunnel. Other issues, in particular the possibilities to detect hydrogen releases and the effect of water suppression systems, are also of potential significance.
- Fire suppression. There has been much debate, and controversy, over the potential benefits or disadvantages of installing water suppression systems inside tunnels. While actively pursued in some parts of the world, e.g. Australia and Japan, fixed-suppression water systems were considered unproven, and not cost-effective in others, e.g. The World Road Association (World Road Association, 1999) opposed the introduction of water suppression systems into road tunnels and earlier editions

of *NFPA 502* (NFPA, 2004) remained cautious. It is now more widely accepted (e.g. NFPA, 2008) that water suppression can be an important part of the overall fire safety strategy for a road tunnel, both for life safety and property protection.

- An alternative to water sprays and mists is provided by aqueous film-forming foam (AFFF), designed principally for extinguishing liquid hydrocarbon fires.
- Egress and tunnel user behaviour. The safe evacuation of tunnel users in the event of an emergency has received much attention in recent years, prompted in part by the series of catastrophic fires in a number of alpine road tunnels in Europe, e.g. the Mont Blanc tunnel in 1999. Some recent international conferences on human behaviour in fire provide useful review on the current understanding of human behaviour in the event of a tunnel fire.
- Provisions for emergency lighting, audio instruction, safe shelters, escape passages etc are all important in the overall question of *means of escape*. A recent directive from the European Parliament (2004) imposes strict new regulations on the minimum level of safety within the main trans-European road tunnels.

The Phenomena Identification and Ranking Table (PIRT) exercise highlighted that hydrogen powered road vehicles in the confined space of a tunnel could pose a serious hazard of fire and explosion to the tunnel and its users. The HyTunnel internal project was established to contribute to the European and global activity to establish the nature of the hazard posed by these vehicles inside tunnels and its relative severity compared to that posed by traditionally powered (hydrocarbon internal combustion) vehicles.

The main objectives of the HyTunnel project have been:

- To review tunnel regulations, standards and practice in respect to the management of hazards and emergencies, e.g. vehicle fumes and smoke & heat in the event of fire.
- To identify appropriate accident scenarios for further investigation, in respect to the vehicles involved, the hydrogen release mechanism and the tunnel environment.
- To review previously published experimental and modelling work of relevance to hydrogen releases inside tunnels.
- To extend our understanding of hydrogen hazards inside tunnels by means of new physical experiments and numerical modelling activities as appropriate.
- To document suggested guidelines for the safe introduction of hydrogen powered vehicles into tunnels.

9.8.2 Achievements of the activity, the current state:

Review of the tunnel regulations and standards identified relevant requirements and current practices in respect to the management of hazards and emergencies in the event of a fire. Of particular relevance in Europe is the recently published EU Directive on minimum safety levels now required in the main road tunnels on the trans-European Road Network (*Directive 2004/54/EC*).

Internationally, *NFPA 502 (Standard for Road Tunnels, Bridges, and other Limited Access Highways)* and the World Road Association (PIARC) *Fire and Smoke Control in Tunnels* are both widely cited and used. Two further publications from the World Road Association (Report 05.11.B *Cross Section Design for Uni-Directional Road Tunnels* and Report

05.12.B *Cross Section Design for Bi-Directional Road Tunnels*) provide useful summaries of tunnel requirements in selected countries.

Various aspects of regulations and standards that apply to road tunnels, in particular in respect of the provision of smoke control and ventilation, were identified in the preceding section. While not intending to provide a complete review of regulations and standards applying to road tunnels, some of the main issues are summarised below. While much consideration has been given in recent years to escape passages, cross-bore access, refuge shelters etc for means of escape, e.g. in the new EU Directive, this is considered to be outside the context of HyTunnel.

- Maximum length of tunnel where only natural ventilation is provided.
The maximum length of tunnel that requires no form of mechanical ventilation varies from about 200 to 800 m, depending on country, traffic density, tunnel gradient, urban or rural location etc. The new EU Directive (2004) specifies that ‘mechanical ventilation system shall be installed in all tunnels longer than 1 000 m with a traffic volume higher than 2 000 vehicles per lane’. A typical (‘broad brush’) value of 400 m is suggested by the author.
- Restrictions on longitudinal ventilation
Longitudinal ventilation (given the tunnel is mechanically ventilated) is either discouraged or forbidden in two-way or congested tunnels, and if accepted in these cases is generally the subject of a risk analysis. Transverse or semi-transverse ventilation is, however, the preferred option for two-way or high traffic volume (subject to congestion) tunnels.
For rural, one-way tunnels, longitudinal ventilation is now generally accepted in tunnels of any length. Obviously this is subject to engineering limitations, e.g. the pollution levels remain acceptable at the exit portal where they will be highest (unless intermediate ventilation shafts are included).
- Other restrictions on ventilation
As discussed above, there is generally a maximum allowed air speed within a tunnel. Where quoted, values are broadly in the range of 7 to 11 m/s in respect to means of escape. However, lower values (say 2 m/s) may be specified in the case of emergency fire ventilation, if the aim is to maintain stratification of the smoke layer for as long as possible (applies more to transverse ventilation).
- Traffic space cross-section
The traffic space of a road tunnels is generally either of a rectangular or an arch profile (‘horse-shoe’) section. Regulations and guidelines may stipulate minimum clearance distances and bore widths (which depends on the number of lanes). Provision for sidewalks (often elevated) may also be included.
While continuous emergency lanes are uncommon, the provision for emergency lay-byes is often required.
- Road surface construction and drainage
Road surfaces are typically either exposed concrete, or have an asphalt/bituminous covering. However, regulations may not allow asphalt/ bituminous coverings, e.g. Spain, as it is considered that they may contribute to fire spread, or they may be discouraged.
Drainage of water, fuel or other spills is included in the tunnel design by including a transverse gradient (i.e. downwards towards the side of the tunnel bore). Typically values between 0.5 and 2.5 % may be specified. Provision for prevention of the spreading of hazardous spills is generally required where hazardous cargoes are

allowed to use the tunnel. This may be in the form of gutters or other measures, and there is likely to be a requirement for liquid sumps.

- Max gradients

The maximum tunnel gradient is generally specified in national guidelines, and may vary depending on traffic density and means of ventilation. Typical maximum gradients are 5 to 6 %.

- Traffic control

Hazardous cargoes are generally controlled, e.g. escorted in groups. For general vehicle use, there may be recommended minimum separation distances, e.g. the distance covered in 2 s is stated in the new EU Directive (2004). Overtaking is generally prohibited, especially in two-way tunnel bores. Stopping (except in emergency or due to congestion) and turning/reversing is also prohibited. Drivers may be recommended to turn their radios on so that emergency information can be relayed.

Additional speed limits may be applied in tunnels if deemed necessary, e.g. where the lanes narrow inside the tunnel. It is generally accepted, however, that on main highways to impose additional restrictions on speed serves no benefit and may unnecessarily disrupt the flow of traffic (i.e. the tunnel should be built appropriately to serve the highway where it is located).

In the event if a vehicle fire starting, it is recommended, where possible, for the driver to drive the vehicle out of the tunnel.

A review of modelling activity from the published literature related to hazard and risk assessment due to fires in tunnels was undertaken, particularly focusing on

- Hydrogen dispersion modelling studies in tunnel environment,
- Fire and explosion modelling studies, and
- Hydrogen release experiments relevant to tunnels.

The review included recent publications and international conferences. The following series of conference proceedings are noted, in particular, as a useful source of information on hazard management and fire safety in tunnels generally:

- *Aerodynamics and Ventilation of Vehicle Tunnels*. BHR Group Conference Series (most recent being the 12th International Symposium, held in Portoroz, Slovenia from 11-13 July 2006).
- *Tunnel Fires*. Tunnel Management International (most recent being the 5th International Conference, held in London, UK from 25-27 October 2004).
- The on-going series *International Conference on Hydrogen Safety*, organised in conjunction with HySafe, is a useful source of current information on all aspects of hydrogen safety including vehicles and tunnels. The most recent conference was held at San Sebastian, Spain, from 11-13 September 2007.

Overall, the interaction of the ventilation system, tunnel geometry and hydrogen release is complicated, and recourse to numerical modelling is required.

Some of the positive and negative effects that ventilation inside a tunnel may have in respect to a release of hydrogen gas or on the smoke and heat from a fire (not necessarily a H₂ vehicle) can be summarised as follows:

- ✓ The supply of air may dilute the hydrogen such that it is below the flammability limit.
- ✓ The dispersed hydrogen may be transported safely out of the tunnel through either a portal or via an exhaust ventilation duct or shaft.
- ✓ The ventilation system may break down a stratified layer of flammable hydrogen gas mixture such that the resultant fully mixed gas is below the flammable limit.
- ✗ The released hydrogen may be transported such that the cloud of flammable gas mixture is extended well away from the point of release, either within the traffic space or along ventilation ducts or shafts.
- ✗ Hot smoke gases from a fire may get transported to neighbouring H₂ vehicles, exposing them to thermal hazard.
- ✗ Strong mechanical ventilation may create turbulence within the tunnel sufficient to affect the combustion regime (of hydrogen in particular) if ignition occurs.

The review was used to identify appropriate accident scenarios for further investigation, as part of the HyTunnel project, in respect to the vehicles involved, the hydrogen release mechanism and the tunnel environment. The scenarios identified in discussion with industry partners covered hydrogen dispersion, combustion and explosion experiments relevant to tunnels, and important physical parameters such as

- the variation in tunnel geometry (tunnel cross-section, gradient, obstacles),
- vehicle parameters (liquid, CGH₂, release location and direction) ,
- ambient and ventilation conditions

Hazard & risk assessment were performed in terms of:

- size of flammable gas clouds
- Ignition probability
- Exposure times of flammable gas clouds
- resulting overpressures as a function of gas cloud size

The research of this work has led to some interesting findings. For example, some findings of the dispersion study are as follows:

- Horseshoe cross section tunnel indicates lower hazard than equivalent rectangular cross-section tunnel with regards to flammable cloud volume and its longitudinal and lateral spread
- Increasing height of the tunnel indicates safer conditions to tunnel users for buoyant releases of H₂
- Compressed gas H₂ (CGH₂) releases pose greater hazard than natural gas releases, but still not significant
- Increase of ventilation velocity decreases the cloud size and hence results in lower hazard;
- CFD simulation results not conclusive on the following aspects:
 - Level and extent of hazard with no ventilation versus ventilation
 - Hazard posed by liquid hydrogen (LH₂) versus CGH₂ releases

Some findings of the explosion research are as follows:

- Overpressures registered for different scenarios in the 1/5 scale 78.5 m tunnel SRI experiment only (uniform mixtures, “unessential” obstruction) are in the range 0-1.7 bars;
- Overpressures calculated for different scenarios are in the range 0-12 bars depending on scenarios and tools; Good agreement between CFD simulations and

- SRI experiment, significant difference between simulations for real scale tunnel (not all models are described in details necessary for reproduction by other groups);
- HySafe concentrated mainly on uniform mixtures (driven by availability of unique SRI experiments) until now. “Step back” compared to EIHP project, where non-uniform distribution from different release scenarios and then combustion of non-uniform mixtures were numerically simulated. The second step back compared to EIHP approach, is suggestion to change non-uniform mixture created during dispersion on uniform mixture for combustion (Q9 by GexCon);
 - “No pressure decay” environment, i.e. “long safety distances”;
 - FZK experiments proved that DDT is possible in principle. Ceiling design and mitigation measures are important.

The results of the research were disseminated through presentation at international seminars and conferences such as presentation and publication at 2nd International Conference on Hydrogen Safety (San Sebastián, September 2007).

9.8.3 Outlook for further research work:

A number of topics were identified for further study. Some of these are as follows:

- Realistic scenarios in tunnels (release downwards under the car) with delayed ignition of non-uniform mixtures (start from an EIHP scenario)
- Scientifically grounded requirements to location and parameters of PRD
- Impinging jet fires and conjugate heat transfer in conditions of blowdown
- Releases into congested space with DDT, generally experiments with more realistic mixtures in appropriate scale
- Develop hydrogen safety engineering methodology and apply it to a tunnel scenario (long term)

9.8.4 List of Deliverables for IP 2:

- D49 Report on regulations, tunnel ventilation, provisional accident scenarios
- D62 Review of previous experimental and modelling activities relevant to hydrogen hazards in tunnels, and summary of findings from initial modelling work
- D89 Activity report to include results from modelling study and experimental work.
- D111 HyTunnel Final Report – aims to summarise all results and findings, and to be disseminated via the HySafe website publishing and via other dissemination channels as appropriate (in preparation)

10 Progress of the Cluster “Risk Management”

10.1 Work Package WP5: Hydrogen Safety Information System – HySafe-IS

Lead Contractor: JRC / DNV

Contractors involved: Air Liquide, BAM, FZK, HSL, INASMET, INERIS, KI, NCSR, StatoilHydro, TNO, UNIPI, WUT

10.1.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

In order to be able to perform proper risk analyses of H₂ applications, access to historical events is of vital importance. Knowledge of such events, H₂ physical properties and experiments was wide, but fragmented between institutions, persons and country borders. Based on the overall/main aims of NoE HySafe, collecting, sharing, systemizing and improving H₂ skills and know-how, the consortium should work for establishing a tool for closing the existing gaps and encourage cooperation between its partners to reach the goals for the NoE. Seen in light of this situation back in 2004, a separate Work Package (WP5) was formed and given the following objectives:

- contribute to the integration and harmonization of fragmented experience and knowledge on hydrogen safety in Europe and international across professions and countries;
- contribute to the progress in common understanding of hydrogen safety and risk; which are the hazards, causes and consequences of accidents/incidents associated with hydrogen;
- be a harmonised tool for safety and risk assessment associated with hydrogen applications by providing input to analyses and safety management work;
- enable generation of common generic accident and incident statistics;
- serve as a common methodology and reference format for future hydrogen incident/accident data collection and storage;
- be a source for the understanding and experience transfer of hydrogen accident phenomena, scenarios and hazard potential; what are the hazards; what can go wrong, how and why do accidents/incidents develop, etc.;
- keep all stakeholders (authorities, public, research, industry) updated and informed with recent accidents/incidents involving the use of hydrogen, thus contributing to spread of knowledge and best practice as well as to building up a realistic perception of the risks related to use of hydrogen in industrial applications.

10.1.2 Achievements of the activity, the current state:

One of the first activities was to define the structure and specification of the database, named HIAD (ref. Deliverable D22), and based on this start developing the software tool. The first version of HIAD was made available for the partners of NoE HySafe in July 2006. Along with the tool a User Manual was published (Deliverable D60). Throughout the next year, the software was improved to enable both Data Entry and Data Retrieval. In the same period several partners have joined forces to populating the HIAD with H2 accidents and incidents. By June 2008 the targeted number of 200 entries in the database was reached. In 2007, it was decided to reframe the scope of WP5 to develop a Hydrogen Safety Information System (HySafe-IS), in which HIAD was to constitute one of the building blocks. In 2007-2008 work has been undertaken to specify the contents of HySafe-IS and plans for how to populate it with information. A first proposal was issued for comments in December 2008. Procedures for HIAD data collection and data quality assurance was published in March 2008 (no deliverable numbers were defined) to assist and increase the efficiency and standardisation of these activities which form important work in operating the database. In the autumn of 2008 work was started to develop a new HIAD module to enable the users to interrogate HIAD (the HIAD DAM).

As per 8 December 2008 the status of WP5 deliverables and achievements are summarised below:

- Specific agreements have been established with JRC-Ispra (IT) and Tukes (FIN) for accessing relevant H2 accidents and incidents in the databases MARS and VARO, respectively
- A HIAD Quality Assurance Expert Group is formed and has started working
- HIAD holds information of a total of 266 events
- A first version of the HIAD DAM has been launched for testing among the partners
- Draft layout and contents of HySafe-IS is made available for input and comments among the partners

10.1.3 Outlook for further research work:

It is foreseen that one of IA HySafe's most important operational vehicles is the HySafe-IS. As a consequence, it is of vital importance that the Association develop plans for maintenance, i.e. how to keep the contents of HySafe-IS up-to-date at all times and assess whether it holds all relevant information related to H2 safety. This involves both the technical (non-accident) parts and HIAD. Regarding the latter, all partners should join forces in continuing data collection and quality assurance.

10.1.4 List of Deliverables for WP5:

[1] D22: Report on Specification and definition of the HySafe - Hydrogen incident and accident database contents

[2] D60: Documentation for the operation of HIAD, like user manual, guidelines for data entry, code manual, etc

[3] D80: The 1st "HySafe Hydrogen Accident Statistical Report"

10.2 Work Package WP11: Safety Measures - Prevention and Mitigation

Lead Contractor: StatoilHydro

Contractors involved: FZK, BRE, CEA, DNV, FZJ, GexCon, HSE/HSL, INERIS, DTU/Risø, TNO, UNIPI, UPM, UU, WUT

10.2.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

Before HySafe started knowledge gaps were identified coupled to significant deficiencies in terms of safe technical solutions, including mitigation techniques, and in the availability of widely accepted and harmonised standards and methodologies, together with associated regulatory issues. This especially concerns applications of new hydrogen technologies and public introduction of hydrogen

In the first JPA it was written that “Introduction of a performance-based approach to fire and explosion prevention/mitigation/protection systems in the hydrogen industry is the most efficient way to open gates for innovations and guarantee acceptable safety levels. This approach could be based only on robust scientific knowledge of the phenomena, combined with utilisation of relevant risk-based approaches.

The main objectives of the WP11 activity were identified as:

- Encourage work to develop improved prevention and mitigation concepts for various industries
- Identifying the current capabilities and potential future capabilities in modelling of prevention and mitigation measures.
- Evaluate performance of “off-the-shelf” hydrogen sensors through experiments
- Input to guidelines for prevention and mitigation for selected hydrogen applications

10.2.2 Achievements of the activity, the current state:

A main objective has been to get a survey of experimental facilities and numerical capabilities with regard to effect of mitigation measures. The results of this work have been reported in D43/61 and is briefly summarised in figures 1 and 2 below.

| Mitigation measure/ | Available test facilities in HySafe | FZJ | UNIPI | WUT | GexCon | TNO | HSE/HSL | JRC | INERIS | Fh-ICT | BA M | FZK | CEA |
|-------------------------------------|-------------------------------------|-----|--------|-----|--------|-----|-------------|--------|--------|-------------|--------|--------|--------|
| Gas detection | | | Y (RS) | | | | Y (RS & SS) | Y (RS) | X (RS) | Y (RS & SS) | X(S S) | Y (RS) | X (RS) |
| Fire detection | | | | | | | | | | | | | |
| Ventilation (continuous, emergency) | | | Y (RS) | | | | Y (RS & SS) | | X (RS) | Y (RS & SS) | | Y (RS) | X (RS) |
| Emergency shutdown (ESD) of release | | | | | | | | | | Y (RS & SS) | | | |

| | | | | | | | | | | | | |
|---|--------|--------|--------|--------|--------|-------------|--|--|--------|--|--------|--------|
| Flushing release area with inert gases (e.g. CO ₂ , N ₂) | | | | Y (SS) | X (RS) | Y (RS) | | | Y (SS) | | | Y (RS) |
| Sprinklers/water mists/deluge | | | | Y (RS) | | Y (RS & SS) | | | | | | Y (RS) |
| Recombiners/igniters | Y (SS) | | | | | | | | | | X (RS) | Y (RS) |
| Explosion venting (including also relief panels) | | Y (RS) | | | X (RS) | Y (RS) | | | Y (RS) | | | |
| Fire and explosion resistant walls | | | | | X (RS) | Y (RS) | | | Y (RS) | | | |
| Deflagration and detonation arresters | | | Y (RS) | | | Y (RS) | | | | | | |

X – Test facility, Y – Test facility, hydrogen tests carried out, RS – Real¹ Scale, SS – Small Scale

Figure 1: Survey of experimental facilities and test results on mitigation in NoE HySafe (from update of D43/61)

| Capabilities for mitigation modelling in HySafe | REKO-DIREKT (FZJ) | VEX code (WUT) | FLACS (GexCon) | Fluent (UU) | AutoRe a Gas™ (TNO) | GAS-FLOW 2.3 (FZK) | BLAST_3D (TNO) | CAST3M (CEA) |
|---|-------------------|----------------|----------------|-------------|---------------------|--------------------|----------------|--------------|
| Gas detection | | | Y | | | | | |
| Fire detection | | | | | | | | |
| Ventilation (continuous, emergency) | | | X | | | X | Y? | X |
| Emergency shutdown (ESD) of release | | | X | | | | | |
| Flushing release area with inert gases (e.g. CO ₂ , N ₂) | | | Y | | | | | |
| Sprinklers/water mists/deluge | | | Y | | | X | X | X |
| Recombiners /igniters | X | | | | | X | X | X |
| Explosion venting (including also relief panels) | | Y | X | Y | X | | | |
| Fire and explosion resistant walls | | | X | | | X | X | |
| Deflagration and detonation arresters | | Y | | | | | | |

X – Tool that can be used for modelling of mitigation effect, but no publications related to effect on hydrogen releases

Y – Tools where validation of effect related to hydrogen experimental data on mitigation have been published

Figure 2: Capability of numerical tools related to modelling of effect of mitigation (from update of D43/61)

¹ Real scale – Test facilities with dimensions in the same order as for public hydrogen applications (garages, refuelling stations enclosures, etc.)

Safety barriers

Another activity in WP11 was the identification of the safety functions built into a generic refueling station. The station selected is mainly identical to the HyQRA base station, but assuming truck delivery. The safety functions are evaluated using the barrier diagram methodology. Hazard identification was carried out and was represented as a barrier diagram using a software that allows for qualitative and also quantitative evaluations. This gives a good basis to overview the safety systems provided and allows evaluating them with regard to completeness, independency of each barrier, barrier improvements etc. . The outcome is valuable for feedback to engineers and is an excellent basis to communicate safety issues to authorities and other stakeholders.

Status related to need for prevention and mitigation measures introducing hydrogen into the public area:Hydrogen refuelling stations

Identification and implementation of risk reducing measures seem to be more developed for hydrogen refuelling stations compared to tunnels and garages/repair shops. The reason might be that the stations are developed by industrial companies with long time hydrogen experience from production and use, and several of these companies are also offshore oil and gas companies or industrial gas companies where safety management (risk based or deterministic) has high focus. However, experience from the demonstration projects, e.g. CUTE and HighFleet::CUTE show that the refuelling technology still needs to be further developed and improved. Some of the challenges are coupled to very high storage pressure and high flow during the filling process, and filling equipment mainly based on natural gas experience. Another challenge is the public users which usually have limited experience with handling of high-pressure gas systems.

Garages and repair shops

Requirements and guidelines exist which also are relevant for hydrogen. However, most of these recommendations are based on conventional liquid fuels (flammable liquid, heavy toxic exhaust gases, fires). Hydrogen is a buoyant gas and the probability of explosions in confined areas might be higher – this must be taken into consideration for design these types of buildings. Further reference is given to InsHyde. For the risk of tunnels reference is made to HyTunnel.

10.2.3 Outlook for further research work:

The work on prevention and mitigation have demonstrated that there are several safety measures within prevention and mitigation and many of these are already implemented in hydrogen installations/applications, also for public use, such as refuelling stations. However, there are also still some gaps related to their effectiveness in real accident situations and for the very high source pressures in many important hydrogen applications such as refuelling stations and vehicles. Also some mitigation measures, such as ventilation, venting and deluge/water mists might have a negative influence in some accident situations since they might increase the turbulence and thus the probability for strong deflagrations or deflagration to detonations transition (DDT). Further experimental studies on these subjects would be an activity where IA HySafe could play an important

role since the network provides access to test facilities for both small and real scale experiments.

10.2.4 List of Deliverables for WP 11:

[1] D4. Reports on data for SBEP
 [2] D16. Report on Proposals for tests / other activities – mitigation
 [3] D54 Report on sensor evaluation
 [D43/61] Report on experimental survey and modelling capabilities
 Milestone report

10.3 Work Package WP12: Risk Assessment Methodology

Lead Contractor: DNV

Contractors involved: AL, CEA, DTU/Risø, FZK, GexCon, HSE/HSL, INASMET, INERIS, JRC, StatoilHydro, TNO, UNIPI

10.3.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

Risk assessment methodology was available before 2004. Risk assessment methodology was even being applied to industrial establishments where hydrogen was used. The establishment of hydrogen as an energy carrier would however involve the use of hydrogen where hydrogen has not been in normal use before and by ordinary consumers as well as professional users. This also involves using hydrogen in fields where the application of risk assessment is less common than in industry.

Focusing on the new applications areas the following knowledge gaps were seen as the most important:

- Development of guidelines (pre-normative) for determination of hazardous zones (HZ). This work is coupled to the requirements in the ATEX directive 1999/92/EC. This directive and its underlying harmonised standards, is implemented in the legislation of the EU and EEA member countries, and by definition it also applies to hydrogen applications, but there is little confidence in its real applicability to hydrogen.
- Development of a basis for comparison of risk information, for communication of risk and for evaluation of safety standards.
- Further on safety distances were selected as an important gap/task.

10.3.2 Achievements of the activity, the current state:

Basis for comparison of risk information and communication

The achievements of this work are collected in the reports D26 and D44. Moreover, the issue of risk tolerance has got more attention both within HySafe and beyond. An important conclusion from our work is that risk criteria are never absolute, even where

specific criteria are part of the legislation. Establishment of “basic” criteria thus is thus not seen as a purposeful objective.

Further, the basis for communication of risk has been established with the D44, which is also an important step as most partners and even the HySafe DJPA have been using different terminology and/or terminology not in accordance with European and ISO standards.

Hazardous zones

The work on explosive atmosphere hazardous zones has been based on the ATEX directive and underlying standards; especially the interpretation of the ATEX directive in Italian legislation, as this interpretation encompasses the use of risk assessment based evaluations for establishing the hazardous zones as an alternative to the standard templates. The work has resulted in a paper to ICHS2 giving guidelines for ATEX hazardous zoning for a hydrogen applications as well as calculation examples for a hydrogen station. This paper is a part of HySafe D64 on hazardous zones.

Safety distances

The work on safety distances has resulted in a report (D84) and the establishment of a benchmark base case (HySafe BBC) for testing of the methodology for safety distances and for quantitative risk assessment. The quantitative risk assessment has been carried out in HyQRA, while safety distance calculations have been carried out by several partners in WP12. An abstract was submitted to ICHS3 and when the paper is published, the D84 will be updated accordingly.

10.3.3 Outlook for further research work:

The work on risk criteria has been taken up by IEA HIA Task 19 on Hydrogen Safety <http://www.ieahydrogensafety.com/>.

Among the IA HySafe founding members, there are several also participating in this IEA task. With IA HySafe opening up to new members, there is certainly a potential for more members from the participants in Task 19.

The activities on risk criteria, on safety distances and on risk assessment methodology in general (similar to HyQRA) will continue within this task until autumn 2010. Collaboration with the IEA HIA Task 19 seems a cost effective way of continuation for the first 18 months.

10.3.4 List of Deliverables for WP12:

D26 Summary on HySafe Risk Assessment methodologies/approaches including and priorities
D44 Report describing established definitions and classifications of incidences and accidents
D64 Report on HZ methodology for H2 including calculation examples
D84 Report on safety distances, including ICHS paper

10.4 Work Package WP16: Contribution to Standards and Legal Requirements

Lead Contractor: BAM

Contractors involved: AL, BMW, BRE, CEA; DNV, HSL, INERIS, JRC, StatoilHydro, DTU/Risø, UNIPI, UU, Volvo

10.4.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

While the use of hydrogen in the chemical industry is not new at all, its use as fuel or for other energetic purposes certainly is. This means that the legal and normative framework for it is not there. Neither can it be created in advance because nobody can tell today which will be the most important applications in ten years from now. It must grow in parallel to the technology.

Standards are mainly made in ISO TC 197 “Hydrogen Technologies” and also in IEC TC 105 “Fuel Cells”. The objectives of WP 16 were to participate in these committees either directly or by causing other European experts to do it in order to ensure an appropriate representation of Europe in the panel and the working groups. The working group tried to ensure by active participation to standardisation groups that consensual knowledge on hydrogen safety is adequately taken into account in the process of building new standards related to hydrogen technologies and also to make proposals to standardisation organisations for new work on hydrogen safety related standardisation to be launched, whenever required. Whenever required, the experts will be backed up on specific issues by researchers working within the network. Partners will report on standardisation activity through the biennial report on hydrogen safety as well as through HySafe website. Standardisation work is expected to take place both at international and European level.

Regulations are made nationally and also on the EU level. The influence of scientific experts is of course limited here. Nevertheless the work package should try by information and education to contribute to a certain equalization of the demands in the different countries. In some countries it is not easy, but possible to run a hydrogen car on public roads; in other countries there is no way at all to do it. The working group should contribute to this process by providing hydrogen safety expertise to authorities. Partners will share their expertise in hydrogen safety with public authorities faced with the approval of hydrogen technologies. Authorities across Europe who could benefit from this help will be identified for further exchanges and support to take place.

10.4.2 Achievements of the activity, the current state:

Most of the work of this group is not so much an objective as such but rather a service for other topics and their experts. Many of the results of WP 16 can be found in the deliverables and reports of other work packages. The results are software rather than hardware.

The experts of WP 16 held a number of meetings during which they discussed matters of current interest in the international committees. This related mainly to the activities of ISO TC 197 and IEC TC 105. To be noted is also the participation in the development of a European regulation for the type approval of hydrogen road vehicles. The European Commission had invited experts to comment a draft, and HySafe, represented by WP 16, submitted such a comment which was approved by the group after intensive discussions.

As far as the effect on the international standard committees is concerned the general impression is that the weight of the European P members has increased. This is necessary because with India and China ISO TC 197 has now two new Asian members which will add considerable weight to the committee.

An internet forum was installed which makes it possible to exchange the relevant papers among the interested parties and to collect opinions on them. This is to prevent that a paper which poses problems for one partner is more or less automatically approved by the others simply because they do not know about these problems.

It is certain that a great part of the European experts on standardization is now working together more closely and is exchanging views and opinions. There is no way to provide one vote from all European P members, but certain coordination is already obvious. This became apparent recently on occasion of the discussion about the chairmanship of ISO TC 197.

WP 16 contributed with its expertise and its results to quite a number of other work packages. One of them is WP 1 (Biennial report on hydrogen safety); the report comprises a chapter on standards and regulations which was provided by WP 16 experts.

Also WP 14 (International Conference on Hydrogen Safety) profited by invited and submitted papers dealing with standards and regulations.

Finally this is also a permanent topic in the events staged by WP 15 (e-Academy). Students and other learners need not only to know what they can do or should not do with hydrogen but also in which context they are moving.

10.4.3 Outlook for further research work:

The development of standards and regulations for hydrogen and fuel cell technologies are far from over, but only beginning now since the important applications (cars, heating appliances, and portable electronics) are coming closer and closer to the market. Simply applying the existing papers on the basis of an analogy will soon no longer be enough. So we expect an increasing need for scientific expertise by the political or commercial bodies involved in this.

We see here an important field of activity for the International Association for Hydrogen Safety which will continue the work of HySafe.

10.4.4 List of Deliverables for WP 16:

[1] D18. Sub-task 16.2 Activity report

[2] D27. Sub-task 16.3 List of authorities

[3] D48. Activity report

[4] D74. Report on permeation

10.5 Internal Project IP3: HyQRA

Lead Contractor: GexCon, TNO, UNIPI

Contractors involved: BRE, DNV, FZJ, FZK, GexCon, HSL, JRC, KI, NCSR, SH, TNO, UC, UNIPI, UPM, UU, WUT

10.5.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

Only limited systematically information on suitable quantitative risk assessment was available. As quantitative risk assessment builds the bridge from science to industry relevant methodology it was decided to set up this internal project. The aim with the activity is to develop a reference Quantitative Risk Assessment (QRA) methodology for hydrogen technologies applying, where necessary, simplified methods for acceptable answer times as required for engineering tools.

The tool shall support the following steps:

- a. Hazard identification
- b. Frequency estimation
- c. Consequence assessments
- d. Risk estimation
- e. Validation of acceptance criteria for the application under consideration
- f. Assessment of measures for risk reduction

Finally the framework(s) should be prototypically validated with at few relevant cases.

10.5.2 Achievements of the activity, the current state:

After the common definition of the HyQRA Benchmark Base Case (BBC) refuelling station scenario, including detailed geometry, piping and flow diagram, etc, all backed up by the associated HyApproval work, 8 HySafe members participated in the benchmarking exercise.

With the motivation of gradually better validated modelling of physics, in particular with modern CFD tools, numerous assumptions and analytical steps should be improved:

7. Optimal scenario selection
8. Methods/assumptions on leak probabilities
9. Ignition probability models (time dependent, S, I, C)
10. Acceptance criteria, structural response
11. Develop screening models (where appropriate)
12. Include fire modeling

The results are summarised in deliverable D106. As quantitative risk assessment was also on the agenda of the IEA HIA Task 19 both groups cooperated closely on this key topic.

10.5.3 Outlook for further research work:

A continuation of the benchmarking efforts seems to be desirable. Application of the QRA framework to accident scenarios in particular in tunnels, referring to HyTunnel, could be organised in IA HySafe or part of separate project work. Some first contacts to the L-SurF consortium provided a promising feedback.

10.5.4 List of Deliverables for IP03 HyQRA:

- D93 HyQRA-Report on ignition modeling for QRA; TNO
- D94 Report on characterization of the risk from an inhomogeneous gas cloud; GEXCON
- D106 HyQRA-Report on use of simplified methods for QRA, GEXCON
- D98 HyQRA-Report on frequency modelling, DNV
- D105 HyQRA-Report on how fire modeling should be included in the QRA, HSE/HSL

11 Progress of the Cluster “Dissemination”

11.1 Work Package WP1: *Biennial Report on Hydrogen Safety (BRHS)*

Lead Contractor: WUT

Contractors involved: AL, BAM, BMW, BRE, CEA, DNV, Fh-ICT, FZJ, FZK, GexCon, HSE, INASMET, INERIS, JRC, NCSR, NH, DTU/Risø, TNO, UC, UNIPI, UC, UPM, UU, WUT, KI

11.1.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

Based on the thematic structure proposed within the first activity period, this Biennial Report on Hydrogen Safety was intended to deliver periodical information on existing knowledge, gaps and progress on hydrogen safety issues. It should pull together existing scientific and technical information shared between members of the consortium and beyond when available. References upon which writing contributions are based will provide the first inputs of a more complete reference database that will be developed at a later stage.

This report should provide to interested parties comprehensive scientific information on different aspects of hydrogen safety, ranging from basic physical and chemical knowledge (dispersion, combustion) up to practical information related for instance to state of the art risk control measures or emergency response plan.

Information published in this report should reflect scientific and technical quality, impartiality, transparency as well as duty of prevention.

11.1.2 Achievements of the activity, the current state:

As planned the report was written as a collaborative effort of many partners. The second issue of the document was placed on the PmWiki platform integrated on the HySafe website accessible to all partners and it is planned to be published in paper version if an interested publisher will be found.

11.1.3 Outlook for further research work:

This report will be updated every two years to provide technical support to people in their everyday work and therefore deserves the alias “Handbook for Hydrogen Safety”. So, the intended recipients should be safety engineers, designers, users, fire-brigades, public authorities, policy makers as well as students and professors at Universities.

This report will be amended with conclusions from next International Conferences on Hydrogen Safety round tables and invited paper contributions. On the other hand the conference and the general HySafe research directions shall interact with the gaps identified in this report.

11.1.4 List of Deliverables for WP1:

D110. BRHS 2nd issue

11.2 Work Package WP14: International Conference on Hydrogen Safety (ICHS)

Lead Contractor: UNIFI

Contractors involved: CEA, FZK, JRC, TNO, UU, INASMET, SH, Volvo

11.2.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

Although there has been a large number of conferences regarding hydrogen and fuel cells in general, there was no conference dedicated solely to the topic of hydrogen safety.

The main competition for the ICHS series was to serve as a reference event for the innovation and quality of topics.

Another objective of the ICHS series was to spread the results obtained from the research activities of the HySafe NoE.

The Organising Committee organizes the ICHS with the contribution of other EU NoE or IP groups working in hydrogen topics to avoid duplication. Exponents from the industry, associations, control bodies and others parties interested in hydrogen safety will also participate, as well as other international projects.

11.2.2 Achievements of the activity, the current state:

The achievements of this work package are summarised in the following list:

- The 1st International Conference on Hydrogen Safety took place on the September, 8-10, 2005 in Pisa, Italy.
- The 2nd International Conference on Hydrogen Safety took place on the September, 11-13, 2007 in San Sebastian, Spain.
- The 3rd International Conference on Hydrogen Safety will be held in September, 16-18 2009 in Ajaccio, Corsica, France.
- The proceedings of the 1st and 2nd conferences were already published on the HySafe web-site and also distributed to all the participants.
- A special issue of the “International Journal of Hydrogen Energy” has been published with 16 selected papers of the 1st ICHS (International Journal of Hydrogen Energy, 32, 2007). Also a special issue of the “International Journal of Hydrogen Energy” for selected papers of the 2nd ICHS are under publications.

The conferences showed a high grade of integration between several international projects, since HyFleet::CUTE (EU), StorHy (EU), NaturalHy (EU), HyPer (EU), Ardenty (J) and Canadian Hydrogen Safety Program (CDN) were partners in the event organization. The

ICHSS showed also a high grade of participation of international bodies as ISO, IEA, HELP and H2 Code and Systems for Hydrogen Safety. Moreover, the conferences were held in association with IPHE and, for the 3rd ICHS, with an additional involvement of US DoE and IEA.

The ICHS conference series has been successful both for the public, with more than 700 participants coming from about 25 different countries of the whole world, and for the scientific program with about 220 memories. The 2nd ICHS showed a great number of participants who have already been in the 1st ICHS, thus highlighting the success of the ICHS series in term of continuity and also a great interest in disseminating the hydrogen safety problems/results in the international community.

The number of abstracts arrived for the 3rd ICHS are 130 from 18 countries.

11.2.3 Outlook for further research work:

As mentioned in the strategy document of IA HySafe:

“...HySafe will continue the successful series of its conferences, the International Conference on Hydrogen Safety ICHS.

It will be organised every two years in collaboration with the principal International and European projects and institutions in this thematic area. HySafe will establish the resources to set up the various Committees (Organising, Scientific and Local Committees) involving, besides the HySafe partners, other International and European representatives. These Committees will benefit the experience gained from the last two conferences to guarantee the quality and improvement of the conference....”

“...The ICHS, as well as HySafe itself, can join specific activities and projects becoming an international point of reference and providing targeted services to research, industry and regulatory bodies...”

“.... It can be concluded that the ICHS series may have a positive balance between the various activities of HySafe. During these three-day’s events, other products of HySafe can also be presented, published and/or sold. In this manner, the conference may serve as a vehicle to consolidate the position of HySafe....”

11.2.4 List of Deliverables for WP 14:

- | | |
|----------|---|
| [1] D31 | Proceedings of the first ICHS |
| [2] D95 | Proceedings of the 2nd ICHS |
| [3] D120 | 3rd ICHS is a Milestone related to the call for paper and abstracts submission for the 3 rd ICHS |

11.3 Work Package WP15: *e-Academy of Hydrogen Safety*

Lead Contractor: UU

Contractors involved: BRE, FZJ, FZK, GexCon, KI, UC, UNIPI, UPM, WUT

11.3.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

There were no coordinated educational and training activities in Europe in the area of hydrogen safety before March 2004, when the European e-Academy of Hydrogen Safety commenced its activities within the framework of the HySafe consortium. Before the start of the HySafe project, there were no activities to develop dedicated higher educational programmes in the world, including absence of a key element for establishing of any specific educational programme - a curriculum. There were no efforts to jointly deliver courses, and finally there were no graduates with the skill-set needed to cope with hydrogen safety issues at highest level. The thrust in e-Academy from the beginning until now is on postgraduate programmes in hydrogen safety. There were cases of doctoral studies at some of HySafe partners. However, the level of this activity could be characterized as rudimentary and fragmented. This is treated as a key instrument in lifting barriers imposed by the safety of hydrogen to its introduction as an energy carrier. This strategy is complimentary to the US Department of Energy (DoE) approach, where initial training activities are aimed mainly at first responders, children at schools, and technical staff. To remedy this unsatisfactory situation the workpackage objectives were set as follows:

- Integration of academic and other institutions through the development and implementation of international curriculum on hydrogen safety engineering.
- Development of a database of organisations working in hydrogen industry to form a market of potential trainees and to disseminate results of mutual activities of the network.
- Creation of a pool of specialists for the delivery of joint training/teaching on hydrogen safety and joint supervision of research students.

11.3.2 Achievements of the activity, the current state:

Achievements of the European e-Academy of Hydrogen Safety:

- (i) Development of the International Curriculum on Hydrogen Safety Engineering with contribution of more than 60 experts throughout the globe (annual D30, www.hysafe.org/Curriculum).
- (ii) Implementation of the International Curriculum on Hydrogen Safety Engineering by the development of new higher education courses and modules:
 - a. PgCert/PgDip/MSc course in Hydrogen Safety Engineering by UU (www.hysafe.org/MScHSE).
 - b. CPD course *Safe Production, Transportation and Use of Hydrogen as a Fuel* by WUT.
 - c. Module *Hydrogen Safety* in the context of the existing course *Renewable Energy* by UNIPI.
 - d. Module *Safety in Hydrogen Vehicles* by UPM.
- (iii) Establishment of the World's first postgraduate course in Hydrogen Safety Engineering (PgCert in HSE commenced in January 2007, full MSc course in HSE commences in January 2009 at the University of Ulster, www.hysafe.org/MScHSE).
- (iv) Establishment of the European Summer School on Hydrogen Safety (FP6 Marie Curie Actions HyCourse project, 2006-2010, www.engj.ulst.ac.uk/esshs/hycourse/) under auspices of HySafe and in collaboration with US DoE. Joint delivery by HySafe partners and international experts of ESSHS:
 - a. 1st ESSHS (15-24 August 2006, Belfast): 86 participant from 23 countries;
 - b. 2nd ESSHS (30 July – 8 August 2007, Belfast): 79 from 31 countries;
 - c. 3rd ESSHS (21-30 July 2008, Belfast): 87 participants from 30 countries;

- d. 4th ESSHS (planned for 6-15 September 2009, Ajaccio, Corsica).
- (v) Establishment of the International Short Course Series “Progress in Hydrogen Safety” for joint delivery of educational/training in the state-of-the-art of hydrogen safety (www.engj.ulst.ac.uk/esshs/iscsphs/):
- Short course No.1: “Hydrogen and fuel cell technologies: Safety Issues”, 29 September - 3 October 2008, Belfast, United Kingdom;
 - Short course No.2: “Hydrogen regulations, codes and standards”, 26 - 30 January 2009, Belfast, United Kingdom;
 - Short course No.3: “Safety of hydrogen fuelled vehicles” (programme to follow), 27 April - 1 May 2009, Belfast, United Kingdom;
 - Short course No.4: “The hydrogen and fuel cell infrastructure” (programme to follow), 15 - 19 June, Ajaccio, Corsica, France.
- (vi) Creation of a pool of specialists from both academic and non-academic institutions able to deliver teaching on hydrogen safety engineering at the highest level by introduction of latest research results into the educational process (please see the programmes and names of Keynote Speakers for the European Summer School on Hydrogen Safety, www.engj.ulst.ac.uk/esshs/hycourse/, and the International Short Course Series Progress in Hydrogen Safety, www.engj.ulst.ac.uk/esshs/iscsphs/, and list of contributors to the International Curriculum on Hydrogen Safety, www.hysafe.org/Curriculum).
- (vii) Joint supervision of research students:
- A list of consolidated topics for research students at the organisations of the HySafe partnership (www.hysafe.org/ConsTopics). The FP6 Marie Curie Actions have been used to acquire funding for four of these topics: a grant (contract No. MEST-CT-2005-020245, HySAFEST project: *Early Stage Training in Fundamentals of Hydrogen Safety*) has been awarded to complement HySafe activities in this area.
 - Three Work-in-Progress workshop/sessions for young researchers in hydrogen safety have been organised (www.hysafe.org/WIPSep2007, <http://www.engj.ulst.ac.uk/esshs/2ndesshs/2ndesshsprogramme.php>, www.hysafe.org/WIPJuly2008).
- (viii) Creation and support of a database of organisations working in the hydrogen industry to form a market of potential trainees and to disseminate the results from mutual activities of the network. Annual deliverable D17 *Database of Organisations Working in the Hydrogen Industry* is available at www.hysafe.org/OrganisationsDB. Currently there are more than 6000 entrees in the Database that exceeds planned 5000 entrees during 5 years of the project.
- (ix) Creation and support of a database with references to peer reviewed journal papers on hydrogen safety, published by HySafe partners (www.hysafe.org/PublHySafe).
- (x) Creation and support of An Alumni Database (www.hysafe.org/AlumniDB).

11.3.3 Outlook for further education related work:

The following WP15 activities will be continued within the International Association for Hydrogen Safety (IA HySafe, Committee for Education and Training):

- Joint delivery of educational and training courses through well-established channels such as the European Summer School on Hydrogen Safety, the International Short Course Series “Progress in Hydrogen Safety”, and new undertakings such as the European University of Hydrogen Safety (experts from the International Association HySafe will be involved as Keynote Speakers and organisers).

- The Database of Organisations Working in the Hydrogen industry (www.hysafe.org/OrganisationsDB) will be maintained on the HySafe website (www.hysafe.org) and updated continually.
- An on-line version of the International Curriculum on Hydrogen Safety Engineering (www.hysafe.org/Curriculum) will be maintained on the HySafe.
- The Alumni Database (www.hysafe.org/AlumniDB) will be maintained on the HySafe website.
- The list of consolidated topics for research students (www.hysafe.org/ConsTopics) will be maintained on the HySafe website.
- The list of peer reviewed journal publications by HySafe-partners (www.hysafe.org/PublHySafe) will be maintained on the HySafe website.

11.3.4 List of Deliverables for WP15:

[1] D17 (annual). Database of Organisations Working in the Hydrogen Industry, www.hysafe.org/OrganisationsDB.

[2] D30 (annual). Draft for development of the International Curriculum on Hydrogen Safety Engineering, www.hysafe.org/Curriculum

12 Progress of the Cluster “Management”

12.1 Work Package WP7: Strategies

Lead Contractor: FZK

Contractors involved:

12.1.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

There was only little coordination and not an agreed agenda regarding hydrogen safety research. The community was split in automotive, gas and nuclear expert groups. There was no common roadmapping, no common strategy, and a poor information exchange.

Therefore the objective of this work package, originally consisting of the two work packages WP4 for the prioritization of the network activities and WP7 for the roadmapping was to:

- Maintain internal and external mapping priorities
- Assess technical progress made within HySafe, and outside, to maintain the network at the level of the state of the art
- Prepare the follow-up to the HySafe Network of Excellence beyond the 5 years seed financing of the EC by developing the business plan for the European Institute for Hydrogen Safety “HySafe”
- Establish the HySafe Safety Action Plan supporting EC funded projects in all aspects of hydrogen safety, including guidelines, reporting frameworks, maintenance of safety relevant documentation, and dissemination strategies for internal/external project results

12.1.2 Achievements of the activity, the current state:

In an initial effort the network supported by external experts set up a phenomena identification and ranking table (PIRT) for the internal road mapping and definition of research headlines. The initial PIRT has been revised in 2008.

This work package also organised the yearly activity planning in the joint programs of activities and the revision of the network’s orientation.

New dedicated project proposals for EC FP6 and national programs were coordinated or at least supported via WP7. Some examples for this vital activity are the preparations of the HyGuide, IgnHyd, InsHyde, HyTunnel, HyPer, HyQRA, HySchool, HyGlobe, HySafest, HyFrac, HyNano and HyGarage proposals. A few of them succeeded as externally or internally funded projects, others were at least partially treated as internal sub-tasks. The coordinator and 8 further partners represented the HySafe consortium in the important HyFIT project proposal, responding to the EC INFRA call. Although in a first response no support from EC was indicated the partners are still striving to re-submit a revised version to the H2&FC JTI.

Other external projects like HyApproval or HYTHEC for instance were supported by safety peer reviews of their key documents or by safety workshops arranged by HySafe. To provide a unique assessment framework for the safety performance of EC supported projects a "Safety Action Plan" was drafted. It was based on a similar obligatory reporting scheme which is applied in US DOE supported projects.

However, the major achievement of this work package was – as a follow-up of the task force activities – to provide all the strategic planning and practical preparations for the founding of the International Association for Hydrogen Safety, IA HySafe. The legal form and actual accommodation of the association have been determined, IPR and financial issues like membership fees etc were clarified, some first strategic partnerships, in particular with the JRC and EHA, have been initiated. Finally the IA HySafe has been founded on 26 February 2009 in Brussels with a huge majority of the NoE as founding members.

12.1.3 Outlook for further strategic work:

The further strategy development will be transferred to the executive board of the IA HySafe. In particular the president will take care for the industry interests in an industry liaison committee.

Besides it is planned to cooperate closely with the JRC, which is legally not entitled to join the IA HySafe as a standard partner. First ideas for a cooperation agreement have been exchanged. The executive board will continue to pursue a suitable arrangement. Another strong partnership with the EHA is envisaged.

Regarding the further work prioritisation the network relies on a yearly common updating of an activity program and a strong interaction with the JTI for H2 and fuel cells.

12.1.4 List of Deliverables for WP 7:

- D7 Report on review data for SBEP, Risø
- D28 Report on priorities and further steps in JPA, Risø
- D39 Project proposals and announcements on website, FZK
- D47 Draft Business Plan, FZK
- D50 Report with recommendations on priorities and further steps in JPA, Risø
- D77 Progress report on the preparation of the "European Centre for Hydrogen Safety" FZK
- D78 Report with recommendations on priorities and further steps in the 4th JPA, Risø
- D85 Report on the Updating of the PIRT, CEA
- D86 Proposal for the Safety Action Plan, FZK
- D90 Business Plan EU Institute for Hydrogen Safety 'HySafe', FZK
- D100 Report with recommendations on priorities and further steps in the 5th JP, Risø
- D117 International Association for Hydrogen Safety HySafe founded, FZK

12.2 Work Package WP17: Overall Management and Coordination

12.2.1 State of the art and knowledge gaps before 2004, and main objectives of this activity:

The management work package had to provide and maintain the whole framework required to achieve the integration of the fragments, of the heterogeneous individual partners, in a competitive community.

So, the general objectives were to:

- Maintain management structure
- Coordinate the activities of the network
- Lead and finalise the internal projects InsHyde, HyTunnel and HyQRA
- Support the transfer of activities to the International Association (IA) HySafe (ICHS, HIAD/HySafe-IS, BRHS...)
- Provide single point of contact between Commission and Partners
- Administrate Community contribution
- Implement changes in consortium
- Provide legal service to Governing Board and Coordination Committee of HySafe network
- Support the task force “HySafe continuation” and the foundation of the IA HySafe in close collaboration with WP7
- Maintain the Network Management Handbook
- Represent the network internationally and further the international collaboration (e.g. via IPHE, IEA, ERANET, JTI, ...)

Besides the physical meetings the other vital communication channel was the project website. The separate work package WP13 was integrated in WP17 because of its strategic importance. The objectives related to the website were to:

- Prepare for a redesign of the website
- Prepare for the transfer to the IA HySafe
- Support the development and implementation of the HySafe-IS of WP5
- Grant to NoE partners a structured way to communicate with the NoE participants and to provide for the partners an effective access to the repository of the documents, the experimental database and the benchmark exercise database and to informational pages.
- advertise the HySafe project and to promote the dissemination of the information agreed to be publicly accessible
- Securing mail lists and newsgroups.
- Provide comfortable search features for the databases of Literature on Hydrogen Safety of Industry involved in H2&FC
- Promote the website (Google top ranking when searching for “hydrogen safety”)
- Support the increasing usage of the ‘Wiki’ server for collaborative work like for the BRHS (WP1) and other documents including deliverables.

12.2.2 Achievements of the activity, the current state:

The coordinator supported by the project management office (PMO) and by the coordination committee (CC) set-up and developed further the network’s organisational

structure. With the concept of work package clusters a new management layer was introduced to ease the management of the large number of activities. An advisor and supporter group and a diversity committee were established and later a special expert group on the material issues (WP18) was introduced.

The coordinator also arranged the extension of the network by the Russian partner Kurchatov Institute successfully applying to the EC INCO call FP6-2006-TTC-TU.

Communication means, in particular the networks website, the regular newsletter and telephone conferences, were set-up and maintained. Meeting schedules and decision procedures were improved and captured in the management handbook.

For the website www.hysafe.net a special CMS system with a sophisticated access and visibility control has been programmed to provide online staff administration, meeting planning, easy file uploading and other features to support all network activities including the dissemination efforts. For example a Wiki system has been integrated in the website to support the editing of common reports and a newsgroup forum was established to support the discussions on new standards and regulations in particular.

The website maintains currently about 2000 documents, including the 120 deliverables, milestone reports, internal and external scientific publications, presentations. Intentionally the majority of the deliverables have been made public and directly available from the website.

With the EC reporting and reviewing activities were coordinated and the due delivery of project results was controlled in meetings and in direct contact with responsible authors. The coordinator and other members of the CC represented and presented the network at more than 60 external events, like conferences workshops etc with oral presentations or posters. Among these the yearly European Technical Review meetings, the Hannover Fair, the IEA HIA Task 19 expert meetings and the yearly US NHA conference have to be highlighted. Additionally, several questionnaires, radio and even TV interviews were provided to inform about the network's activities.

Achievements Regarding Integration

A detailed integration evaluation is given in the following tables:

Integration of Knowledge

| Indicator | Finally after five years | |
|---|---|--|
| | Milestones/ Achievements | Degree of Achievement (0-5 stars) |
| Common identification of knowledge gaps | Definition of headlines; effective revision of the JPA and PIRT; agreement on suitable content of project proposals | ☆☆☆☆ |
| Common internal research strategies, redefinition process of headlines, SBEPs,... | Intensified SBEP activities | ☆☆☆☆ |
| Maintenance of the handbook (BRHS) | Conversion to collaborative WEB2.0 environment PmWiki, common revision for 2 nd issue | ☆☆☆☆ |

| | | |
|--------------------------------------|---|------|
| Feeding the experience database HIAD | > than 250 event cases (world largest database on H2 incidents and accidents) | ☆☆☆☆ |
|--------------------------------------|---|------|

Integration of Tools

| Indicator | Finally after five years | |
|---|--|-----------------------------------|
| | Milestones/ Achievements | Degree of Achievement (0-5 stars) |
| Integration of hardware tools (IEF), maintenance of catalogue | Online presentation of all tools, recapitulating charts | ☆☆☆☆ |
| Integration of software tools, participation in SBEPs, new common tools (proposal for HySafe tools, HIAD, etc.) | Broad participation in most SBEPs, LOI for HIAD long term maintenance drafted with JRC | ☆☆☆☆☆ |
| Exchange of experimental know-how, measurement workshops | Prototypically integrated workshops on experimental techniques | ☆☆☆☆☆ |

Integration of Education, Training and Dissemination

| Indicator | Finally after five years | |
|---|---|-----------------------------------|
| | Milestones/ Achievements | Degree of Achievement (0-5 stars) |
| Educational program, maintenance of curriculum | Very successful and finally with a broader involvement of all university partners and beyond | ☆☆☆☆ |
| Organisation of the ICHS | Common organisation of the 2 nd ICHS and pragmatic, efficient development and set-up of the 3 rd ICHS | ☆☆☆☆☆ |
| Common Reporting of the state of the art via BRHS | Common editing of the 2 nd issue on PmWiki basis | ☆☆☆☆ |
| Disseminating the experience database HIAD | Common concept of the future HySafe-IS, quality assurance commonly set up and final success filling HIAD with more than 250 cases | ☆☆☆☆ |

Integrated Coordination

| Indicator | Finally after five years | |
|--|--|-----------------------------------|
| | Milestones / Achievements | Degree of Achievement (0-5 stars) |
| Common Proposals for Projects | HyFIT, HyGaragePrep... | ☆☆☆☆ |
| Common Planning Procedure (JPA), quality of document and involvement of partners | Consolidation of the JPA definition procedure, even including new partners | ☆☆☆☆ |

General Integration

| Indicator | Finally after five years | |
|----------------------|---|-----------------------------------|
| | Milestones/ Achievements | Degree of Achievement (0-5 stars) |
| Rules | Management Handbook improvement | ☆☆☆☆ |
| Staff exchange | Between CEA, FZK, WUT and UU | ☆☆☆☆ |
| Change Management | Introduction of Task Force concept Re-design of WP5 | ☆☆☆☆ |
| Setting up IA HySafe | Common design of strategy plan and statutes, selection of legal form, membership fees of the IA. Actual founding before end of NoE with a huge majority of the NoE partners | ☆☆☆☆☆ |