TOWARDS HYDROGEN SAFETY EDUCATION AND TRAINING

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ABSTRACT

The onset and further development of the hydrogen economy are known to be constrained by safety barriers, as well as by the level of public acceptance of new applications. *Educational and training programmes in hydrogen safety*, which are currently absent in Europe, are considered to be a key instrument in lifting these limitations and to ensure the safe introduction of hydrogen as an energy carrier. Therefore, the European Network of Excellence 'Safety of Hydrogen as an Energy Carrier' (NoE HySafe) embarked on the establishment of the e-Academy of Hydrogen Safety. This work is led by the University of Ulster and carried out in cooperation with international partners from five other universities (Universidad Politecnica de Madrid, Spain; University of Pisa, Italy; Warsaw University of Technology, Poland; Instituto Superior Technico, Portugal; University of Calgary, Canada), two research institutions (Forschungszentrum Karlsruhe and Forschungszentrum Juelich, Germany), and one enterprise (GexCon, Norway). The development of an International Curriculum on Hydrogen Safety Engineering, aided by world-class experts from within and outside NoE HySafe, is of central importance to the establishment of the e-Academy of Hydrogen Safety. Despite its key role in identifying the knowledge framework of the subject matter, and its role in aiding educators with the development of teaching programmes on hydrogen safety, no such curriculum appears to have been developed previously. The current structure of the International Curriculum on Hydrogen Safety Engineering, and the motivation behind it, are described in this paper. Future steps in the development of a system of hydrogen safety education and training in Europe are briefly described.

1.0 INTRODUCTION

There appears to be a need for education in hydrogen safety because of the introduction of hydrogen as an energy carrier and hydrogen technologies should provide at least the same level of safety, reliability, and comfort as with today's fossil energy carriers. Hydrogen is known to have some properties that make its behaviour during accidents different from that of most other combustible gases. When no use is made from hydrogen's greatest 'safety asset', buoyancy, it can become 'more dangerous' than conventional fuels such as gasoline, LPG and natural gas. When mixed with air, hydrogen's lower flammability limit is higher than that of LPG or gasoline, but its flammable range is very large (4-75% hydrogen in air). In the concentration range of 15-45%, the ignition energy of hydrogen is one-tenth of that of gasoline. The 'quenching gap', i.e. the smallest hole through which a flame can propagate - is considerably smaller for hydrogen than for today's fossil fuels. This implies that requirements for mitigation, such as flame arrestors and similar equipment, must be more stringent. It is a strong reducing agent and contact with metal oxides (rust) leads to an exothermic reaction. It can cause material embrittlement and diffuses more easily through many conventional materials used for pipelines and vessels, and through gaps that are normally small enough to seal other gases safely. The safety and combustion literature indicates that releases of hydrogen are more likely to cause explosions than releases of today's fossil fuels do. In contrast with other compressed gases, lowering the pressure of hydrogen during release increases its temperature, i.e. hydrogen has a negative Joule-Thomson coefficient at ambient temperature. There are concerns that when hydrogen is released from a high-pressure vessel, this increase in temperature may contribute to self ignition. Many countries' building codes require garages to have ventilation openings near the ground to remove gasoline vapour, but high-level ventilation is not always addressed. As a result, accidental releases of hydrogen in such buildings will inevitably lead to the formation of an explosive mixture at the ceiling-level. 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. Owing to the extreme lightness of the molecule, this is particularly true with hydrogen.

For many decades, hydrogen has been used extensively in the process industries (e.g. refineries and ammonia synthesis) and experience has shown that hydrogen 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 [1]. Interestingly, these technologies rely on the same anomalous properties, such as the large diffusivity and extreme lightness, that make hydrogen more dangerous than 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 can not 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, virtually all vehicle demonstration projects by manufacturers involve the use of hydrogen as a compressed gas at extremely high pressures (over 350 bar). There is no precedent for the safe handling of hydrogen 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. Since a similar dedication to safety, e.g. training general consumers to a professional level, would become impractical, hydrogen safety education should 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. A group that must be targeted as well by hydrogen safety education. These are the educators, local regulators, insurers, rescue personnel, investors, and public service officials. Their involvement is essential to the acceptance and use of the new technology by the general public. Without the establishment of a consolidated consumer market there will be no transition from our present fossil-fuel economy into a sustainable one based on hydrogen. This process depends entirely on the public acceptance and use of hydrogen technologies.

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 impose a serious setback on innovative developments required to propel this transition, and, ongoing efforts to achieve public acceptance of the new technology might be thwarted. Recently, the European Commission identified a shortage [2,3,4] of experts in the key disciplines (natural sciences, engineering, technology) 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 [5]. 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. 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. 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, 3.12% in Japan and 2.91% in Korea. The gap between the United States and Europe, in particular, is currently about €120 billion a year, 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 [6] 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 trans-national R&D expenditure in the United States. 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. 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 [6].

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 time-span 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 early stages of the professional career, and a broad enough basis to acquire additional skills as needed in the later stages. 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, discussed further in this paper, aims at tackling these three causes of detriment to Europe's research base and innovation strength. It is important to be aware of the fact that Europe is the 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 is fragmentation caused by language barriers, the enclosure of the educational systems within national borders. The establishment of an International Curriculum on Hydrogen Safety Engineering, one that will be used as a blueprint for the development of educational and training programmers at universities throughout Europe, will stimulate the mobility of students and faculty, international collaboration at all levels, and 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 fulfil a leading role in achieving global understanding of, and agreement on dealing with hydrogen safety matters.

2.0 INTERNATIONAL CURRICULUM ON HYDROGEN SAFETY ENGINEERING

The development of an International Curriculum on Hydrogen Safety Engineering must be viewed upon as a process to identify and to demarcate the knowledge framework of the subject matter. Such a process helps to define the dicipline of Hydrogen Safety Engineering to form a basis for the development of new educational programmes, and determines its relationship to other branches of engineering (see Figure 1). This, to avoid duplication of educational efforts, but also to achieve cross-fertilisation with existing engineering programmes through the introduction of topics with an emphasis on hydrogen safety. 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 during the development of the curriculum:

what kind of organisations will employ graduates in hydrogen safety (industry, engineering consultancies, research institutions, teaching institutions, rescue brigades, fire brigades, legislative bodies, insurance companies, governmental bodies),

at what level will graduates in hydrogen safety operate within the organisation (design, construction, operation, manufacture, teaching, research, development of standards and guidelines), 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, continuous professional development).

Given the wide spectrum of the emerging hydrogen economy, it seems that both all-round undergraduate education based on the engineering science core in Figure 1, supplemented by topics and additional courses with an emphasis on hydrogen safety, as well as postgraduate degree programmes dedicated to hydrogen safety, are needed. An International Curriculum on Hydrogen Safety Engineering, which is the basis of educational and training programmes at universities throughout Europe should therefore not only cover the nodes in the HySafe activity matrix shown in Figure 2, but also provide a mechanism to introduce hydrogen safety topics at both levels. Furthermore, because the topics connected to the nodes in Figure 2 are subject to continuous change as the hydrogen economy evolves, the curriculum needs to be comprehensive enough to absorb these changes and new knowledge generated along the way. To comply with these requirements, 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.[7], who adopted a similar approach for the development of a model curriculum for Fire Safety Engineering. The current modular structure is summarised in Table 1, and the detailed topical content of the curriculum may be viewed at the e-Academy page of the HySafe consortium [8].

The four basic modules, i.e. thermodynamics; fluid dynamics; heat and mass transfer; solid mechanics, are mainly intended for undergraduate instruction mainly (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, and accidental ignition and combustion of hydrogen. 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 provide support to 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; deflagrations and detonations, define the knowledge framework that 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 relevant to the nodes in the HySafe-activity matrix (Figure 2). These topics are initially based on the existing literature, and updated continuously as new knowledge becomes available, particularly from the HySafe network. 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.

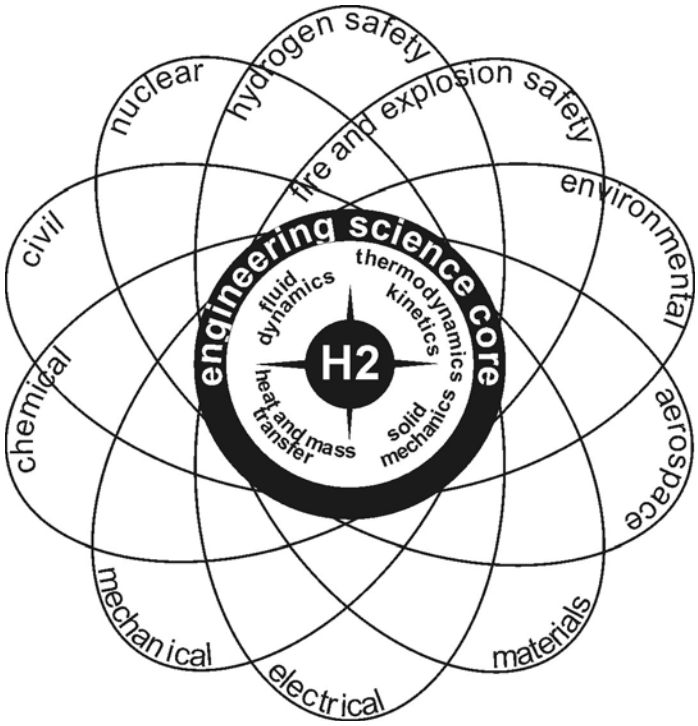

Figure 1. Hydrogen Safety in relation to other branches of engineering.

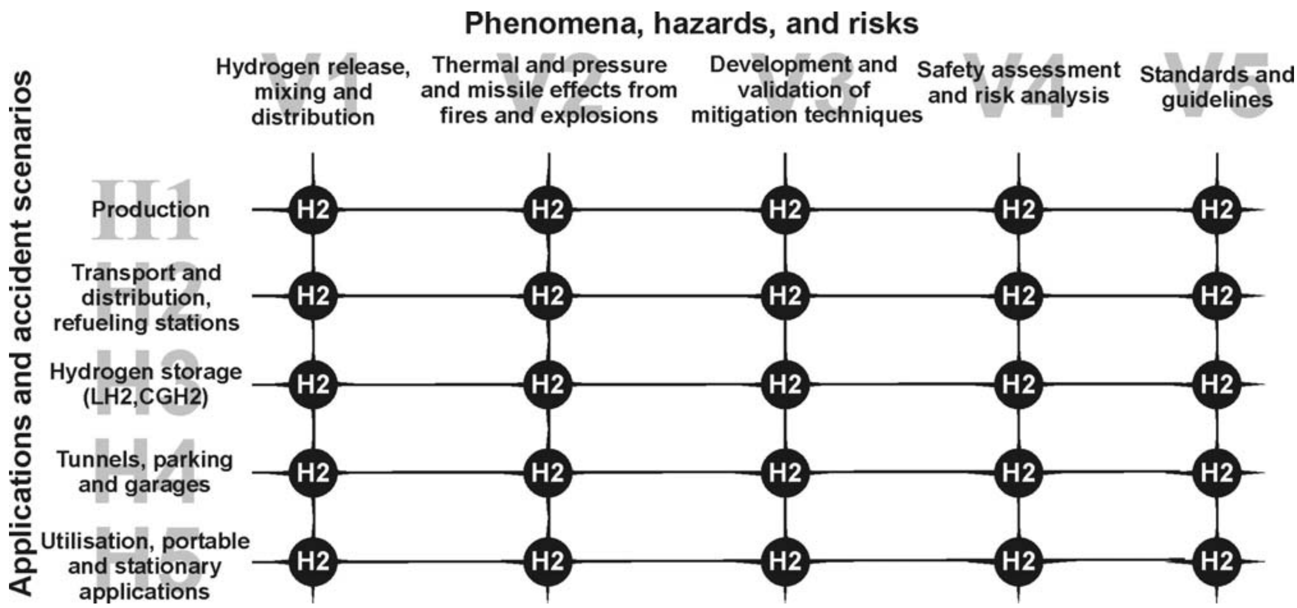

Figure 2. The HySafe activity matrix.

The four applied modules, i.e. fire and explosion effects; hydrogen mitigation; risk assessment; computational hydrogen safety engineering, are intended to provide graduates with the skill-set needed to tackle 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 (Figure 2). Like the fundamental modules, the role of these modules is also pivotal in the development of the curriculum. Methodologies and front-line techniques to deal with hydrogen safety problems are extracted from the HySafe network and incorporated into these modules. Modifications to these modules due to new information are followed by tuning of the topical content of the basic and fundamental modules to preserve coherence throughout the entire curriculum.

Table 1. Structure of International Curriculum on Hydrogen Safety Engineering.

Basic modules
Module thermodynamics
Module fluid dynamics
Module heat and mass transfer
Module solid mechanics
Fundamental modules
Module introduction to hydrogen as an energy carrier
Module combustion 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
Module hydrogen mitigation
Module risk assessment
Module computational hydrogen safety engineering

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 maintains a database of organisations working in the hydrogen industry (this may be viewed at the e-Academy page of the HySafe consortsium [8]. As an exercise, it was attempted to use this database to assess the market of potential trainees in hydrogen safety. A questionnaire was sent to 600 companies and institutions contained 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 continuous 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 (notice that these percentages do not sum up to 100%; this is due to 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.

3.0 e-LEARNING AND HYDROGEN SAFETY EDUCATION

The European Commission has launched a number of measures [9,10] 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 employers 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 endeavour.

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. The development of the International Curriculum on Hydrogen Safety Engineering, as described in the previous section, will improve this situation because the mechanism of extracting the state-of-the-art in hydrogen safety from the HySafe network, and the coherent coupling of this knowledge into existing engineering curricula is the best guarantee for quality. 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 fulfil a leading role in exporting knowledge on hydrogen safety to the world.

4.0 CONCLUSIONS

Despite the growing hydrogen economy and the consequential demand for knowledge and codes in the field of safety, there are practically no hydrogen safety training and educational programmes in Europe. The establishment of the e-Academy of Hydrogen Safety by the NoE HySafe is the first step in the implementation of a developing culture of training and education in hydrogen safety in Europe. By contributing knowledge to priority areas as energy, the environment, education and training [11], as well as to the Bologna process which aims at establishing a European Higher Education Area (EHEA) by 2010, this development concurs with political objectives set the European Union.

The development of an International Curriculum on Hydrogen Safety Engineering, followed by the development of teaching materials and the implementation of courses at a number of universities is an important first step in establishing a culture of hydrogen safety in Europe. The initial stage of the development of an International Curriculum on Hydrogen Safety Engineering as the backbone of the e-Academy of Hydrogen Safety is presented, and, its need in relation to Europe’s innovative and competitive strength at the onset of the hydrogen economy is described. Because of 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, and to couple it with existing science and engineering curricula. A modular structure, consisting of basic modules, fundamental modules, and applied modules appears to be the most appropriate for this purpose. The current version of the curriculum may be viewed on the e-Academy page of HySafe [8].

Since the development of an International Curriculum on Hydrogen Safety Engineering would make no sense without a market of trainees, it was attempted to probe 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 deploy educational/training programmes at a number of universities throughout Europe. The e-learning mode of education and training is seen as the most appropriate in the initial stage to overcome limitations in teaching resources and mobility restrictions of trainees. To propel this development further, the Marie Curie actions [12] will be used and efforts are underway to create a European Summer School on Hydrogen Safety.

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