ACHIEVEMENTS OF THE EC NETWORK OF EXCELLENCE HYSAFE

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In many areas European research has been largely fragmented. To support the required integration and to focus and coordinate related research efforts the European Commission created a new instrument, the Networks of Excellences (NoEs). The goal of the NoE HySafe has been to provide the basis to facilitate the safe introduction of hydrogen as an energy carrier by removing the safety related obstacles.

The prioritisation of the HySafe internal project activities was based on a phenomena identification and ranking exercise (PIRT) and expert interviews. The identified research headlines were "Releases in (partially) confined areas", "Mitigation" and "Quantitative Risk Assessment". Along these headlines existing or planned research work was re-orientated and slightly modified, to build up three large internal research projects "InsHyde", "HyTunnel", and "HyQRA". In InsHyde realistic indoor hydrogen leaks and associated hazards have been investigated to provide recommendations for the safe use of indoor hydrogen systems including mitigation and detection means. The appropriateness of available regulations, codes and standards (RCS) has been assessed. Experimental and numerical work was conducted to benchmark simulation tools and to evaluate the related recommendations. HyTunnel contributed to the understanding of the nature of the hazards posed by hydrogen vehicles inside tunnels and its relative severity compared to other fuels. In HyQRA quantitative risk assessment strategies were applied to relevant scenarios in a hydrogen refuelling station and the performance was compared to derive also recommendations.

The integration process was supported by common activities like a series of workshops and benchmarks related to experimental and numerical work. The networks research tools were categorised and published in online catalogues. Important integration success was provided by commonly setting up the International Conference on Hydrogen Safety, the first academic education related to hydrogen safety and the Hydrogen Safety Handbook. Finally, the network founded the International Association for Hydrogen Safety, which opens the future networking to all interested parties on an international level.

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.

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[2]Approximately 120 researchers from the 25 institutions; contact details on www.hysafe.net.

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 – (NoE logo see Fig. 1) 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.

Figure 1. Logos of the Network of Excellence (left) and International Association for Hydrogen Safety (right)

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, consisted of 24 institutions from 12 European countries (including Russia) and of one Canadian university. There are 12 partners from public research institutions, 7 industry partners, 5 universities and one governmental authority.

More than 120 scientists of these institutions have been nominated to contribute to the network. This number was the basis for determining the maximum EC grant of 7 million Euro for 5 years. The total budget including the partners contributions has been 13 million Euro for same 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 intends to maintain the network's successful activities like the international hydrogen safety conference, the website and databases, the handbooks etc. All network activities – 15 work packages and 3 internal projects – were arranged in four activity clusters (see Fig. 2). 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 Table 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.

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

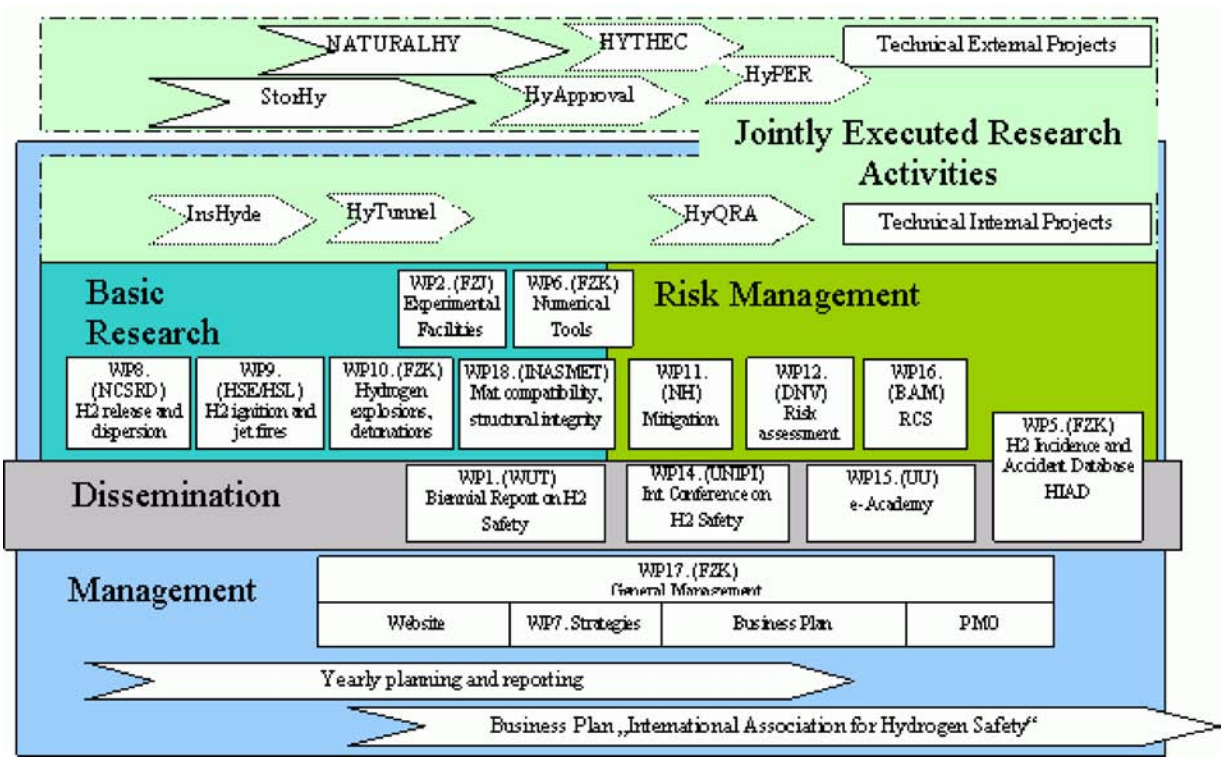

Figure 2. HySafe activity clusters

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

Name of institution	Abbrev.	Country
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	**NCSRD**	**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

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].

NUMERICAL TOOLS

A series of single effect tests was identified to allow for model verification [16] and a large collection of Standard Benchmark Exercise Problems (SBEPs) was compiled, where the focus relied 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.

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.

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.

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 H_2 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 en 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 H_2 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].

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].

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]).

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.

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 [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.

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. With the open workshops and the internet forum HySafe initiated a coordination of the European voting which is based on the collected scientific experience. Although this is a step in the right direction a fully concerted voting from all European P might be difficult to reach even with further alternative measures.

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: optimal scenario selection, methods/assumptions on leak probabilities, ignition probability models, acceptance criteria, structural response, develop screening models (where appropriate) and fire modelling.

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.

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.

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.

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 are 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), Ardenthy (J) and Canadian Hydrogen Safety Program (CDN) were partners in the event organization; also a broad participation of international bodies including 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.

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 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 presentations. 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 relative large number of abstracts which have been delivered for the 3rd ICHS (130 from 18 countries) indicates that this HySafe activity has met the demand of the relevant community.

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].

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.

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, a 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.

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.

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.

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, logo see Fig. 1). Immediately after the founding act 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.

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.

OUTLOOK

The international focus for hydrogen safety will be further developed within IA HySafe. The geographical scope will be extended with the help of the 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.

The successful 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 continued. The HySafe website will be the central tool for internal and external communication.

Although already in the NoE phase some critical safety issues could be addressed and resolved, from a scientific or technical perspective still many issued 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.

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PUBLIC DELIVERABLES

([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.
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