SIXTH FRAMEWORK PROGRAMME
Sustainable Energy Systems

NETWORK OF EXCELLENCE

Contract No SES6-CT-2004-502630
Safety of Hydrogen as an Energy Carrier

Draft for Development of an International Curriculum on
Hydrogen Safety Engineering
WP 15 Deliverable D30

Lead Participant: UU (A.E. Dahoe, V.V. Molkov)
Partners: UNIPI, UPM, WUT, IST, UC, FZK, FZJ, GexCon

Dissemination Level: PU (Public),

Document Version: Final draft for development curriculum
(updated and corrected 04.08.2005)
Date of submission: 29.07.2005
Due date of delivery: 29.07.2005
Contents

1 INTRODUCTION 4

2 DESCRIPTION OF THE MODULES 9

3 BASIC MODULES 14

3.1 MODULE THERMODYNAMICS ................................. 14

3.1.1 INTRODUCTORY STATEMENT ............................. 14

3.1.2 PREREQUISITE MATTER .................................. 14

3.1.3 CONTENTS OF THE MODULE ............................. 14

3.1.3.1 States of matter (U: 4 hrs) ....................... 14

3.1.3.2 First law of thermodynamics (U: 6 hrs) .......... 14

3.1.3.3 Second law of thermodynamics (U: 6 hrs) ........ 14

3.1.3.4 Chemical thermodynamics (U: 6 hrs) ............. 14

3.1.3.5 Phase equilibrium (U: 6 hrs) ...................... 14

3.1.3.6 Thermodynamics and electrochemistry (U: 4 hrs) 15

3.2 MODULE FLUID DYNAMICS ................................... 15

3.2.1 INTRODUCTORY STATEMENT ............................. 15

3.2.2 PREREQUISITE MATTER .................................. 15

3.2.3 CONTENTS OF THE MODULE ............................. 15

3.2.3.1 Definitions (U: 2 hrs) .............................. 15

3.2.3.2 Fluid statics (U: 2 hrs) ............................ 15

3.2.3.3 Mathematical models of fluid motion (U: 6 hrs; G: 4 hrs) 15

3.2.3.4 Dimensional analysis and similitude (U: 6 hrs; G: 4 hrs) 16

3.2.3.5 Incompressible potential flow (U: 6 hrs; G: 4 hrs) 16

3.2.3.6 Boundary layer concepts (U: 6 hrs; G: 4 hrs) ..... 16

3.2.3.7 Incompressible turbulent flow (G: 4 hrs) ........ 16

3.2.3.8 One-dimensional compressible flow (U: 6 hrs; G: 4 hrs) 16

3.2.3.9 Two-dimensional compressible flow Gasdynamics (U: 6 hrs; G: 4 hrs) 17

3.2.3.10 Compressible turbulent flow (G: 4 hrs) .......... 17

3.3 MODULE HEAT AND MASS TRANSFER ........................ 17

3.3.1 INTRODUCTORY STATEMENT ............................. 17

3.3.2 PREREQUISITE MATTER .................................. 17

3.3.3 CONTENTS OF THE MODULE ............................. 17

3.3.3.1 Basic modes of heat transfer and particular laws (U: 4 hrs) 17

3.3.3.2 One-dimensional steady state conduction (U: 4 hrs) 17

3.3.3.3 Multidimensional steady-state conduction (U: 4 hrs) 18

3.3.3.4 Unsteady conduction (U: 6 hrs; G: 4 hrs) .......... 18

3.3.3.5 Forced convection: laminar flow (U: 3 hrs; G: 2 hrs) 18

3.3.3.6 Forced convection: equations of motion (U: 3 hrs; G: 2 hrs) 18

3.3.3.7 Natural convection (U: 3 hrs; G: 2 hrs) .......... 18

3.3.3.8 Boiling and condensation (U: 3 hrs; G: 2 hrs) .... 18

3.3.3.9 Heat exchangers (U: 3 hrs; G: 2 hrs) ............ 18

3.3.3.10 Radiation heat transfer (U: 6 hrs; G: 4 hrs) ..... 18

3.3.3.11 Isothermal mass transfer (U: 3 hrs; G: 2 hrs) ... 19

3.3.3.12 Simultaneous heat and mass transfer (U: 4 hrs; G: 2 hrs) 19

3.4 MODULE SOLID MECHANICS ................................. 19
4 FUNDAMENTAL MODULES

4.1 MODULE INTRODUCTION TO HYDROGEN AS AN ENERGY CARRIER

4.1.1 INTRODUCTORY STATEMENT ................................................. 22
4.1.2 PREREQUISITE MATTER ....................................................... 22
4.1.3 CONTENTS OF THE MODULE .................................................. 22
  4.1.3.1 Hydrogen as an energy carrier (U: 2 hrs; G: 2 hrs) .............. 22
  4.1.3.2 Introduction to hydrogen applications and case studies (U: 5 hrs; G: 5 hrs) .................................................. 22
  4.1.3.3 Equipment for hydrogen applications (U: 5 hrs; G: 5 hrs) ....... 23
  4.1.3.4 Possible accident scenarios (U: 2 hrs; G: 2 hrs) .............. 23
  4.1.3.5 Definitions and overview of phenomena and methodologies related to hydrogen safety (U: 3 hrs; G: 3 hrs) .......... 23

4.2 MODULE FUNDAMENTALS OF HYDROGEN SAFETY ...................... 23

4.2.1 INTRODUCTORY STATEMENT ................................................. 23
4.2.2 PREREQUISITE MATTER ....................................................... 24
4.2.3 CONTENTS OF THE MODULE .................................................. 24
  4.2.3.1 Hydrogen properties (U: 10 hrs; G: 6 hrs) ....................... 24
  4.2.3.2 Influence of hydrogen on equipment (U: 6 hrs; G: 6 hrs) ....... 24
  4.2.3.3 Hydrogen thermo-chemistry (G: 6 hrs) ............................. 24
  4.2.3.4 Governing equations of multi-component reacting flows (G: 6 hrs) .................................................. 25
  4.2.3.5 Premixed flames (G: 6 hrs) ........................................... 25
  4.2.3.6 Diffusion flames (G: 6 hrs) ........................................... 25
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.2.3.7</td>
<td>Partially premixed flames (G: 2 hr)</td>
<td>25</td>
</tr>
<tr>
<td>4.2.4</td>
<td>Turbulent premixed combustion (G: 6 hrs)</td>
<td>26</td>
</tr>
<tr>
<td>4.2.5</td>
<td>Turbulent non-premixed combustion (G: 6 hrs)</td>
<td>26</td>
</tr>
<tr>
<td>4.2.5.1</td>
<td>Ignition and burning of liquids and solids (G: 8 hrs)</td>
<td>26</td>
</tr>
<tr>
<td>4.2.5.2</td>
<td>Fire through porous media (G: 2 hrs)</td>
<td>26</td>
</tr>
<tr>
<td>4.3</td>
<td>MODULE RELEASE, MIXING AND DISTRIBUTION</td>
<td>27</td>
</tr>
<tr>
<td>4.3.1</td>
<td>INTRODUCTORY STATEMENT</td>
<td>27</td>
</tr>
<tr>
<td>4.3.2</td>
<td>PREREQUISITE MATTER</td>
<td>27</td>
</tr>
<tr>
<td>4.3.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>27</td>
</tr>
<tr>
<td>4.3.3.1</td>
<td>Fundamentals of hydrogen release and mixing (G: 4 hrs)</td>
<td>27</td>
</tr>
<tr>
<td>4.3.3.2</td>
<td>Handling hydrogen releases (G: 6 hrs)</td>
<td>27</td>
</tr>
<tr>
<td>4.4</td>
<td>MODULE HYDROGEN IGNITION</td>
<td>27</td>
</tr>
<tr>
<td>4.4.1</td>
<td>INTRODUCTORY STATEMENT</td>
<td>27</td>
</tr>
<tr>
<td>4.4.2</td>
<td>PREREQUISITE MATTER</td>
<td>28</td>
</tr>
<tr>
<td>4.4.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>28</td>
</tr>
<tr>
<td>4.4.3.1</td>
<td>Hydrogen ignition properties and ignition sources (G: 3 hrs)</td>
<td>28</td>
</tr>
<tr>
<td>4.4.3.2</td>
<td>Prevention of hydrogen ignition (G: 3 hrs)</td>
<td>28</td>
</tr>
<tr>
<td>4.5</td>
<td>MODULE HYDROGEN FIRES</td>
<td>28</td>
</tr>
<tr>
<td>4.5.1</td>
<td>INTRODUCTORY STATEMENT</td>
<td>28</td>
</tr>
<tr>
<td>4.5.2</td>
<td>PREREQUISITE MATTER</td>
<td>29</td>
</tr>
<tr>
<td>4.5.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>29</td>
</tr>
<tr>
<td>4.5.3.1</td>
<td>Fundamentals of hydrogen fires (G: 4 hrs)</td>
<td>29</td>
</tr>
<tr>
<td>4.6</td>
<td>MODULE DEFLAGRATIONS AND DETONATIONS</td>
<td>29</td>
</tr>
<tr>
<td>4.6.1</td>
<td>INTRODUCTORY STATEMENT</td>
<td>29</td>
</tr>
<tr>
<td>4.6.2</td>
<td>PREREQUISITE MATTER</td>
<td>29</td>
</tr>
<tr>
<td>4.6.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>29</td>
</tr>
<tr>
<td>4.6.3.1</td>
<td>Deflagrations (G: 6 hrs)</td>
<td>29</td>
</tr>
<tr>
<td>4.6.3.2</td>
<td>Detonation (G: 6 hrs)</td>
<td>30</td>
</tr>
<tr>
<td>4.6.3.3</td>
<td>Transitional hydrogen explosion phenomena (G: 6 hrs)</td>
<td>30</td>
</tr>
<tr>
<td>5</td>
<td>APPLIED MODULES</td>
<td>30</td>
</tr>
<tr>
<td>5.1</td>
<td>MODULE FIRE AND EXPLOSION EFFECTS ON PEOPLE, STRUCTURES AND THE ENVIRONMENT</td>
<td>30</td>
</tr>
<tr>
<td>5.1.1</td>
<td>INTRODUCTORY STATEMENT</td>
<td>30</td>
</tr>
<tr>
<td>5.1.2</td>
<td>PREREQUISITE MATTER</td>
<td>31</td>
</tr>
<tr>
<td>5.1.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>31</td>
</tr>
<tr>
<td>5.1.3.1</td>
<td>Thermal effects of hydrogen combustion (G: 4 hrs)</td>
<td>31</td>
</tr>
<tr>
<td>5.1.3.2</td>
<td>Blast waves (G: 4 hrs)</td>
<td>31</td>
</tr>
<tr>
<td>5.1.3.3</td>
<td>Calculation of pressure effects of explosions (G: 4 hrs)</td>
<td>31</td>
</tr>
<tr>
<td>5.1.3.4</td>
<td>Structural response, fragmentation and missile effects (G: 4 hrs)</td>
<td>31</td>
</tr>
<tr>
<td>5.1.3.5</td>
<td>Fracture mechanics (U: 4 hrs)</td>
<td>32</td>
</tr>
<tr>
<td>5.2</td>
<td>MODULE ACCIDENT PREVENTION AND MITIGATION</td>
<td>32</td>
</tr>
<tr>
<td>5.2.1</td>
<td>INTRODUCTORY STATEMENT</td>
<td>32</td>
</tr>
<tr>
<td>5.2.2</td>
<td>PREREQUISITE MATTER</td>
<td>32</td>
</tr>
<tr>
<td>5.2.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>32</td>
</tr>
<tr>
<td>5.2.3.1</td>
<td>Prevention, protection and mitigation (G: 4 hrs)</td>
<td>32</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td>Hours</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>5.2.3.2</td>
<td>Basic phenomena underpinning mitigation technologies</td>
<td>4</td>
</tr>
<tr>
<td>5.2.3.3</td>
<td>Standards, regulations and good practices related to hydrogen safety</td>
<td>4</td>
</tr>
<tr>
<td>5.2.3.4</td>
<td>Inertisation</td>
<td>4</td>
</tr>
<tr>
<td>5.2.3.5</td>
<td>Containment</td>
<td>4</td>
</tr>
<tr>
<td>5.2.3.6</td>
<td>Explosionventing</td>
<td>4</td>
</tr>
<tr>
<td>5.2.3.7</td>
<td>Flame arresters and detonation arresters</td>
<td>4</td>
</tr>
<tr>
<td>5.3</td>
<td>MODULE COMPUTATIONAL HYDROGEN SAFETY ENGINEERING</td>
<td>34</td>
</tr>
<tr>
<td>5.3.3</td>
<td>CONTENTS OF THE MODULE</td>
<td>34</td>
</tr>
<tr>
<td>5.3.3.1</td>
<td>Introduction to CFD</td>
<td>4</td>
</tr>
<tr>
<td>5.3.3.2</td>
<td>Introduction to thermodynamic and kinetic modeling</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.3</td>
<td>Mathematical models in fluid dynamics</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.4</td>
<td>Finite Difference Method</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.5</td>
<td>Solution of the generic transport equation</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.6</td>
<td>Solution of weakly compressible Navier-Stokes equations</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.7</td>
<td>Solution of compressible Navier-Stokes equations</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.8</td>
<td>Turbulent flow modeling</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.9</td>
<td>Combustion modeling</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.10</td>
<td>Multiphase flows</td>
<td>6</td>
</tr>
<tr>
<td>5.3.3.11</td>
<td>Special topics</td>
<td>6</td>
</tr>
<tr>
<td>5.4</td>
<td>MODULE RISK ASSESSMENT</td>
<td>37</td>
</tr>
<tr>
<td>5.4.3.1</td>
<td>Effect analysis of hydrogen accidents</td>
<td>6</td>
</tr>
<tr>
<td>5.4.3.2</td>
<td>Risk assessment methodologies</td>
<td>6</td>
</tr>
<tr>
<td>5.4.3.3</td>
<td>Hazard identification and scenario development</td>
<td>4</td>
</tr>
<tr>
<td>5.4.3.4</td>
<td>Vulnerability analysis</td>
<td>4</td>
</tr>
<tr>
<td>5.4.3.5</td>
<td>Application of hazard identification in the basic processes of the hydrogen economy</td>
<td>5</td>
</tr>
<tr>
<td>5.4.3.6</td>
<td>Application of vulnerability analysis to mitigation technologies in the hydrogen economy</td>
<td>5</td>
</tr>
</tbody>
</table>

6 CONCLUSIONS 39

BIBLIOGRAPHY 40

1 INTRODUCTION

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. Experts who have contributed to the curriculum development up to now are listed in Table 1. 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 report. Future steps in the development of a system of hydrogen safety education and training in Europe are briefly described.

Table 1: List of contributors to the curriculum.

<table>
<thead>
<tr>
<th>Name</th>
<th>Institution/Company</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barakli, D.</td>
<td>The European Commission’s Joint Research Center</td>
<td>The Netherlands</td>
</tr>
<tr>
<td>Bauwens, L.</td>
<td>University of Calgary</td>
<td>Canada</td>
</tr>
<tr>
<td>Bjerkedveldt, D.</td>
<td>Telemark</td>
<td>Denmark</td>
</tr>
<tr>
<td>Crespo, A.</td>
<td>Universidad Politecnica de Madrid</td>
<td>Spain</td>
</tr>
<tr>
<td>Dahoe, A.E.</td>
<td>University of Ulster</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Donze, M.</td>
<td>Delft University of Technology</td>
<td>The Netherlands</td>
</tr>
<tr>
<td>Dorofeev, S.B.</td>
<td>FM Global</td>
<td>United States of America</td>
</tr>
<tr>
<td>Engebo, A.</td>
<td>Det Norske Veritas</td>
<td>Norway</td>
</tr>
<tr>
<td>Faudou, J.-Y.</td>
<td>Air Liquide</td>
<td>France</td>
</tr>
<tr>
<td>Gallego, E.</td>
<td>Universidad Politecnica de Madrid</td>
<td>Spain</td>
</tr>
<tr>
<td>Garcia, J.</td>
<td>Universidad Politecnica de Madrid</td>
<td>Spain</td>
</tr>
<tr>
<td>Hansen, O.</td>
<td>GexCon</td>
<td>Norway</td>
</tr>
<tr>
<td>Jordan, T.</td>
<td>Forschungszentrum Karlsruhe</td>
<td>Germany</td>
</tr>
<tr>
<td>Kirillov, I.</td>
<td>Kurchatov Institute</td>
<td>Russia</td>
</tr>
<tr>
<td>Makarov, D.V.</td>
<td>University of Ulster</td>
<td>United Kingdom</td>
</tr>
<tr>
<td>Marangon, A.</td>
<td>University of Pisa</td>
<td>Italy</td>
</tr>
<tr>
<td>Martinfuertes, F.</td>
<td>Universidad Politecnica de Madrid</td>
<td>Spain</td>
</tr>
</tbody>
</table>
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 hydrogens 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 spacing 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. 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 (IAEA-TECDOC-1196 (2001) [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 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, 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 fuelling 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 (COM (2003) 226 final [2], SEC (2003) 489 of 30.4.2003 [3], COM (2005) 576 final [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 (COM (2001) 331 final [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 (COM (2002) 499 final [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 (COM (2002) 499 final [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 todays expert-skills have become obsolete, graduates possess the ability to acquire tomorrows expert-skills.

The International Curriculum on Hydrogen Safety Engineering, discussed further in this report, 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 programmes 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.

The European Commission has launched a number of measures (SEC (2003) 905 [7], COM (2000) 318 final [8]) 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 endeavours.

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.

2 DESCRIPTION OF THE MODULES

Developing an International Curriculum on Hydrogen Safety Engineering entails identifying and demarcating the knowledge framework of the subject matter. The process results in a definition of Hydrogen Safety Engineering as a basis for development of new educational programmes, and it determines its relationship with 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, etc),

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

The emerging hydrogen economy will require both undergraduates and professionals with a post-graduate degree dedicated to hydrogen safety. The undergraduate programme should be well-rounded in the engineering science core in Figure 1, but also supplemented by topics and additional courses with an emphasis on hydrogen safety. An International Curriculum on Hydrogen Safety Engineering, proposed as the basis of educational and training programmes at universities throughout Europe, will 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 all 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. (1995) [9], who adopted a similar approach for the development of a model curriculum for Fire Safety Engineering. The current modular structure is summarised in Table 3, and the detailed topical content of the curriculum may be viewed at the e-Academy page of the HySafe consortium (http://www.hysafe.org).
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, 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 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; hy-
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 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.

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 consortium (http://www.hysafe.org). As an exercise (see deliverable D17), 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.

Table 3: Structure of International Curriculum on Hydrogen Safety Engineering.

<table>
<thead>
<tr>
<th>Basic modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module thermodynamics</td>
</tr>
<tr>
<td>Module fluid dynamics</td>
</tr>
<tr>
<td>Module heat and mass transfer</td>
</tr>
<tr>
<td>Module solid mechanics</td>
</tr>
<tr>
<td>Fundamental modules</td>
</tr>
<tr>
<td>Module introduction to hydrogen as an energy carrier</td>
</tr>
<tr>
<td>Module fundamentals of hydrogen safety</td>
</tr>
<tr>
<td>Module release, mixing and distribution</td>
</tr>
<tr>
<td>Module hydrogen ignition</td>
</tr>
<tr>
<td>Module hydrogen fires</td>
</tr>
<tr>
<td>Module explosions: deflagrations and detonations</td>
</tr>
<tr>
<td>Applied modules</td>
</tr>
<tr>
<td>Module fire and explosion effects on people, structure, and the environment</td>
</tr>
<tr>
<td>Module accident prevention and mitigation</td>
</tr>
<tr>
<td>Module computational hydrogen safety engineering</td>
</tr>
<tr>
<td>Module risk assessment</td>
</tr>
</tbody>
</table>
3 BASIC MODULES

3.1 MODULE THERMODYNAMICS

3.1.1 INTRODUCTORY STATEMENT

This is a background module in classical thermodynamics and intended for undergraduate instruction only. It is similar to any other undergraduate engineering thermodynamics course, 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 topics covered by this module are based on the texts by Abbott & Van Ness (1972) [10], Moran & Shapiro (2000) [11], Smith, Van Ness & Abbott (2001) [12], and Sonntag, Borgnakke & Van Wylen (2003) [13].

3.1.2 PREREQUISITE MATTER

Calculus up to ordinary differential equations, classical mechanics.

3.1.3 CONTENTS OF THE MODULE

3.1.3.1 States of matter (U: 4 hrs)


3.1.3.2 First law of thermodynamics (U: 6 hrs)


3.1.3.3 Second law of thermodynamics (U: 6 hrs)


3.1.3.4 Chemical thermodynamics (U: 6 hrs)

3.1.3.5 Phase equilibrium (U: 6 hrs)


3.1.3.6 Thermodynamics and electrochemistry (U: 4 hrs)


3.2 MODULE FLUID DYNAMICS

3.2.1 INTRODUCTORY STATEMENT

This module serves as a first introduction to fluid dynamics at the undergraduate level, and extends to cover more advanced topics at the graduate level. This, to aid the understanding of fluid dynamical problems related to hydrogen safety engineering. The topics in this module are based on the texts by Hughes & Brighton (1999) [14], Massey & Ward-Smith (1998) [15], Prasuhn (1980) [16], and White (2003) [17]. Additional references are given along with the topics.

3.2.2 PREREQUISITE MATTER

Calculus, classical mechanics, thermodynamics.

3.2.3 CONTENTS OF THE MODULE

3.2.3.1 Definitions (U: 2 hrs)


3.2.3.2 Fluid statics (U: 2 hrs)


3.2.3.3 Mathematical models of fluid motion (U: 6 hrs; G: 4 hrs)

Contents  Integral equations: conservation of mass, momentum, angular momentum, energy, and second law of thermodynamics. Differential equations: continuity equation, momentum equation, momentum equation for frictionless flow,

3.2.3.4 **Dimensional analysis and similitude** (U: 6 hrs; G: 4 hrs)


3.2.3.5 **Incompressible potential flow** (U: 6 hrs; G: 4 hrs)


3.2.3.6 **Boundary layer concepts** (U: 6 hrs; G: 4 hrs)


3.2.3.7 **Incompressible turbulent flow** (G: 4 hrs)


3.2.3.8 **One-dimensional compressible flow** (U: 6 hrs; G: 4 hrs)

3.2.3.9 Two-dimensional compressible flow Gasdynamics (U: 6 hrs; G: 4 hrs)


3.2.3.10 Compressible turbulent flow (G: 4 hrs)


3.3 MODULE HEAT AND MASS TRANSFER

3.3.1 INTRODUCTORY STATEMENT

This module is similar to any other heat transfer course and intended for instruction at the undergraduate and graduate level. The topics in the module are covered by Holman (1997) [22], and Incropera & De Witt (2002) [23], and Pitts & Sissom (1977) [24], Kaviany (2002) [25], Welty, Wicks, Wilson & Rorrer (2001) [26]. Additional references are given along with the topics.

3.3.2 PREREQUISITE MATTER

Calculus up to ordinary differential equations, thermodynamics and fluid dynamics, Laplace transforms.

3.3.3 CONTENTS OF THE MODULE

3.3.3.1 Basic modes of heat transfer and particular laws (U: 4 hrs)


3.3.3.2 One-dimensional steady state conduction (U: 4 hrs)

3.3.3.3 **Multidimensional steady-state conduction (U: 4 hrs)**

**Contents** Analytical solution techniques. Conductive shape factor.

3.3.3.4 **Unsteady conduction (U: 6 hrs; G: 4 hrs)**


3.3.3.5 **Forced convection: laminar flow (U: 3 hrs; G: 2 hrs)**

**Contents** Thermal boundary layer: flat plate; Pohlhausen solution. Isothermal pipe flow. Heat transfer in pipe flow.

3.3.3.6 **Forced convection: equations of motion (U: 3 hrs; G: 2 hrs)**


3.3.3.7 **Natural convection (U: 3 hrs; G: 2 hrs)**

**Contents** Dimensionless groups: Grashoff, Prandtl and Nusselt numbers. Vertical flat plate. Empirical correlations: isothermal surfaces, free convection in enclosed spaces, mixed free and forced convection.

3.3.3.8 **Boiling and condensation (U: 3 hrs; G: 2 hrs)**


3.3.3.9 **Heat exchangers (U: 3 hrs; G: 2 hrs)**


3.3.3.10 **Radiation heat transfer (U: 6 hrs; G: 4 hrs)**

3.3.3.11 Isothermal mass transfer (U: 3 hrs; G: 2 hrs)


3.3.3.12 Simultaneous heat and mass transfer (U: 4 hrs; G: 2 hrs)


3.4 MODULE SOLID MECHANICS

3.4.1 INTRODUCTORY STATEMENT

The topics in this module are for undergraduate instruction only. They identify the subject matter of solid mechanics and provide a broad enough basis to develop an understanding of hydrogen safety problems. The particular texts used to select the material contained in this module are: Beer & Johnston (1981) [29], Beer & Johnston (1992) [30], Fitzgerald (1982) [31], Higdon, Ohlsen, Stiles, Weese & Riley (1985) [32], Mase (1970) [33], and Nash (1998) [34].

3.4.2 PREREQUISITE MATTER

Analysis, linear algebra, vector analysis, differential and integral calculus.

3.4.3 CONTENTS OF THE MODULE

3.4.3.1 Analysis of stress (U: 6 hrs)


3.4.3.2 Deformation and strain (U: 6 hrs)

3.4.3.3 Tension and compression (U: 6 hrs)

Contents Internal effects of forces (axially loaded bar, normal stress, normal strain, stress-strain curve, ductile and brittle materials, Hooke's law, modulus of elasticity). Mechanical properties of materials (proportional limit, elastic limit, elastic and plastic ranges, yield point, ultimate strength or tensile strength, breaking strength, modulus of resilience, modulus of toughness, percentage reduction in area, percentage elongation, working stress, strain hardening, yield strength, tangent modulus, coefficient of linear expansion, Poisson's ratio, general form of Hooke's law, specific strength, specific modulus). Dynamic effects. Elastic vs. plastic analysis.

3.4.3.4 Statically indeterminate force systems (U: 4 hrs)


3.4.3.5 Thin walled pressure vessels (U: 2 hrs)

Contents Nature of stresses. Limitations. Applications.

3.4.3.6 Direct shear stresses (U: 4 hrs)


3.4.3.7 Torsion (U: 4 hrs)


3.4.3.8 Shearing force and bending moment (U: 4 hrs)


3.4.3.9 Centroids, moments of inertia, and products of inertia of plane areas (U: 4 hrs)
3.4.3.10 Stresses in beams (U: 4 hrs)


3.4.3.11 Elastic deflection of beams: double integration method (U: 4 hrs)


3.4.3.12 Statically indeterminate elastic beams (U: 4 hrs)

Contents Statically determinate beams. Statically indeterminate beams. Types of statically indeterminate beams.

3.4.3.13 Special topics in elastic beam theory (U: 4 hrs)

Contents Shear center. Unsymmetric bending. Curved beams.

3.4.3.14 Plastic deformation of beams (U: 4 hrs)


3.4.3.15 Columns (U: 4 hrs)


3.4.3.16 Strain energy methods (U: 4 hrs)

3.4.3.17 Combined stresses (U: 4 hrs)


3.4.3.18 Members subject to combined loadings (U: 4 hrs)

Contents Axially loaded members subject to eccentric loads. Cylindrical shells subject to combined internal pressure and axial tension. Cylindrical shells subject to combined torsion and axial tension/compression. Circular shaft subject to combined axial tension and torsion, and combined bending and torsion.

4 Fundamental Modules

4.1 Module Introduction to Hydrogen as an Energy Carrier

4.1.1 Introductory Statement

This module may be used for instruction at the undergraduate and the graduate level. Its purpose is to provide a brief overview of the use of hydrogen as an energy carrier and safety issues connected to it. Appropriate references are cited along with the topics.

4.1.2 Prerequisite Matter

Undergraduate programme in Mechanical Engineering, Chemical Engineering or Applied Physics.

4.1.3 Contents of the Module

4.1.3.1 Hydrogen as an energy carrier (U: 2 hrs; G: 2 hrs)

Contents Overview of hydrogen programmes in Europe, USA, Japan and other countries. Environmental, societal and safety aspects of the hydrogen economy: reduction of greenhouse gases, renewable energy, sustainable energy supply, etc.

4.1.3.2 Introduction to hydrogen applications and case studies (U: 5 hrs; G: 5 hrs)

Contents Production: centralised and decentralised hydrogen production (hydrogen production via reforming, hydrogen production via electrolysis, hydrogen production via thermolysis, photo-electrolysis, biophotolysis and fermentation,
hydrogen as an industrial byproduct, plasma reforming, hydrogen liquefaction, hydrogen production via conversion, small-scale photo-electrolysis), Accidental hydrogen production. Storage and distribution: hydrogen transmission to stationary systems (pipelines, liquid supply and/or gaseous supply, stationary storage), hydrogen supply for transport systems (re-fuelling stations, on-board storage), hydrogen supply for portable systems (cylinders and cartridges, refilling and recycling centres), garages and repair workshops, etc.

Case studies.

4.1.3.3 Equipment for hydrogen applications (U: 5 hrs; G: 5 hrs)

Contents Main components of hydrogen equipment: compressor, gates, check valves, piping, pipelines, storage, liquefier/evaporator, fuel cells, internal combustion engines. Sensors for hydrogen detection. Equipment for passive and active mitigation, etc.

4.1.3.4 Possible accident scenarios (U: 2 hrs; G: 2 hrs)

Contents Accident scenarios in production, storage distribution, and utilisation. Case studies. Accident scenarios in the chemical process industries: gas to liquid conversion (methane to methanol), fertiliser production (ammonia process), chlorine production plants (hydrogen-chlorine hazard). Accident scenarios in the petrochemical industries. Accident scenarios in the power grid: transformer explosions, batteries, power turbines (coolant).

4.1.3.5 Definitions and overview of phenomena and methodologies related to hydrogen safety (U: 3 hrs; G: 3 hrs)


4.2 MODULE FUNDAMENTALS OF HYDROGEN SAFETY

4.2.1 INTRODUCTORY STATEMENT

This is a postgraduate module. Its purpose is to provide a basis for the knowledge framework covered by related fundamental modules (i.e. modules release, mixing and distribution; hydrogen ignition; hydrogen fires; explosions: deflagrations and detonations), and the applied modules (i.e. fire and explosion effects on people, structures, and the environment; accident prevention and mitigation; risk assessment; computational hydrogen safety engineering). Appropriate references are cited along with the topics. References covering a wide range of topics in combustion are: Barnard and Bradley (1985) [35], Drysdale (1999) [36], Glassman (1996) [37], Griffiths & Barnard (1995) [38], Kanury (1977) [39], Kuo (1986) [40], Lewis and von Elbe (1987) [41], Poinset & Veynante (2001) [42], Toong (1983) [43], Turs (2000) [44], Warnatz, Maas & Dibble (2005) [45] and Williams (1985) [46]. Other references are cited along with the topics.
4.2.2 PREREQUISITE MATTER

Modules on thermodynamics, fluid dynamics, heat and mass transfer, and solid mechanics, and knowledge of basic chemistry.

4.2.3 CONTENTS OF THE MODULE

4.2.3.1 Hydrogen properties (U: 10 hrs; G: 6 hrs)


4.2.3.2 Influence of hydrogen on equipment (U: 6 hrs; G: 6 hrs)


4.2.3.3 Hydrogen thermo-chemistry (G: 6 hrs)


4.2.3.4 Governing equations of multi-component reacting flows (G: 6 hrs)


4.2.3.5 Premixed flames (G: 6 hrs)


4.2.3.6 Diffusion flames (G: 6 hrs)


4.2.3.7 Partially premixed flames (G: 2 hr)

Contents Non-uniform mixtures: triple flames. Insight into diffusion flame stabilisation on the burner. Application of mixture fraction concept to non-uniform mixtures.
4.2.4 Turbulent premixed combustion (G: 6 hrs)


4.2.5 Turbulent non-premixed combustion (G: 6 hrs)


4.2.5.1 Ignition and burning of liquids and solids (G: 8 hrs)


4.2.5.2 Fire through porous media (G: 2 hrs)

4.3 MODULE RELEASE, MIXING AND DISTRIBUTION

4.3.1 INTRODUCTORY STATEMENT

This is a postgraduate module on release and mixing phenomena that are specific to the safe handling of hydrogen as an energy carrier. Its purpose is to provide the student with the technical background needed for the applied modules (i.e. fire and explosion effects on people, structures, and the environment; accident prevention and mitigation; risk assessment; computational hydrogen safety engineering). Appropriate references are cited along with the topics.

4.3.2 PREREQUISITE MATTER

Modules on thermodynamics, fluid dynamics, heat and mass transfer and solid mechanics.

4.3.3 CONTENTS OF THE MODULE

4.3.3.1 Fundamentals of hydrogen release and mixing (G: 4 hrs)


4.3.3.2 Handling hydrogen releases (G: 6 hrs)


4.4 MODULE HYDROGEN IGNITION

4.4.1 INTRODUCTORY STATEMENT

This is a postgraduate module. Its purpose is to provide the student with the technical background needed for the applied modules (fire and explosion effects on people,
structures, and the environment; accident prevention and mitigation; risk assessment; computational hydrogen safety engineering). Appropriate references are cited along with the topics.

4.4.2 PREREQUISITE MATTER

Modules on thermodynamics, fluid dynamics, heat and mass transfer, solid mechanics.

4.4.3 CONTENTS OF THE MODULE

4.4.3.1 Hydrogen ignition properties and ignition sources (G: 3 hrs)

Contents


4.4.3.2 Prevention of hydrogen ignition (G: 3 hrs)

Contents


4.5 MODULE HYDROGEN FIRES

4.5.1 INTRODUCTORY STATEMENT

This is a postgraduate module on fires and thermal effects arising from accidental combustion involving hydrogen. Its purpose is to provide the student with the technical background needed for the applied modules (fire and explosion effects on people, structures,
and the environment; accident prevention and mitigation; risk assessment; computational hydrogen safety engineering). Appropriate references are cited along with the topics.

4.5.2 PREREQUISITE MATTER
Modules on thermodynamics, fluid dynamics, heat and mass transfer and solid mechanics.

4.5.3 CONTENTS OF THE MODULE
4.5.3.1 Fundamentals of hydrogen fires (G: 4 hrs)

Contents

4.6 MODULE DEFLAGRATIONS AND DETONATIONS
4.6.1 INTRODUCTORY STATEMENT
This is a postgraduate module on explosion with an emphasis on hydrogen safety. Its purpose is to provide a basis for the module explosion effects, and the applied modules (accident prevention and mitigation, risk assessment, and computational hydrogen safety). Appropriate references are cited along with the topics.

4.6.2 PREREQUISITE MATTER
Modules on thermodynamics, fluid dynamics, heat and mass transfer and solid mechanics.

4.6.3 CONTENTS OF THE MODULE
4.6.3.1 Deflagrations (G: 6 hrs)

Contents

4.6.3.2 Detonation (G: 6 hrs)


4.6.3.3 Transitional hydrogen explosion phenomena (G: 6 hrs)


5 APPLIED MODULES

5.1 MODULE FIRE AND EXPLOSION EFFECTS ON PEOPLE, STRUCTURES AND THE ENVIRONMENT

5.1.1 INTRODUCTORY STATEMENT

This is a postgraduate module on fire and explosion effects of hydrogen. Appropriate references are cited along with the topics.
5.1.2 PREREQUISITE MATTER

The basic modules (thermodynamics, fluid dynamics, heat and mass transfer, solid mechanics) and the fundamental modules (introduction to hydrogen as an energy carrier, fundamentals of hydrogen safety, hydrogen release, mixing and distribution, hydrogen ignition, hydrogen fires, deflagrations and detonations).

5.1.3 CONTENTS OF THE MODULE

5.1.3.1 Thermal effects of hydrogen combustion (G: 4 hrs)


5.1.3.2 Blast waves (G: 4 hrs)


5.1.3.3 Calculation of pressure effects of explosions (G: 4 hrs)


5.1.3.4 Structural response, fragmentation and missile effects (G: 4 hrs)

5.1.3.5 Fracture mechanics (U: 4 hrs)


5.2 MODULE ACCIDENT PREVENTION AND MITIGATION

5.2.1 INTRODUCTORY STATEMENT

This is a postgraduate module on mitigation techniques relevant to the safe storage, distribution and handling of hydrogen.

5.2.2 PREREQUISITE MATTER

The basic modules (thermodynamics, fluid dynamics, heat and mass transfer, solid mechanics), the fundamental modules (introduction to hydrogen as an energy carrier; fundamentals of hydrogen safety; release, mixing and distribution; hydrogen ignition; hydrogen fires; deflagrations and detonations) and the applied module fire and explosion effects. This module may be taught simultaneously with the fundamental modules and the applied module on explosion effects on people, structures and the environment.

5.2.3 CONTENTS OF THE MODULE

5.2.3.1 Prevention, protection and mitigation (G: 4 hrs)

Contents Use of inherent safety features and controls. Hydrogen detection. Overpressure protection of storage vessels and piping systems, safety valves, odorisation. Passive mitigation systems: inherently safe design, mechanical reinforcement, stopping walls, compartmentalization, natural convection, catalytic recombiners, etc. Active mitigation systems: detection (sensors), combustion suppression, preventive ignition, pressurisation of safety zones, thermal recombiners, forced convection, etc. Case studies and analysis of experimental data on hydrogen mitigation techniques.
5.2.3.2 Basic phenomena underpinning mitigation technologies (G: 4 hrs)


5.2.3.3 Standards, regulations and good practices related to hydrogen safety (G: 4 hrs)


5.2.3.4 Inertisation (G: 4 hrs)

Contents Hydrogen removal: thermal recombiners; passive autocatalytic recombiners (effect of geometric and operational constraints, influence of convection, quantitative assessment of effectiveness with regard to hydrogen dilution to non-flammable or less sensitive mixtures); preventive ignition: igniters (glow plug igniters, spark igniters, catalytic igniters), the role of high quality flow simulation in optimizing the location of igniters (avoid DDT), hydrogen dilution (by steam, nitrogen, carbon dioxide): post-accident inertisation by injection of an inert gas (effect on limiting pressure buildup; preclusion of flame acceleration); regulations, codes and standards.

5.2.3.5 Containment (G: 4 hrs)

Contents Compartimentalisation, regulations, codes and standards.
5.2.3.6 Explosion venting (G: 4 hrs)


5.2.3.7 Flame arresters and detonation arresters (G: 4 hrs)

Contents  Applications of flame arresters and detonation arresters; principles of operation of flame arresters and detonation arresters; installation in process systems, maintenance, regulations, codes and standards. References: Korzhavin, Klimenko & Babkin (2004) [111].

5.3 MODULE COMPUTATIONAL HYDROGEN SAFETY ENGINEERING

5.3.1 INTRODUCTORY STATEMENT

This module concerns the computational modeling of hydrogen release, mixing, distribution and accidental combustion at different scenarios. It is a postgraduate module intended to provide a general understanding of the computational methods, tools and models applied to hydrogen safety engineering. The references used to compile this module include: Cox (1995) [112], Cox & Kumar (2002) [113], Ferziger & Peric (2002) [114], Patankar (1980) [115], Poinrot & Veynante (2001) [42], Pope (2000) [64], Roy, Frolov & Givi (1997) [116] and Warsi (1999) [117]. Specific references are given along with the topics.

5.3.2 PREREQUISITE MATTER

Calculus, the basic modules (thermodynamics, fluid dynamics, heat transfer), differential analysis, and partial differential equations.

5.3.3 CONTENTS OF THE MODULE

5.3.3.1 Introduction to CFD (G: 4 hrs)

5.3.3.2 Introduction to thermodynamic and kinetic modeling (G: 6 hrs)

Contents Basic numerical notions and methods for chemical thermodynamics and kinetics simulations: stiff ODE systems, polynomial representation of thermodynamic properties, detailed / skeletal / reduced kinetic scheme, mechanism, sensitivity analysis, kinetic model reduction (ILDM, CSP, etc.). Integrated software systems for kinetic and thermodynamic calculations (Chemkin library, Chemical WorkBench environment). The references used to compile these topics include: Chernyi (2003).

5.3.3.3 Mathematical models in fluid dynamics (G: 6 hrs)

Contents Conservation equations for mass, momentum, energy, species. Characteristic forms of conservation equations steady-state and transient conservation equations; compressible, weakly compressible, incompressible flows; inviscid flow; boundary layer approximation; corresponding mathematical classification (elliptic, hyperbolic, parabolic differential equations) and characteristic flow behaviour. Generic convection-diffusion transport equation for conserved scalar: transient, convection, diffusion and source terms.

5.3.3.4 Finite Difference Method (G: 6 hrs)


5.3.3.5 Solution of the generic transport equation (G: 6 hrs)


5.3.3.6 Solution of weakly compressible Navier-Stokes equations (G: 6 hrs)

Contents Navier-Stokes equations as generic transport equations: finite-difference analogue of the momentum equations, pressure field problem. Arrangement of
variables on the grid: staggered grid, collocated grid, representation of the pressure gradient term, representation of the mass conservation equation. SIMPLE-similar algorithms for pressure-velocity coupling (SIMPLE, SIMPLER, PISO): pressure and velocity corrections, pressure correction equation, implementation of the boundary conditions. Relative nature of pressure for incompressible and weakly compressible flows.

5.3.3.7 Solution of compressible Navier-Stokes equations (G: 6 hrs)

Contents Overview of methods for compressible flows, pressure-correction methods for arbitrary Mach number, pressure-velocity-density coupling, implementation of the boundary conditions, non-reflecting boundary condition.

5.3.3.8 Turbulent flow modeling (G: 6 hrs)


5.3.3.9 Combustion modeling (G: 6 hrs)

Contents Turbulent diffusion combustion: phenomenological description, interaction between flame and turbulence, combustion regimes, flame structure (jet and fire). Overview of models for 1 step irreversible, infinitely fast chemistry: mixture fraction concept, Burke-Schumann model, eddy-dissipation concept (EDC) for mean reaction rate. Models with finite rate chemistry: flamelet and PDF models. Premixed combustion: laminar, quasi-laminar, turbulent combustion, flame wrinkling, premixed combustion diagram; models based on the turbulent burning velocity correlations, gradient method, eddy-break-up model (EBU), Bray-Moss-Libby model (BML), flame surface density models, interplay between the models. Overview of approaches to non-uniform mixture combustion. References: Veynante & Vervisch (2002) [119].
5.3.3.10 Multiphase flows (G: 6 hrs)


5.3.3.11 Special topics (G: 6 hrs)


5.4 MODULE RISK ASSESSMENT

5.4.1 INTRODUCTORY STATEMENT

This is a postgraduate module on risk assessment in Hydrogen Safety Engineering. Its structure is derived from the document Guidance for Safety Aspects of Proposed Hydrogen Projects by the US Department of Energy (2004) [123].

5.4.2 PREREQUISITE MATTER

The basic modules (thermodynamics, fluid dynamics, heat and mass transfer, solid mechanics), the fundamental modules (introduction to hydrogen as an energy carrier; fundamentals of hydrogen safety; release, mixing and distribution; hydrogen ignition; hydrogen fires; deflagrations and detonations) and the applied modules fire and explosion effects on people, structures, and the environment, and, accident prevention and mitigation. This module may be taught simultaneously with the fundamental modules and the applied modules. General background on the nature of explosion and fire hazards and the methodology of Risk Assessment can be obtained from the standard work by Lees (1996) [124, 125, 126]. More information on hydrogen specific hazards will be extracted from the International Conference on Hydrogen Safety in Pisa, Italy (8-10 September 2005), organised by M. Carcassi.

5.4.3 CONTENTS OF THE MODULE

5.4.3.1 Effect analysis of hydrogen accidents (G: 6 hrs)

Contents Effect on people and tolerance limits: jet impact from high-momentum releases, damage by low temperature releases, asphyxiation by hydrogen, thermal effects from fires, pressure effects from explosions [124, 125, 126], materials for hydrogen services [127]. Environmental effects of hydrogen accidents. References: Lees (1996) [124, 125, 126] and Perry & Green (1997) [127].
5.4.3.2 Risk assessment methodologies (G: 6 hrs)


5.4.3.3 Hazard identification and scenario development (G: 4 hrs)


5.4.3.4 Vulnerability analysis (G: 4 hrs)


5.4.3.5 Application of hazard identification in the basic processes of the hydrogen economy (G: 5 hrs)

Contents Application of hazard identification techniques and layers of protection analysis to production, storage and distribution installations in a selection of the detailed topical content given under Introduction to hydrogen applications of module Introduction to hydrogen as an energy carrier. Case studies and European hydrogen incident/accident database.

5.4.3.6 Application of vulnerability analysis to mitigation technologies in the hydrogen economy (G: 5 hrs)
6 CONCLUSIONS

Despite the growing hydrogen economy and the consequential demand for knowledge and codes in the field of hydrogen 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 a first step in overcoming this deficiency. 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 (http://www.hysafe.org) and further development of the curriculum will mainly consist of further enrichment of these modules.

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 (see deliverable D17). 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 (http://www.cordis.lu/mariecurie-actions/scf/home.html) will be used and efforts are underway to create a European Summer School on Hydrogen Safety.
BIBLIOGRAPHY


45


