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On the development of an International Curriculum on Hydrogen Safety Engineering and its implementation into educational programmes

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Abstract

The present paper provides an overview of the development of an International Curriculum on Hydrogen Safety Engineering and its implementation into new educational programmes. The curriculum is being developed as part of the educational and training activities of the European Network of Excellence "Safety of Hydrogen as an Energy Carrier" (HySafe). It has a modular structure consisting of five basic, six fundamental and four applied modules. The reasons for this particular structure are explained. To accelerate the development of teaching materials and their implementation in training/educational programmes, an annual European Summer School on Hydrogen Safety will be held (the first Summer School was from 15–24 August 2006, Belfast, UK), where leading experts deliver keynote lectures to an audience of researchers on topics covering the state-of-the-art in hydrogen safety science and engineering. The establishment of a postgraduate certificate course in hydrogen safety engineering at the University of Ulster (starting in January 2007) as a first step in the development of a worldwide system of hydrogen safety education and training is described.
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Keywords: Hydrogen safety; Education; Hydrogen economy

1. Introduction

Hydrogen safety is known to be of vital importance to the onset and further development of the hydrogen economy. The development and introduction of hydrogen technologies, as well as the level of public acceptance of hydrogen applications, are presently being constrained by safety barriers. Hydrogen is perceived to be dangerous because it has some properties that make its behaviour during accidents different from that of most other combustible gases. It may cause material embrittlement and diffuses more easily through many conventional materials used for pipelines and vessels. Gaps that are normally small enough to seal other gases safely are found to leak hydrogen profusely. Unlike other combustible gases, it has a Joule–Thompson inversion temperature (i.e. the temperature above which the Joule–Thompson coefficient becomes negative and expansion leads to warming instead of cooling) which is well below that of many applications involving gaseous hydrogen. This makes hydrogen more susceptible to ignition after sudden releases from high pressure containment. When hydrogen's greatest safety asset, buoyancy, is not properly taken into account in the design of infrastructures and technologies for production, storage, transportation and utilisation, it becomes more dangerous than conventional fuels such as gasoline, LPG and natural gas. Many countries' building codes, for example, require garages to have ventilation openings near the ground to remove gasoline vapour, but high-level ventilation is not always addressed. As a result, even very slow releases of hydrogen in such buildings will inevitably lead to the formation of an explosive mixture, initially at the ceiling-level. The safety and combustion literature indicates that releases of hydrogen are more likely to cause explosions than releases of today's fossil fuels do. Moreover, combustion insights have revealed that burning behaviour becomes far less benign when the limiting reactant is also the more mobile constituent of a combustible mixture [1]. Owing to the extreme lightness of the molecule, this is particularly true with hydrogen. A mixture of hydrogen with air has a lower flammability limit which is higher than that of LPG (1.7% [2]) or gasoline (1.0% [2]), but the flammable

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range is very wide (4–75%) [2]. In the concentration range of 15–45%, the ignition energy of hydrogen is one-tenth of that of gasoline and the quenching gap, i.e. the smallest spacing through which a flame can propagate, is considerably smaller for hydrogen (0.61 mm [3]) than for today's fossil fuels (2.0 mm for methane, 1.8 mm for ethane and propane [3]). This implies that requirements for mitigation, such as flame arrestors and similar equipment, must be more stringent.

For many decades, hydrogen has been used extensively in the process industries (e.g. refineries and ammonia synthesis) and experience has shown that it can be handled safely in industrial applications as long as appropriate standards, regulations and best practices are being followed. This is particularly true for the nuclear industry, where the high safety standards have resulted in the development of sophisticated hydrogen mitigation technologies [4]. Interestingly, these technologies rely on the same anomalous properties, such as the large diffusivity and extreme lightness that make hydrogen so different compared to conventional fuels. For example, these properties are used to preclude the formation of flammable mixtures after accidental hydrogen releases, and to prevent further development towards more dangerous concentrations, once the flammability limit is exceeded (hydrogen removal by buoyancy, application of catalytic re-combiners, or benign burns, dilution by mixing with an inert gas, e.g. steam). This experience, however, is very specific and cannot easily be transferred to the daily use of new hydrogen technologies by the general public. Firstly, because new technologies involve the use of hydrogen under circumstances that are not yet addressed by research, or taken into account by existing codes and recommended practices. For example, vehicle demonstration projects by manufacturers involve the use of hydrogen as a compressed gas at extremely high pressures (over 350 bar), or, in liquefied form at an extremely low temperature (−253 °C). There is no precedent for the safe handling of hydrogen by the general public at such conditions and current codes and standards for hydrogen were not written with vehicle fueling in mind. Secondly, in industries, hydrogen is handled by people who received specific training at a professional level, and, installations involving hydrogen are subject to professional safety management and inspection. The hydrogen economy, on the other hand, involves the use of hydrogen technologies by general consumers and a similar dedication to safety, e.g. training general consumers to a professional level, would become impractical. The safety of hydrogen technologies and applications must therefore be ensured before entering the consumer market.

Presently, public acceptance and understanding of the safety of hydrogen is such that accidents with hydrogen not only cause resistance to its use, but also cause people to disregard social, economic, political and environmental improvements that may result from a hydrogen economy. Currently, hydrogen is being produced from fossil fuels, particularly from natural gas by steam reforming. But it can also be produced from a variety of other sources (e.g. nuclear, geothermal, solar, wind, hydroelectric plants, biomass, etc.), some of which can operate at large and small scale in areas that are currently suffering fuel poverty. The replacement of fossil fuels by hydrogen from alternative sources will not only benefit people in fuel poverty areas by reducing their dependency on the diminishing resource of imported fossil fuels—it might also enable fossil fuel importing economies to become leading exporters of hydrogen [5]. The consequential demand for ever increasing quantities of hydrogen, and the possibility of producing hydrogen in fuel poverty areas will lead to social improvement by employment opportunities [5]. The replacement of fossil fuels by hydrogen also contributes to averting disastrous effects from pollutant emissions and global warming. It is well-known that combustion products from fossil fuels cause health problems and acid rain due to emissions of particulates, carbon monoxide, sulfur and nitrogen oxides, and other local air pollutants. Continued fossil fuel consumption will not only increase the number of pollution related deaths in cities like Delhi, Beijing and Mexico City [5], but also the magnitude of problems involving reduced agricultural productivity and the loss of biodiversity [5]. There is also an increasing scientific community which has come to the belief that the use of fossil fuels is causing the world's climate to change because of carbon dioxide emissions [5]. Hydrogen is a clean fuel with no carbon dioxide emissions and can be produced by carbon-free or carbon-neutral processes. When utilised in combustion processes, it produces water only, and reduced amounts of nitrogen oxides.

Educational and training programmes in hydrogen safety are considered to be a key instrument in lifting barriers imposed by the safety of hydrogen. Owing to the impracticality of training general consumers to a professional level in hydrogen safety, such training programmes should primarily target professionals engaged in the conception or creation of new knowledge, products, processes, methods, systems, regulations and project management in the hydrogen economy. Between this community of scientific and engineering professionals, including entrepreneurs developing hydrogen technologies, and general consumers of hydrogen applications, there is another group of vital importance to the successful introduction of hydrogen into our social infrastructure that needs to be targeted as well. These are the educators, local regulators, insurers, fire brigades and rescue personnel, investors, and public service officials. Their involvement is indispensable to the acceptance and use of the new technology by the general public, and hence a consolidated consumer market as the principal driving force behind the hydrogen economy. Without their involvement there will be no transition from our present fossil-fuel economy into a sustainable one based on hydrogen. With this in mind, the European Network of Excellence "Safety of Hydrogen as an Energy Carrier" (NoE HySafe) has begun to establish the e-Academy of hydrogen safety.

The e-Academy of hydrogen safety is part of the dissemination cluster of the NoE HySafe, whose objectives are [6,7]: (i) to achieve common understanding and common approaches for addressing hydrogen safety issues; (ii) 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 from numerical prediction tools; (iii) to integrate and harmonise the fragmented research base; (iv) to provide contributions based on safety and risk studies to EU-legal requirements, standards, codes of practice and guidelines; (v) to support education and training in hydrogen safety to achieve an improved technical culture for the safe handling of hydrogen as an energy carrier. To establish the e-Academy of hydrogen safety, the following activities are employed: (i) development of international curriculum on hydrogen safety engineering; (ii) coherent implementation of teaching/learning on hydrogen safety into existing courses and modules; (iii) development of new courses and modules, including optional modules for existing safety courses; (iv) joint training exploiting different modes of education: short courses, summer schools, block-releases, continuous professional development courses, etc.; (v) 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; (vi) promotion of academic mobility programmes, e.g. by integration of regional academic programmes into a common European course on hydrogen safety engineering with the possibility to distribute course modules in different countries; (vii) joint supervision of research (PhD) students; (viii) creation of a database of organisations working in hydrogen industry to form a market of potential trainees and to disseminate the results from mutual activities of the network; (ix) and the introduction of joint distance teaching/learning courses in hydrogen safety on the international market.

Due to the absence of a curriculum on the subject, a substantial effort is being devoted to the development of an International Curriculum on Hydrogen Safety Engineering as a first step in the establishment of the e-Academy of hydrogen safety. The development of the International Curriculum on Hydrogen Safety Engineering is led by the University of Ulster and carried out in cooperation with international partners from four other universities (Universidad Politecnica de Madrid, Spain; University of Pisa, Italy; Warsaw University of Technology, Poland; University of Calgary, Canada), three research institutions (Forschungszentrum Karlsruhe and Forschungszentrum Juelich, Germany; Building Research Establishment, United Kingdom), one enterprise (GexCon, Norway) and one foundation (Det Norske Veritas, Norway). This development is also aided by experts from within the NoE HySafe and external experts from all over the world (see Table 1), representing educational institutions, research organisations, industrial corporations and governmental bodies. This paper exposes the current structure of the International Curriculum on Hydrogen Safety Engineering, the motivation behind it, and further steps in the development of a system of hydrogen safety education and training are described.

Table 1
List of contributors to the draft for development of the International Curriculum on Hydrogen Safety Engineering

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2. The International Curriculum on Hydrogen Safety Engineering

2.1. Motivation

Sufficient and well-developed human resources in hydrogen safety and related key areas are of vital importance to the emerging hydrogen economy. With our present fossil-fuel-based economy increasingly being replaced by a hydrogen economy, a shortfall in such knowledge capacity will hamper Europe's innovative strength and productivity growth. A lack of professionals with expert knowledge in hydrogen safety and related key areas will not only impose a serious setback on innovative developments required to propel this transition, but also thwart ongoing efforts to achieve public acceptance of the new technology. Recently, the European Commission identified a shortage of experts in the key disciplines (natural sciences, engineering, technology [8–10]) relevant to hydrogen safety. The workforce in R&D is presently relatively low, as researchers account for only 5.1 in every thousand of the workforce in Europe, against 7.4 in the US and 8.9 in Japan [10,11]. An even larger discrepancy is observed if one considers only the number of corporate researchers employed in industry: 2.5 in every thousand in Europe, against 7.0 in the US and 6.3 in Japan [9]. Moreover, the number of young people attracted to careers in science and research appears to be decreasing. In the EU, 23% of the people aged between 20 and 29 years are in higher education, compared to 39% in the USA [10]. Knowing that research is a powerful driving force for economic growth, and a continuous supply of a skilled workforce is of paramount importance to the emerging hydrogen economy, this situation calls for drastic improvement.

To explore possibilities for improvement it would be helpful to consider what might have caused this situation in the first place. Firstly, there are the quality and attractiveness of Europe for investments in research and development in relation to that of other competing knowledge economies. The quality of research, and the number of young people embarking on higher education in natural sciences, engineering, and technology, depend primarily on investments made in R&D-activities. Presently, this amounts to 1.96% of GDP in Europe, against 2.59% in the United States of America, 3.12% in Japan and 2.91% in Korea. The gap between the United States of America and Europe, in particular, is more than 120 billion euro a year [8], with 80% of it due to the difference in business expenditure in R&D. At this point it is important to notice that the quality of the European research base will not improve, unless larger investments are made in R&D. It has been diagnosed [12] that multinational companies accounting for the greater share of business R&D expenditure, increasingly tend to invest on the basis of a global analysis of possible locations. This results in a growing concentration of transnational R&D expenditure in the United States of America. Moreover, there appears to be a decline in the global attractiveness of Europe as a location for investment R&D as compared to the United States of America. This alarming development could be reversed by improving the quality of the European research base, such that corporate investments in R&D are increased to 3% of GDP in Europe [12]. Secondly, there is the problem of a retiring science and technology workforce that needs to be succeeded by a younger generation of experts. The identified lack of experts in natural sciences, engineering, and technology creates an unstable situation for investment in R&D. This is particularly true if one considers that innovative developments take place over a timespan of several years. No investor will commission research projects to a retiring workforce without a prospect of succession by a capable younger generation. Thirdly, there is the problem of changes in the skill-set sought by employers and investors. The purpose of science and engineering education is to provide the graduate with sufficient skills to meet the requirements of the professional career, and a broad enough basis to acquire additional skills as needed. Because of the transitional nature of the hydrogen economy, and the consequential development and implementation of new technologies, the skill-set sought by employers is expected to change more rapidly than ever before. This phenomenon has already manifested itself in the information technology sector, and is anticipated to occur in the hydrogen economy as well. Science and engineering education related to the hydrogen economy must therefore be broad and robust enough, such, that when today's expert-skills have become obsolete, graduates possess the ability to acquire tomorrow's expert-skills. The International Curriculum on Hydrogen Safety Engineering, aims at tackling these three causes of detriment to Europe's research base and innovation strength by extracting the state-of-the-art in hydrogen safety and related key areas, and by the rapid dissemination of this knowledge at all levels in higher and further education and training. According to the Strategic Research Agenda [13], which acts as a guide for defining a comprehensive research programme that will mobilise stakeholders and ensure that European competences are at the forefront of science and technology worldwide, education will continue to play a pivotal role in spreading hydrogen applications to the broader public until 2050. In the short term outlook from 2005 to 2015, training and education efforts are needed to build the necessary human resources to lead research and to allow a steady stream of trained scientists and technicians to develop the area. The Workgroup on Cross Cutting Issues [14], dealing primarily with the non-technical barriers to the successful implementation of the deployment strategy for hydrogen and fuel cells in Europe, indicates that educational and training efforts are needed during this period to avoid any dissonances that might hinder the building of consumer and non-technical executive confidence. The Workgroup on Cross Cutting Issues [14] has estimated that during the framework 7 period (2007–2013), the educated staff needed may amount to 500 new graduates from postgraduate studies on an annual basis in all of Europe.

The hydrogen economy requires professionals with a postgraduate degree dedicated to hydrogen safety, which is a subset of the aforementioned 500 new graduates. A preliminary study (see Section 2.3) indicates that this subset amounts to 119 graduates on an annual basis. Because graduates in hydrogen safety will be involved in all aspects of the hydrogen economy to ensure safety, it is important that the following issues are taken into account by the curriculum:

- what kind of organisations will employ graduates in hydrogen safety (process industry, energy industry, civil works, aerospace industry, automotive industry, transport and distribution, fire and rescue brigades, insurance, teaching institutions, research institutions, legislative bodies, etc.),
- at what level will graduates in hydrogen safety operate within the organisation (consulting, manufacture, design, teaching, research, operation, construction, legislation, etc.), and,
- which mode of education is the most appropriate to match the skill-set sought at the various levels of engagement within these organisations (undergraduate education, postgraduate

degree, continuing professional development, short courses, etc.).

Moreover, the undergraduate programme should be well-rounded in the engineering science core (see Fig. 1) and supplemented by topics and additional courses with an emphasis on hydrogen safety. Duplication of educational efforts may be avoided by defining hydrogen safety engineering in relation to other branches of engineering, and cross-fertilisation with existing engineering programmes may be achieved by the introduction of topics relevant to hydrogen safety into the engineering science core. The postgraduate programme consists of specialised courses covering the nodes of the HySafe activity matrix shown in Fig. 2. Because the topics connected to the nodes in Fig. 2 are subject to continuous development as the hydrogen economy evolves, the curriculum needs to be comprehensive enough to absorb these changes as new knowledge becomes available.

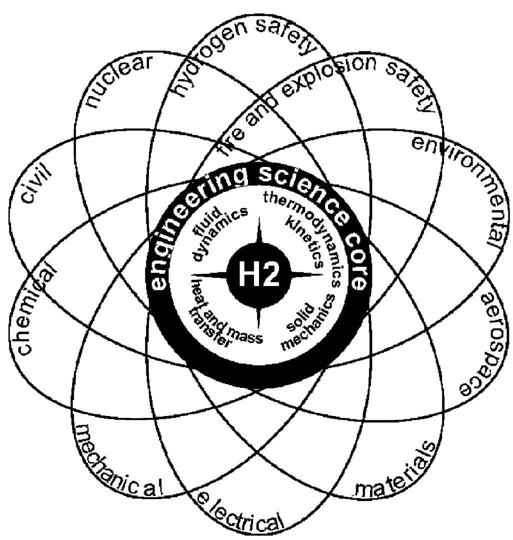

Fig. 1. Hydrogen safety in relation to other branches of engineering science.

2.2. Structure of the curriculum

To comply with the aforementioned requirements, the Draft for Development of the International Curriculum on Hydrogen Safety Engineering is designed to consist of basic modules, fundamental modules, and applied modules. This approach was inspired by Magnusson et al. [15], who adopted a similar approach for the development of a model curriculum for fire safety engineering. The current modular structure is summarised in Table 2, and the current detailed topical content of the Draft for Development of the International Curriculum on Hydrogen Safety Engineering is available at the e-Academy page of the NoE HySafe (http://www.hysafe.org/index.php?ID = 68).

The five basic modules, i.e. thermodynamics; chemical kinetics; fluid dynamics; heat and mass transfer; solid mechanics, are intended for undergraduate instruction (although these modules contain topics belonging to the postgraduate level). They are similar to any other undergraduate course in the respective subject areas, but comprehensive enough to provide a broad basis for dealing with hydrogen safety issues involving hydrogen embrittlement, unscheduled releases of liquefied and gaseous hydrogen, accidental ignition and combustion of hydrogen, etc. The purpose of these modules is twofold. Firstly, to enable the coupling of knowledge relevant to hydrogen safety into existing engineering curricula, and secondly, to support the knowledge framework contained in the fundamental and applied modules.

The six fundamental modules, i.e. introduction to hydrogen as an energy carrier; fundamentals of hydrogen safety; release, mixing and distribution; hydrogen ignition; hydrogen fires; explosions: deflagrations and detonations, form the backbone of hydrogen safety. While these modules, except for the first one, are intended for instruction at the postgraduate level, their topical content may also be used to develop teaching materials for undergraduate instruction to supplement existing engineering curricula with courses dedicated to hydrogen safety. The topical content of these modules is connected to the nodes in the HySafe activity matrix. These topics are initially based on the existing literature, and updated continuously as new knowledge becomes available, particularly from the NoE HySafe.

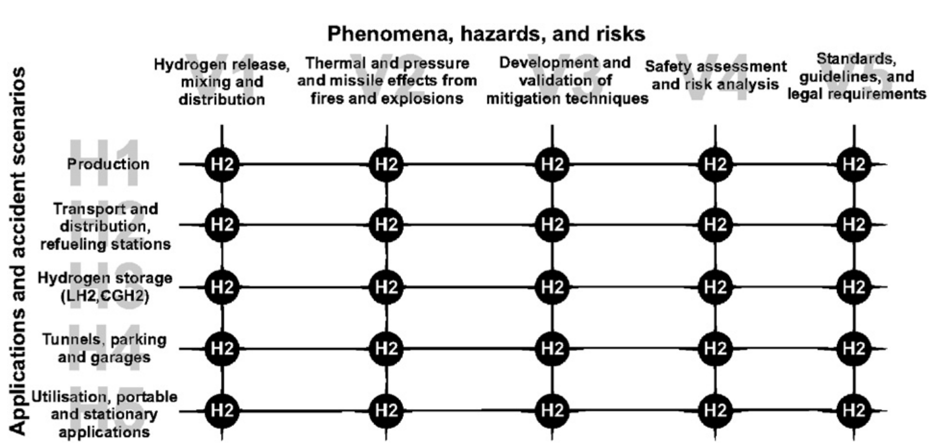

Fig. 2. The HySafe activity matrix.

Table 2
Structure of the International Curriculum on Hydrogen Safety Engineering

Basic modules
Module thermodynamics
Module chemical kinetics
Module fluid dynamics
Module heat and mass transfer
Module solid mechanics
Fundamental modules
Module introduction to hydrogen as an energy carrier
Module fundamentals of hydrogen safety
Module release, mixing and distribution
Module hydrogen ignition
Module hydrogen fires
Module explosions: deflagrations and detonations
Applied modules
Module fire and explosion effects on people, structures, and the environment
Module accident prevention and mitigation
Module computational hydrogen safety engineering
Module risk assessment

Obviously, the fundamental modules play a pivotal role in the curriculum development as the hydrogen economy evolves: new knowledge enters the curriculum through the fundamental modules, and this information is subsequently used to tune the basic and applied modules. Together, these six fundamental modules form the hydrogen safety engineering science core to support the applied modules.

The four applied modules, i.e. fire and explosion effects on people, structures, and the environment; accident prevention and mitigation; computational hydrogen safety engineering; risk assessment, are intended to provide graduates with the skill-set needed to solve hydrogen safety problems. These are postgraduate modules, but their topical content may also be used to develop undergraduate courses on hydrogen safety to complement existing undergraduate engineering curricula. The topics covered by these modules also coincide with the nodes in the HySafe-activity matrix. Like the fundamental modules, the role of these modules is also pivotal in the development of the curriculum. Methodologies and front-line techniques for dealing with hydrogen safety problems are extracted from the HySafe-network and incorporated into these modules. Modification of these modules due to new information is followed by the tuning and refinement of the topical content of the basic and fundamental modules to preserve coherence throughout the entire curriculum.

2.3. Assessment of the need for hydrogen safety education and formation of a market of potential trainees

The development of a curriculum in any branch of engineering would obviously be meaningless without a market of trainees. Since the level of interest in hydrogen safety education primarily depends on the number of people involved in hydrogen related activities, the e-Academy of hydrogen safety has developed, and maintains a database of organisations working in the hydrogen industry. A first attempt to use this database to assess the market of potential trainees in hydrogen safety was made by sending a questionnaire to 600 companies and institutions in the database. There were 28 respondents and an analysis of their replies indicates that 119 potential trainees would be interested in hydrogen safety education on an annual basis. This implies that a projected market of 5000 companies and institutions would yield 1000 trainees on an annual basis. As a result, it will be necessary to deploy educational/training resources at a number of universities throughout Europe to meet this demand for hydrogen safety education. Further analysis of the replies indicates that the relative interest in the various modes of hydrogen safety education is as follows: postgraduate certificate (PGC): 10.7%, postgraduate diploma (PGD): 1.5%, master of science (MSc): 29.3%, short course (SC): 42.2%, and continuing professional development (CPD): 16.3%. It was also attempted to resolve the employment pattern, and hence the skill-set sought by employers. Within these 28 companies and institutions the employment pattern appears to be: 1.3% in design, 13.0% in manufacture, 0.9% in legislation, 0.4% in maintenance, 1.1% in installation, 19.0% in research and 19.0% in teaching (these percentages do not sum up to 100% because of the limited set defining the pattern). Given the small size of the catchment population, these outcomes must be considered preliminary. The process of arriving at these results nevertheless illustrates the mechanism of how the market of trainees in hydrogen safety could be assessed, and how the employment pattern of people working in hydrogen related areas, and the skill-set sought by employers might be resolved.

3. e-Learning and the European Summer School on Hydrogen Safety

The European Commission has launched a number of measures [16,17] to co-ordinate e-learning activities with the aim to propel Europe towards becoming the most competitive and dynamic knowledge-based economy in the world. Universities are using e-learning as a source of added value for their students, and for providing off-campus, flexible, virtual learning through web-based resources. Some universities are entering into strategic partnerships and adopting new business models to serve the changing education market and to face the challenges posed by global competition. From an employer point of view, greater emphasis is being placed on cost savings and on flexible, just-in-time education and training, to provide employees with the necessary skills and competence that match changing business needs. Owing to the transitional nature of the hydrogen economy, the continual introduction of new technologies, and the consequential rapid diversification of the skill-set sought by employers, e-learning is expected to become important in providing education and training in hydrogen safety. Because e-learning does not confine trainees to a specific campus location, employees are given maximal opportunity to acquire new skills and competencies while continuing in full-time employment, and to maintain family and domestic commitments. Moreover, e-learning makes it possible for experts working at the forefront of hydrogen safety to deliver teaching on the state-of-the-art in the field, while continuing their research of scientific endeavour. This is in line with the University of Ulster's aim to promote the further development and expansion of e-learning and blended learning programmes.

While the e-learning market in Europe is estimated at 12 billion euro per year, and is experiencing rapid growth, the lack of good quality e-learning content remains a matter of concern. This is true for well-established subject areas, and even more so for hydrogen safety. To cope with this situation, the European Commission has funded a series of annual European Summer Schools on Hydrogen Safety (HyCourse, contract MSCF-CT-2005-029822, 2006-2010, coordinated by the University of Ulster, http://www.engj.ulst.ac.uk/esshs/hycourse). The First European Summer School on Hydrogen Safety was held at the University of Ulster in Belfast from 15 to 24 August 2006. During each event at least 12 leading experts from all over the world will deliver keynote lectures to an international audience of at least 60 researchers on topics such as: hydrogen release, mixing, and distribution; mechanisms of hydrogen ignition; hydrogen fires; deflagration, detonation and transitional phenomena; computational modelling in hydrogen safety; thermal, pressure and missile effects from fires and explosions; development and validation of mitigation techniques; safety assessment and risk analysis; and standards, guidelines and legal requirements. The nodal points of the HySafe activity matrix will be covered from fundamentals to applications following the topical content of the International Curriculum on Hydrogen Safety Engineering, and junior researchers are given the opportunity to benefit from the experience of leading world-class experts. With hydrogen safety being a novel area, and therefore lacking the prerequisites to prepare a skilled workforce for the technological challenges to come, this approach is considered to be the way forward to create the next generation of researchers and educators in this subject area, and to preserve the life-blood of research. The lecture notes and presentations of the keynote lectures at the European Summer School on Hydrogen Safety will be used for the further development of two high-quality WebCT-based modules, namely, "Principles of Hydrogen Safety" and "Applied Hydrogen Safety", for the delivery of teaching on hydrogen safety in the distance learning mode. An on-line postgraduate certificate course in hydrogen safety engineering will be offered by the University of Ulster from January 2007 where these two modules will be taught.

4. Concluding remarks

The development of an International Curriculum on hydrogen safety Engineering as the backbone of the e-Academy of hydrogen safety is described. To cope with the wide spectrum of the hydrogen economy and its transient nature involving the continual introduction of new technologies, the curriculum is designed to extract knowledge on hydrogen safety as it becomes available for the development of new teaching programmes. To avoid duplication of educational efforts, this knowledge also needs to be coupled into existing engineering curricula. A modular structure, consisting of basic modules, fundamental modules, and applied modules appears to be the most appropriate for achieving this goal.

Because the development of the International Curriculum on Hydrogen Safety Engineering would make no sense without a market of trainees, it was attempted to probe and quantify its existence by means of a questionnaire. Although these results must be considered preliminary because of the small catchment population, there appears to be a potential market of 1000 trainees on an annual basis. To meet this demand for hydrogen safety education it will be necessary to establish educational and training programmes at a number of universities throughout Europe. It was also attempted to resolve the employment pattern to address specific educational and training needs. Further research in this direction will concentrate on determining the distribution of the employment pattern (consulting, manufacture, design, teaching, research, operation, construction, legislation, etc.) and the employer pattern (process industry, energy industry, civil works, aerospace industry, automotive industry, transport and distribution, fire and rescue brigades, insurance, teaching institutions, research institutions, legislative bodies, etc.).

Despite the demand for knowledge in the field of hydrogen safety, there are practically no hydrogen safety training and educational programmes in Europe to address this need. The development of the e-Academy of Hydrogen Safety by the NoE HySafe is a first step in overcoming this deficiency. Moreover, the onset and further development of the hydrogen economy in Europe is being hampered by (i) a shortage of experts in the key disciplines relevant to hydrogen safety; (ii) a decrease in the number of young people attracted to careers in science and research; (iii) a deterioration of Europe's attractiveness for R&D investments; (iv) changes in the skill-set sought by employers; (v) the absence of a skilled-workforce to succeed the retiring S&T workforce; and (vi) the lack of educational resources to prepare tomorrow's researchers and educators for the technological challenges posed by the hydrogen economy. The International Curriculum on Hydrogen Safety Engineering, the development of which is aided by experts working at the forefront of hydrogen safety and related key areas will help to improve this situation and increase Europe's innovative and competitive strength at the onset of the hydrogen economy.

To address the needs of employers (i.e. greater emphasis on cost savings and on flexible, just-in-time education and training, providing employees with the necessary skills and competence to match changing business needs) and needs of professionals working in hydrogen related areas (i.e. providing the latest knowledge on hydrogen safety, removal of restrictions imposed by confinement to a specific campus location) the delivery of teaching in the e-learning mode appears to be the way forward. To meet specific educational needs on hydrogen safety in terms of relevance and timeliness, the EC Marie Curie Actions have been used to organise a series of European Summer Schools on Hydrogen Safety (HyCourse, contract MSCF-CT-2005-029822, 2006-2010, coordinated by the University of Ulster) where 12 leading experts will deliver keynote lectures to 60 researchers. The First European Summer School on Hydrogen Safety was held at the University of Ulster in Belfast from 15 to 24 August 2006. The lecture notes and presentations at the European Summer School on Hydrogen Safety will be used for the further development of two high-quality on-line modules, namely, "Principles of Hydrogen Safety" and 'Applied Hydrogen Safety", for the delivery of teaching in the e-learning mode. From January 2007, a distance learning postgraduate certificate course in hydrogen safety engineering will be offered by the University of Ulster where these two modules will be taught.

It is important to be aware of the fact that Europe is world's greatest knowledge centre because it has over 500 universities with about one million students. The reasons why this competitive potential is not yet fully exploited on the world market of knowledge are (i) fragmentation caused by language barriers; (ii) the enclosure of the educational systems within national borders; and (iii) the lack of harmonisation between educational programmes. The Draft for Development of the International Curriculum on Hydrogen Safety Engineering, one that will be used as a blueprint for the development of educational and training programmes at universities throughout Europe, will assist the harmonisation of educational programmes, stimulate the mobility of students and faculty, promote international collaboration at all levels, and support efforts related to the unification of resources in the area of science and further education. This mobilisation of human capital and resources with an emphasis on hydrogen safety and related key areas will increase Europe's competitive strength as a knowledge economy and enable Europe to fulfill a leading role in achieving global understanding of, and agreement on dealing with hydrogen safety matters. Moreover, the deployment of this curriculum in conjunction with e-learning for the delivery of hydrogen safety education, with the latter being unrestricted in terms of catchment area, will enable Europe to fulfill a leading role in exporting knowledge on hydrogen safety to the world.

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References

[1] Tse SD, Zhu DL, Law CK. Morphology and burning rates of expanding spherical flames in H_2/O_2/inert mixtures up to 60 atmospheres. Proceedings of the 28th symposium (International) on combustion. Pittsburgh; The Combustion Institute; 2000. p. 1793–800.

[2] ISO TR 15916. Basic considerations for the safety of hydrogen systems. International Standard. 1st ed. Reference number ISO TR 15916:2004(E); 2004.

[3] Turns SL. An introduction to combustion: concepts and applications. 2nd ed, New York: McGraw-Hill; 2000.

[4] IAEA-TECDOC-1196. Mitigation of hydrogen hazards in water cooled power reactors. International Atomic Energy Agency, February 1998.

[5] Dunn S. Hydrogen futures: toward a sustainable energy system. Int J Hydrogen Energy 2002;27:235–64.

[6] Jordan T. HySafe—The network of excellence for hydrogen safety. Paper presented at the 16th world hydrogen energy conference, Lyon, France, 13–16 June, 2006. International Association for Hydrogen Energy.

[7] Safety of hydrogen as an energy carrier, Proposal 502630 (HySafe). A Proposal for a Sixth framework network of excellence, annex I—"description of work", December; 2003.

[8] COM (2003) 226 final. Investing in research: an action plan for Europe, communication from the commission. Commission of the European Communities, Brussels; 2003.

[9] SEC (2003) 489 of 30.4.2003. Investing in research: an action plan for Europe. Commission of the European Communities. Commission Staff Working Paper. Brussels; 2003.

[10] COM (2005) 576 final. Commission recommendation. Commission of the European Communities, Brussels; 2005.

[11] COM (2001) 331 final. A mobility strategy for the European research area, communication from the commission to the council and the European parliament. Commission of the European Communities, Brussels; 2001.

[12] COM (2002) 499 final. More research for Europe, towards 3% of GDP. Commission of the European Communities, Brussels; 2002.

[13] Strategic research agenda. The European hydrogen and fuel cell technology platform. Implementation panel; 2005.

[14] Wancura H, Mayo B, Reijalt M, Mertens JJ, Maio P, Claassen P. Draft Implementation Report WG5 Cross Cutting Issues (XCI). The European hydrogen and fuel cell technology platform, Implementation panel; 2006.

[15] Magnusson SE, Drysdale DD, Fitzgerald RW, Motevalli V, Mowrer F, Quintiere J. et al. A proposal for a model curriculum in fire safety engineering. Fire Safety J 1995;25:1,3–39,41–73,75–83,85,87–88.

[16] SEC (2003) 905. e-learning: designing tomorrows education, a mid-term report as requested by the council resolution of 13 July 2001. Commission of the European Communities, Brussels, 2003. Commission Staff Working Paper.

[17] COM (2000) 318 final. e-learning designing tomorrow's education. Communication from the Commission. Commission of the European Communities, Brussels; 2000.