H₂FC e-newsletter

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Progress in Hydrogen and Fuel Cell Technologies

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Thomas Jordan

Dear Colleagues,

"Hydrogen? Isn't this stuff related to hydrogen peroxide and used for dyeing hair blond? But why is it in this bus? And how do you dispose these fuel cells? Isn't there nuclear fuel inside?". These have been questions of two staff members of the Karlsruhe Institute of Technology (KIT) administration during a regular ride on one of the fuel cell bus shuttles of KIT. They addressed these questions to an EvoBus technician running some performance tests of the on board hydrogen system.

To make hydrogen a reality a demand has to be generated. To generate a demand hydrogen applications have to be most cost competitive and accepted as a safe and ecological solution. Although the two staff members may not be representative of the whole population in a statistical sense, the communication does indicate a definite demand for consistent objective information about hydrogen technologies and their potential impact on society.

As soon as the technician explained to the two staff members what hydrogen can do, immediately the next level of questions popped up: "Is this safe?, And when everybody will have this at home?". How could this technician or even us, the H2FC expert community, answer these reasonable questions? We could claim that with a corresponding price tag we can reduce risks to a level, as low as reasonably possible. However, the term "safe" implies how these technologies and associated risks are perceived. A clever work-around avoiding the intricate issue about "risk" and "safety" and a possibly convincing answer is: "we make sure, it is as safe as any other technology". If H2FC helps to fulfil this promise, still the issue remains about associated costs, which finally determines whether a

broad introduction happens or not. The public nor any commercial interest and not any commercial player is willing to accept a considerable higher total cost of ownership for any product providing mobility or fulfilling other energy demands. Even if the research community supported by H2FC provided safe solutions at low costs the energy market is controlled by complex political boundary conditions. Suitable taxation policies and other incentives have proven to help the introduction of new innovative technologies in the renewable energy market.

In conclusion, the research community may prepare the grounds for the broad introduction of cost efficient, reliable and safe hydrogen solutions, accompanied by a broad educational framework. This is what H2FC facilitates. However, the actual launch of hydrogen technologies needs consistent political support and appropriate financial incentives for attracting industries and scaling up of all involved processes. Only with a corresponding commitment at the decisive political level will a commercial hydrogen energy industry initiate and thrive.

Yours sincerely,
Thomas Jordan, co-editor, on behalf of the Editorial Board

Hydrogen damage on steel alloys

Hydrogen does not have a neutral behaviour when it comes into contact with materials. Already at the end of the 19th century, W.H. Johnson reported ˝some remarkable changes produced in iron by the action of hydrogen and acids˝ [1]. The main effect of the action of the hydrogen on the metallic materials is usually an observation of the degradation of the mechanical properties. The aim of this paper is to classify and present the main different degradation mechanisms with respect to different materials and environmental conditions. The mechanisms which are brought about by the presence of hydrogen are grouped and called „hydrogen damage˝ and are summarised in figure 1.

Providing an analysis and explanation of all of the „hydrogen damage˝ mechanisms is not possible in a single article. Thus, this paper will be mainly focused on the main form of hydrogen damage on steel alloys, as steel alloys are materials that still have a very interesting ratio of price / efficiency. Some of the mechanisms displayed in Figure 1, are not relevant for steel alloys, obviously the mechanisms of hydride embrittlement, or (less obvious) the mechanisms of solid solution hardening that concerns mainly niobium and tantalum. Among the hydrogen damage mechanisms relevant for steel alloys, there is the creation of internal defects, and the family of mechanisms leading to hydrogen embrittlement.

One of the difficulties concerning the understanding of hydrogen damage is how to categorise the degradation. Indeed historically, the type of degradation was called according the aspect of the damage (e.g.: blistering, stepwise cracking, hydrogen induced cracking), or the presence of a particular element in the environment (e.g.: sulphide stress cracking).

Then it was shown later that different types of damage were driven by the same or very similar mechanisms [2].

In one of the mechanisms, the hydrogen attack happens only in high temperature (e.g.: 500-600ºC for a quenched and tempered 2.25Cr-1Mo steel) with high pressure of hydrogen while the others happen at ambient temperature. During the hydrogen attack, hydrogen is diffusing inside steel. As steel based alloys are at least composed of iron and carbon, hydrogen can react with the carbon to form methane which is insoluble in the metal. If this reaction takes place close to the surface, the methane can diffuse and there is a methane release. If it happens in the bulk, this phenomenon lleads to a de-carburation of the cementite (iron carbide) which leads to a loss of mechanical properties and an accumulation of

methane in micro-pores leading to initiation of cracks (see figure 2). Carbon steel alloys are typically sensitive to this kind of hydrogen damage [3,4].

The hydrogen damage occuring at ambient temperature can be sorted into two groups: ˝internal hydrogen˝ and ˝external hydrogen˝. These groups are not exclusive and in some condition it can be observed simultaneously degradation from ˝internal˝ and ˝external˝ hydrogen. The ˝internal˝ hydrogen is already present in the material and was loaded during the fabrication steps such as roll forming, machining and drilling (lubricant effect), welding or brazing or the surface treatment (e.g.: carbonizing, cleaning, pickling, phosphating, electroplating). In some case, some thermal (or other), treatment can be done to remove this hydrogen. ➔
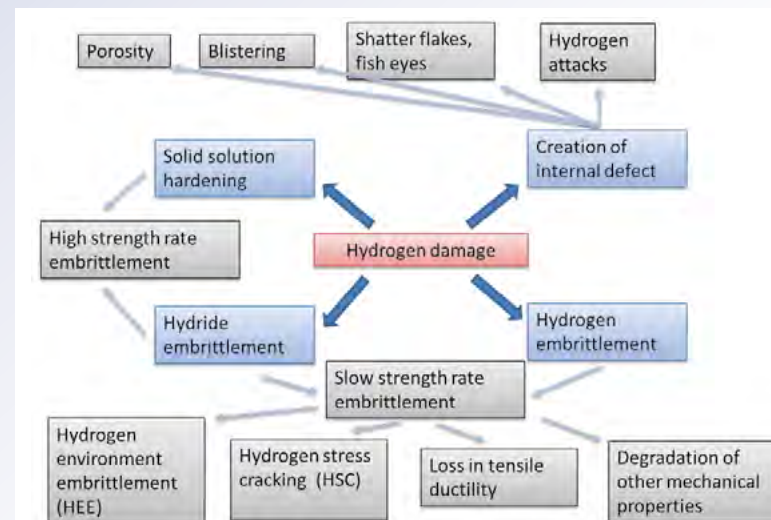

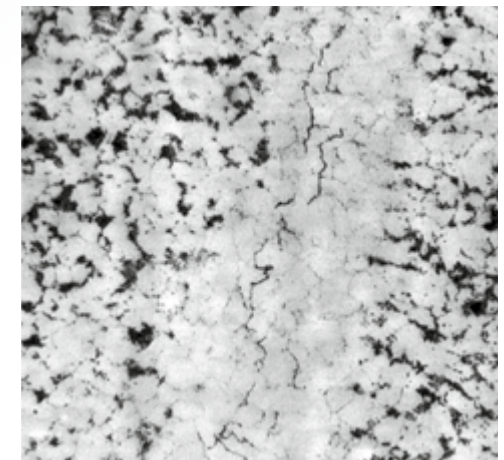*Figure 1. The different forms pf hydrogen damages.*

Figure 2. Initiation of Cracks due to formation of methane in the micro-voids.

→ The ˝external˝ hydrogen is a hydrogen load that takes place during the use of the material. It may happen to off-shore structures under cathodic protection (reduction of water and hydrogen evolution), in acidic environments (corrosion and hydrogen evolution) and be catalysed by compounds such as hydrogen sulphide or cyanides.

Various mechanisms such as hydrogen induced cracking (HIC), stress oriented hydrogen induced cracking (SOHIC) and stepwise cracking (SWC) are related to the ˝internal hydrogen˝. These phenomena can be also referred as porosity, blistering, hydrogen induced blistering. They have in common a similar requirement such as the presence of porosity or micro-void and of a hydrogen load. It is important in some cases that the material, the material remains ductile despite the presence of hydrogen. Here, hydrogen (probably in the form of a proton with a delocalized electron in the metallic conduction band) diffuses in the material up finding porosity or micro-void where the recombination in H2 is possible, accumulates in the defects up to the mechanical failure which leads to the formation of blister or cracks (see figure 3). HIC and SWC are not affected by the presence or absence of mechanical external load. If the cracks are oriented by the external load, the term SOHIC is usually used and cracks have a stepladder shape (see figure 4). Ferritic steels alloys (e.g.: 8Cr-2Mo, 26Cr-1Mo, 29Cr-4Mo, 29Cr-4Mo-2Ni) are particularly sensitive to this form of damage [5].

The degradation mechanisms related to the ˝external˝ hydrogen are usually referred as sulphide stress cracking (SSC) or hydrogen stress cracking (HSC). This type of damage happens in presence of a hydrogen load environment and when the material is under mechanical solicitation. Here also, the hydrogen is diffusing in the material in the form of proton and delocalized electron. The insertions of the protons in the crystallographic network generate local stresses. These stresses, added to the mechanical solicitation of the material, may lead to the formation and the progression of cracks starting from the surface of the material and perpendicular to main stress axis up to the failure of the material (see figure 5). From a macroscopic point of view, the material seems to have a brittle behaviour (loss of ductility) below the elastic limit measured without hydrogen load. High performance alloys, with yield tensile stress around and above 1000MPa, are usually more sensitive to this kind of hydrogen damage, and it is important to notice that the mechanical properties of the material may be recovered if the hydrogen load is stopped in time.

To conclude, this article presented a breif summary of the main machanisms of hydrogen damage on steel alloy. The choice of the proper material, depending on the environmental condition, is very important to avoid the kind of degradation that can lead to critical failure.

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Jean-Baptiste JORCIN*, *Tecnalia, Spain,
jbaptiste.jorcin@tecnalia.com

Figure 3. HIC cracks.

Figure 4. SOHIC cracks (stepladder shape).

Figure 5. SSC cracks.

Hydrogen inventory limit for closed buildings

Motivation

The pressure peaking phenomenon (PPP) was discovered in 2013 by researchers at Ulster by carrying out analytical and numerical studies [1]. However, experimental evidence was missing until recently. PPP takes place when a gas is being released into an enclosure with vent(s). Usually one would expect that in such situation a pressure within the enclosure would grow monotonically from an initial pressure to a steady-state pressure somewhat above the initial one. Generally, this steady-state pressure depends on the flow rate of gas, volume and vent size of the enclosure. In the case of hydrogen the pressure dynamics is "strange" – a transient process of pressure change from the initial to the steady-state is not monotonous and undergoes the peak. It is a unique phenomenon that is characteristic only for hydrogen compared to other fuels. In fact, it can be observed to different extent for other gases lighter than air, e.g. helium.

Thermodynamic model of localised deflagration in closed space

A thermodynamic model was developed to predict a maximum mass of hydrogen, which can be released in an enclosure without a risk of exceeding a specified overpressure threashold of 10 kPa in the case of its combustion. A conceptual calculation scheme of localized mixture in a sealed, unventilated enclosure is given in Figure 1. The model presumes that an enclosure at initial pressure, p_0, is partially filled with air, volume fraction of air is x_a, and partially – with unburnt hydrogen-air mixture, volume fraction is x_u. The model is built on the analysis of state parameters in a two-step thermodynamic process: 1) combustion of the localised hydrogen-air

mixture in a constant volume, leading to pressure rise in the volume occupied by the localized mixture, and 2) expansion of the high-pressure burnt mixture and compression of the air volume, reaching a final uniform overpressure across the whole enclosure. State parameters and mixture properties in a partcular thermodynamic state are given under each state scheme.
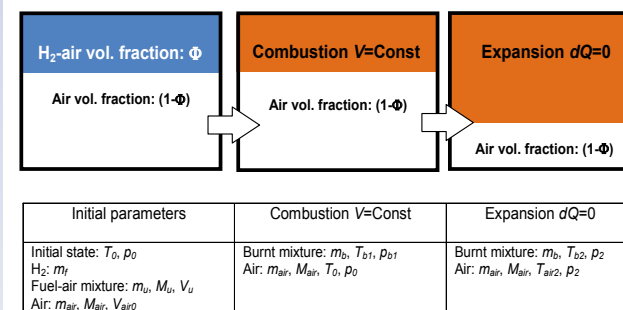

Figure 1. Conceptual calculation scheme for thermoodynamic model of localised mixture deflagration in a closed vessel.

It can be shown that the solution for the final absolute pressure p_2 in the closed vessel is given by the following equation:

$$p_2 = x_u p_{b1} \left(\frac{p_2}{p_{b1}} \right)^{\frac{\gamma_b-1}{\gamma_b}} + x_a p_0 \left(\frac{p_2}{p_0} \right)^{\frac{\gamma_a-1}{\gamma_a}} \qquad (1)$$

where pb_1 is the absolute pressure for combustion of unburnt hydrogen-air mixture in a constant volume (as though it occupied the same fraction of the enclosure x_u as before combustion). The given above model was validated against experimental data by Stamps et al. (2006), who conducted ex

periments on combustion of localized hydrogen-air mixtures, and provided a good agreement.

Hydrogen inventory limit

The transcendental equation (1) was solved for overpressure in a sealed enclosure equal (p_2-p_0)=10kPa, which corresponds to the typical threshold overpressure causing structural damage to low-strength civil structures and buildings. The range of studied hydrogen vol. fractions was 4-20%. Resulting solution is shown in Table 1. The table presents hydrogen volume fraction in unburnt mixture x_{uH2}, volume fraction of the unburnt mixture in the entire enclosure x_u, and "overall" or averaged volume fraction of hydrogen in the entire enclosure $x_{H2} = x_{uH2} \cdot x_u$, which is a simple and convenient measure of hydrogen allowable to be "safely" released in the enclosure. The minimum safely released hydrogen averaged concentration throughout the enclosure is x_{H2} by volume (see Table 1, hydrogen fraction 3.14×10^{-3})! This is by more than an order of magnitude below the lower flammability limit of 4% by volume.

x_{uH2}	x_u	$x_{H2} = x_{uH2} \cdot x_u$
0.04	0.0786	$3.14 \cdot 10^{-3}$
0.08	0.0474	$3.79 \cdot 10^{-3}$
0.12	0.0355	$4.26 \cdot 10^{-3}$
0.16	0.0293	$4.69 \cdot 10^{-3}$
0.20	0.0253	$5.06 \cdot 10^{-3}$

Table 1. Solution of equation (1) for (p_2-p_0)=10kPa.

→

➔ The maximum hydrogen inventory that would allow non-destructive deflagration in the enclosure may be calculated based on the conservative values of overall hydrogen fraction in enclosure $3.14 \cdot 10^{-3}$. Table 2 gives hydrogen inventory limit (both as volume and mass) for different enclosure volumes.

Enclosure volume, m^3	1	10	100	1,000	10,000	100,000	1,000,000
Hydrogen volume, m^3	0.00314	0.0314	0.314	3.14	31.4	314	3140
Hydrogen mass, kg	$2.61 \cdot 10^{-4}$	$2.61 \cdot 10^{-3}$	$2.61 \cdot 10^{-2}$	0.261	2.61	26.1	261.0

Table 2. Hydrogen inventory limit for enclosures of different volume.

Hydrogen mass inventory limit (corresponding to hydrogen concentration x_{H2} = 0,314% by volume) can be approximated by a linear equation:

$$m_{H2} = 2.61 \times 10^{-4} V, \qquad (2)$$

where m_{H2} is the mass of hydrogen (kg), V is the enclosure volume (m^3).

Concluding remark

It is worth noting that the obtained hydrogen inventory limit corresponds to hydrogen concentration x_{H2} = 0,314% by volume averaged across the entire enclosure, and this is significantly lower and more strict safety requirement than the same but based on the value of lower flammability limit of 4% by volume, which is "typically" expected to be a safe solution.

These research results were obtained within FCH JU project "Hyindoor" ("Pre-normative research on safe indoor use of fuel cells and hydrogen systems", grant agreement No. 278534) and were reported in "HyIndoor" public Deliverable

5.1 "Widely accepted guideline on Fuel Cell indoor installation and use" (**http://www.hyindoor.eu/?page_id=372**). Hydrogen inventory limitation using the solution results in Table 2 and equation (2) is one of the HyIndoor project results recommended for inclusion into RCS.

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Dmitriy MAKAROV*, Vladimir MOLKOV
* HySAFER centre, Ulster University, UK,
dv.makarov@ulster.ac.uk

Multi-diagnostics with differential fuel cells: Bridging the gap between laboratory and application

Polymer electrolyte fuel cells (PEFC) are efficient energy converters with the potential of replacing internal combustion engine in automotive applications. Although the technology has reached a pre-commercial state, a good market penetration will rely on affordable fuel cells. To reach this goal, an optimization of the produced power per unit of cell area is of utmost importance, as the cost of a fuel cell system is highly dependent on its total area. Thus, a better understanding of the performance limiting processes, in particular in relation with the water management in the fuel cell, is a key requisite for a successful development of the fuel cell technology.

Why differential cells?

One of the common reactions when seeing results obtained from small 1 cm^2 fuel cells is "is this representative of a real fuel cell"? As a matter of fact, this question is legitimate not only for small scale cells, but for the majority of fuel cell experiments reported in the literature. Classically, experiments are performed on laboratory cells with an area of a few tens of cm^2, in contrast to the several hundreds of cm^2 used for real automotive cells. The downscaling from real technical cells to laboratory scale cells is not straightforward in terms of fluid dynamics: if the typical parallel channels design is kept, it results in short channels and unnaturaly low gas velocities, making water clogging in channels much more likely; as an alternative, laboratory cells with serpentine flow fields have higher gas velocities but suffer from gas bypass between adjacent channels and water accumulations in the U-turn sections. In summary, laboratory cells are well suited to analyse fuel cell materials (e.g. membranes and catalysts), yet without guarantee about the representativity of fluid dynamics and water management. In this context, the *differential*

cells can play an important role. These cells are characterized by short channel lengths and operation at high *stoichiometric ratios* (the ratio between the gas flow fed to the cell and the gas flow necessary for the reaction). This result in gas velocities similar to those of real technical cells – the differential cell can be seen as a small "cut" from a large cell without inhomogeneities along the channels. Their role is to answer the following question: for given local conditions (temperature, humidity and composition of the gas stream), what are the local performance limitations? Such a question is virtually impossible to answer from the direct study of a technical cell, even if one has access to local parameters such as the distribution of current density. The use of differential cells also permits the application of much more sophisticated analysis methods as detailed below. Finally, differential cells have a strong, yet largely unexplored potential for modeling validation, as they are suited for comparison with local 2D models.

Multi-diagnostics: Neutron imaging, impedance spectroscopy, and more …

Neutron imaging is a very powerful method for the *in situ* measurement of water distribution in operating fuel cells, because of its high contrast for liquid water and of the good transparency of usual fuel cell construction materials (e.g. aluminum, steel, graphite, fluoropolymer sealings). However, a detailed understanding of the local peformance limiting processed is obtained only when combining imaging with advanced electrochemical analysis methods. A classical analysis method is *electrochemical impedance spectroscopy* (EIS) – the analysis of the voltage response to small sinusoidal current excitations. This allows to extract the membrane ohmic

resistance and indicators of mass transport losses. A method recently developed at PSI [1] called *pulsed gas analysis* (PGA) allows for getting more precise informations about mass transport losses. It consists in operating the cell during short periods of 1-2 seconds with different gases such as helox (oxygen diluted in helium) or pure oxygen. By applying short gas pulses, one avoids the measurement biases (cell dry out, oxidation of the catalyst) related to a permanent operation with helox or oxygen. A recent study at PSI [2] comparing these methods (EIS and PGA) did show that both can detect the apparition of mass transport losses, but that only PGA provides a quantitative estimation of these losses. In addition, it offers the advantage of distinguishing between different sources of mass transport losses (such as bulk or Knudsen diffusion). The combination of these three methods (imaging, EIS and PGA) can be performed on the testbench available at PSI. Moreover, the test set-up (see Figure 1) can apply this methods simultaneously on six operating differential cells [3]. Additionally, with the support of the H2FC project, the quantification of liquid water was improved by developing a simple calibration method called *double dead-end calibration* (DDEC) [4].
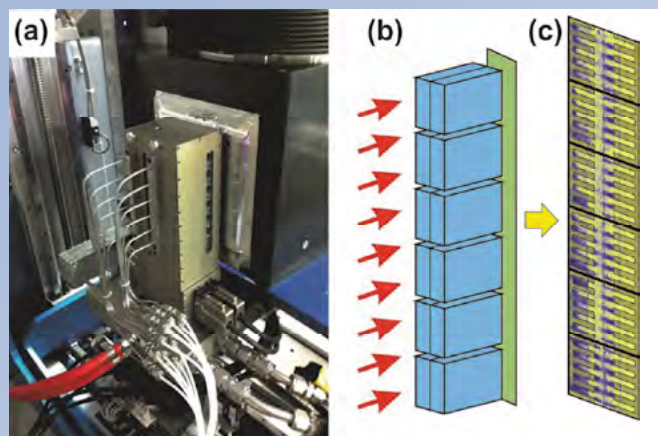
Figure 1. The PSI multi-cell setup for simultaneous neutron imaging and operation of six differential cells. (a) Photography of the setup mounted in the ICON beam line. (b) Scheme of the imaging configuration. (c) Example of measured water distribution.

→ Towards the link to larger cells

While differential cells produce knowledge that is relevant for the behavior of large scale cells on the local scale, fuel cell modeling has a high potential for linking this knowledge quantitatively. Indeed, the data obtained on differential cells can constitute an experimental database for the validation of local 2D fuel cell models that can be used as building blocks 3D models of larger cells – with a possible further validation step on larger systems. First data for a high quality experimental database – including neutron imaging, EIS and PGA measurements on a variety of operating conditions – has been recently collected using the PSI multi-cell setup and will be available soon through the H2FC Cyber Laboratory. In parallel, several initiatives are being conducted to combine experimental and modeling studies on differential cells.

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Pierre BOILLAT*, Pierre OBERHOLZER, Johannes BIESDORF Paul Scherrer Institute (PSI), Switzerland, **pierre.boillat@psi.ch**

Water inside an operating fuel cell

PEMFC and water

Fuel cells are one of the key 'green-energy' technologies currently being developed as an alternative to burning fossil fuels. They convert chemical energy, derived from the oxidation of a fuel such as hydrogen into electricity and heat. The proton exchange membrane fuel cell (PEMFC) is one such electrochemical device, and is an ideal power source for electric vehicles, because its components are relatively light, it is fast-starting at room temperature, and has a high power-density.

The PEMFC is a complicated layered system. It converts hydrogen and oxygen to water using catalytic electrodes separated by a polymer-membrane electrolyte. Oxygen (air) is fed to the cathode, while hydrogen is fed to the anode, where it splits into positive hydrogen ions (protons) and negative electrons. The protons selectively pass through the polymer membrane to the cathode, whereas the electrons must travel to the cathode through an external circuit, thus generating the power. Bipolar plates are used to supply the gases (in channels) and to collect the current (under ribs). The protons and electrons then react with the oxygen at the cathode to form water.

Increasing the PEMFC's performance and longevity, as well as reducing its cost, are still crucial issues to address for the large-scale application of fuel cells, and require a deep understanding of the system's components and behaviour. One of the main issues affecting the power output, stability, and lifetime is the amount and distribution of water within the cell. The water distribution on the active areas should be as homogeneous as possible. Moreover, a critical problem for operation is maintaining the dynamic balance of water within the membrane, so as to maintain the right level of hydration while avoiding drying or flooding the electrodes.

Measuring water content

The distribution of water varies considerably both within and across the various layers of the fuel cell (Fig. 1). Locally, the in-plane and through-plane hydration mostly depends on two factors. First, the cell design, in particular the gas distribution channels design and the choice of a specific membrane-electrode assembly. Secondly, the operating conditions, such as the current density, the hydration/flow of the inlet gases, temperature and pressure.

Recently, a very effective methodology was developed to diagnose how water content is partitioned across the different components of a working cell. Small angle X-Ray (SAXS) and Neutron (SANS) scattering, when used on a specially constructed state-of-the-art, transparent fuel cell, have proved to be highly complementary sensitive probes. We found, thanks to the improvements conducted in the H2FC project, that the unique non-intrusivity of neutrons and the high power of X-Ray synchrotron radiation could be coupled to measure simultaneously the variation in water content in both vertical and horizontal planes throughout a cell[1,2,3].

We now have carried out several SANS and SAXS experiments to systematically screen the impact of operating conditions on local water distribution. We varied the membrane thickness (20 to 200 microns), gas composition, temperature (-10 to 80 °C), current density (up to 0.8 A.cm^{-2}), pressure (up to 3
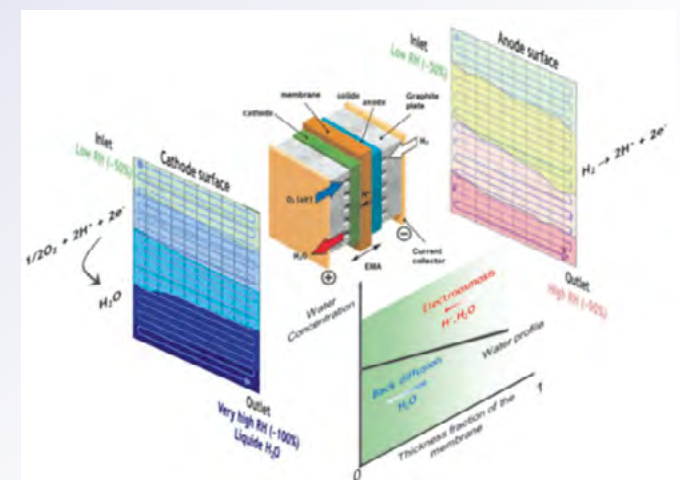
Figure 1. Schematic representation of the 3D water repartition in a PEMFC single cell. Water is heterogeneously distributed in-plane (at the surface of anode/cathode) and through-plane (across membrane thickness).

bars), relative humidity of the fed gases (from 0 to 100%) and investigated transient regimes during on/off cycles (Fig. 2). We were able to record a series of 3D water-distribution maps with unprecedented spatial and temporal resolutions. After developing a specific method to analyse the in-operando data, we could very precisely correlate the water content and distribution to both operating conditions and cell design. These data form a unique set of information to feed advanced cell modeling and optimize the system. →

Figure 2. 25 cm² single cells developed at CEA for the study of water repartition during PEMFC Figure 2. 25 cm² single cells developed at CEA for the study of water repartition during PEMFC operation by (left) SANS on D22 beamline at Institut Laue Langevin (ILL) (Picture of the single cell at -10°C inserted), (right) SAXS on ID02 beamline of European Radiation Synchrotron Radiation Facility (ESRF). operation by (left) SANS on D22 beamline at Institut Laue Langevin (ILL) (Picture of the single cell at -10°C inserted), (right) SAXS on ID02 beamline of European Radiation Synchrotron Radiation Facility (ESRF).

→   Especially, we demonstrated recently for the first time that the local water content in the membrane is not directly correlated to the water content in the surrounding channel. Liquid water can be present in the channel whereas the membrane is not fully hydrated because of the thermal management leading to a higher temperature in the heart of the fuel cell (Fig. 3).

The H2FC project offers the opportunity to open to the PEMFC community this unique facility which provides invaluable and unique information that can be used to optimise the design of the next-generation of high-performance fuel cells.
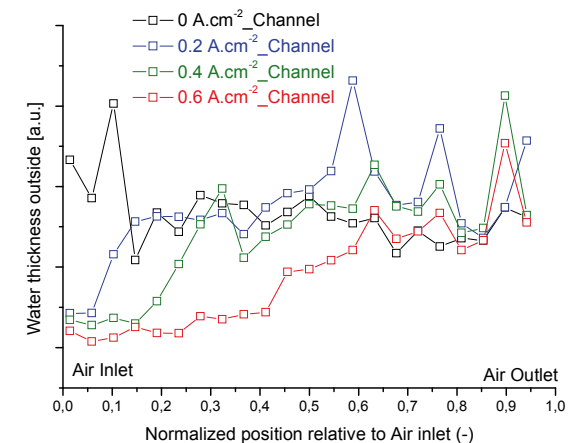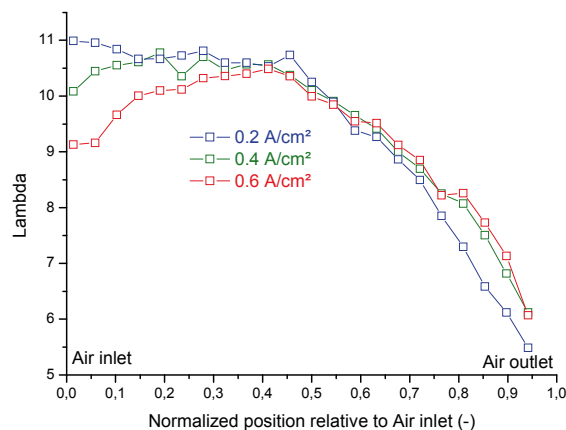
Figure 3. (left) Water content in the membrane in average number of water molecules per sulfonic acid group and (right) water amount outside the membrane, along the flow field in the channel, for different current densities. 80°C H2/Air 1.7bars 40/60%HR st.1.2/2_Counter-flow configuration with Air inlet at the bottom.

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Arnaud MORIN*, Gérard GEBEL, Sandrine LYONNARD
*CEA, Grenoble, FRANCE, +**arnaud.morin@cea.fr**

Advanced analyses of a solid oxide fuel cell operated with biosyngas

Introduction

In line with our article in the first edition of the H2FC News-letter, ENEA has carried out an in-depth investigation of the performance of a high temperature fuel cell (a solid oxide fuel cell (SOFC) supplied by project partner Forschungszentrum Jülich) fed with a range of syngas compositions simulating oxygen-blown gasification of biomass. The SOFC is suited to the biomass- or waste to energy chain due to its capacity to convert carbon-based fuel, with the added benefit of the generated power being renewable and the valorisation of a refuse product.

According to the scientific investigations conducted in the ENEA High temperature fuel cells Operating and Testing Laboratory, converting the biosyngas (characterized by low energy content) in the SOFC gave encouraging results in terms of performance and robustness.

Testing facilities employed

Integration of scientific equipment has been the key to achie-ving a comprehensive assessment of the application, which has also yielded very satisfactory results, proving the compa-tibility of bio-syngas with SOFC techonolgy.

For instance, electrochemical impedance spectroscopy (EIS) showed the evolution of electrochemical processes inside the biosyngas-powered SOFC. X-ray Diffraction (XRD) analysis and Raman spectroscopy provided information about anode-side phase stability, carbon deposition and carbide presence, whereas Scanning Electron Microscopy (SEM) visualized sam-ple morphology transformations at the end of the test coupled with Energy Dispersive X-ray Spectrometry (EDX) for analysis of the elements.

The experiment

Based on a real composition from a gasification plant, a 1000-hour test with simulated biosyngas was carried out on a single SOFC under load. The aim of the test was to check the effects of poisoning and degradation induced by the bio-syngas on the cell, in particular monitoring carbon deposi-tion. The four compositions showed in Table 1 represent the biosyngas composition resulting from gasification with de-creasing oxygen enrichments, from pure oxygen gasification (composition A) down to regular air gasification (composition D, with the highest nitrogen content). The compositions were supplied from experimental facilities operated by the Univer-sity of Rome "La Sapienza".

The single cell was a 10x10 cm^2 cell composed of Ni-YSZ/YSZ/YDC/LSCF (anode/electrolyte/barrier layer/cathode).

Composition	H_2 %mol	H_2O %mol	N_2 %mol	CO %mol	CO_2 %mol	CH_4 %mol
Ref_Hum	80	20	0	0	0	0
A	37	17	1	22	21	2
B	35	17	4	22	20	2
C	33	16	11	20	19	2
D	25	12	34	15	14	1

Table 1. Syngas compositions considered.

The cell performance is marked out by the polarisation (cur-rent-voltage) curve and impedence spectroscopy (frequency response of the cell). The performances of the SOFC fed with hydrogen and with bio-syngas are plotted in the polarisation curve of figure 1. There are no significant differences between the single hydrogen fuel cell performance and the other four

biosyngas compositions, though a clear trend is observed of decreasing performance with increasing nitrogen dilution of the biosyngas.
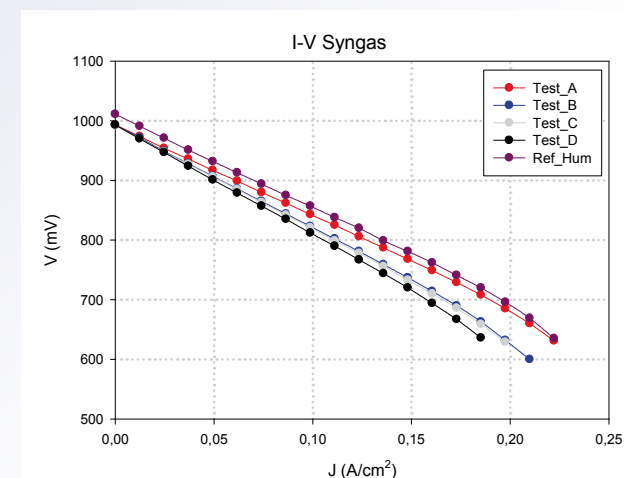
Figure 1. Syngas and Reference polarisation curves.

According to the graph in figure 1, composition C is consi-dered the best trade-off between performance and fluidizing agent costs. Given these premises, the long-term test was started. The cell was kept at a constant current load of 10 A and the corresponding cell voltage monitored (figure 2). Every 250 hours it was disconnected from the power load to carry out the I-V curve measurements (figure 3), after which an impedance spectrogram was taken (figure 4). →
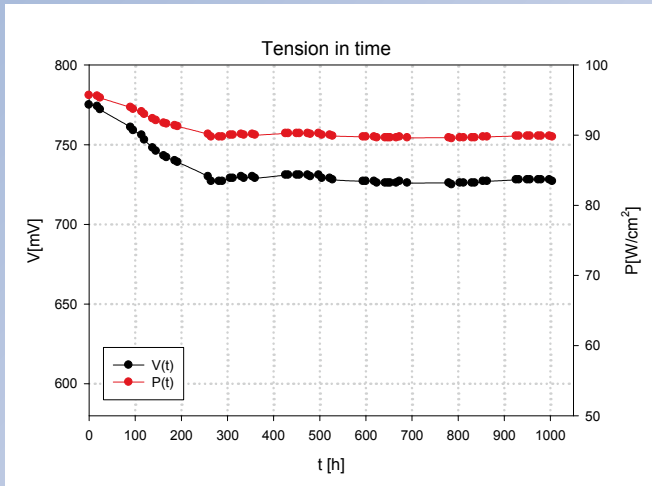
Figure 2. Single cell voltage at 10 A current during the 1000 hours test.

Figure 3. Polarisation curves during the 1000 hours test.

Figure 4. EIS spectra during the 1000 hours test.

→ The results in figures 2 and 3 point out a sharp perfor-mance decrease in the first 250 hours. After this stabilization however, the cell is remarkably constant in performance showing next-to-zero degradation.

To understand the reasons behind this behaviour, electroche-mical impedance spectroscopy is a powerful tool. Analysis of the EIS spectra allows us to hypothesize which electroche-mical processes lead to the decline in cell performance. The spectra of figure 4 represent the imaginary and real compon-ents of the cell resistance derived from the current response to sinusoidal perturbation of the cell voltage (10 mV amplitu-de) around open circuit conditions for a high-to-low frequency sweep. The crucial points on these curves are the intersects

with the real axis: the left intersect (at high frequencies) represents the pure ohmic resistance, induced predominantly by the ion-conducting electrolyte; the distance between this and the right intersect (at low frequencies) represents the resistance due to so-called polarization losses, i.e. losses induced by the sluggishness of the reactions and gas diffusion limitations. Plotting these two components of the overall cell resistance (figure 5, R_int being the ohmic part and R_pol the polarization part), it appears that the cell stabilization is af-fected only by the chemical processes, which could be due to a morphological settlement of the cell electrodes rather than a change in conductivity of the electrolyte or cell assembly.

→

Figure 5. Ohmic and Polarisation resistences of the single cell over time.

→ **Post-test material analysis**

To confirm that the initial degradation effect is not caused by carbon deposition from the carbon-rich biosyngas (perhaps obstructing the gas passages or deactivating reaction sites in the anode), material analysis was carried out after the 1000-hour test. Both X-Ray Diffraction (XRD) and Raman spectroscopy allow to univocally identify the compound and crystallographic phase present on a solid surface at very high resolution, with few complementary aspects. Both techniques were adopted to verify the presence of alien compounds on the surface, in particular carbon species.
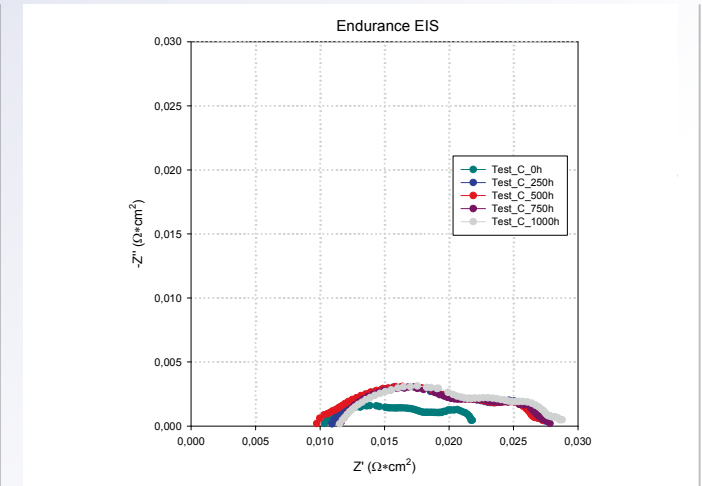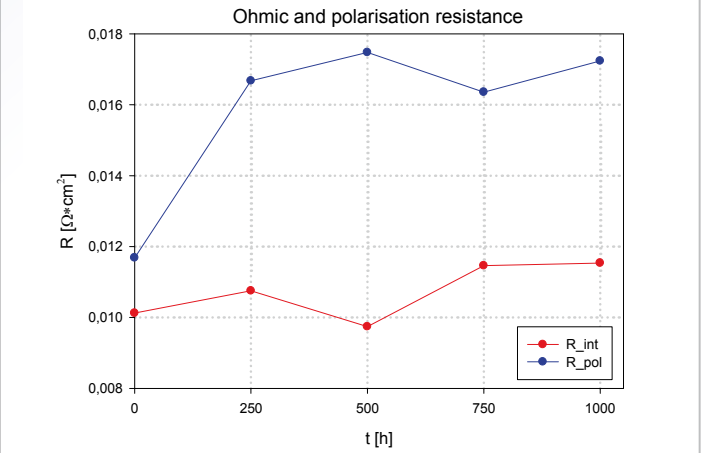
In figure 6 the Raman Spectrum shows only YSZ structures without any peak in the carbon zone (1200-1800 cm-1). The XRD in Figure 7 shows a comparative analysis of the tested anode with the reference test of the virgin, as-delivered anode Finally, a visual search for carbon deposits on the anode through Scanning Electron Microscopy combined with Energy Dispersive X-ray (EDX) Spectrometry also confirmed no trace of carbon present on the anode (Figures 8-9).

Conclusion

In conclusion, preliminary characterization of a single SOFC provided by project partner Forschungszentrum Jülich fed with simulated biosyngas, proved the feasibility of the application, demonstrating a stable performance over 1000 hours of testing without any carbon deposition despite the carbon-rich composition investigated. The results provide the necessary confidence to investigate further the behaviour over longer periods of time and with the progressive inclusion of typical biosyngas contaminants in the fuel mixture to verify the safest window of operating conditions, in order to consider the integration of SOFC systems with biomass and waste gasifiers for a high-efficiency valorisation of refuse products with added renewable and ultra-clean power generation.

Fabio De BERNARDINIS[1], Davide PUMIGLIA[2], Stephen J. MCPHAIL2*

[1]University of Rome "La Sapienza", ITALY,
[2]ENEA, Casaccia Research Centre, ITALY,
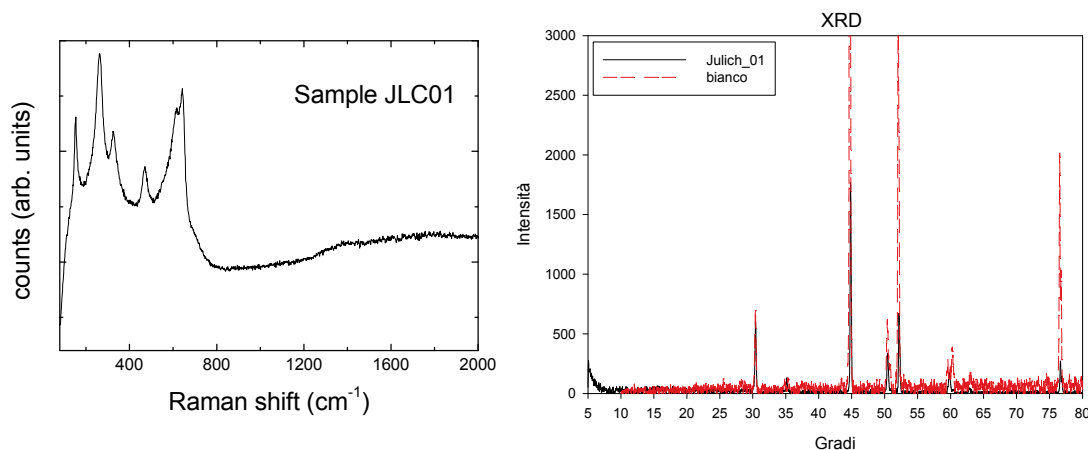**stephen.mcphail@enea.it**

Figure 6. Raman Spectrum of the tested anode.

Figure 7. X-ray Diffraction spectra comparing as-delivered (bianco) and tested anode.
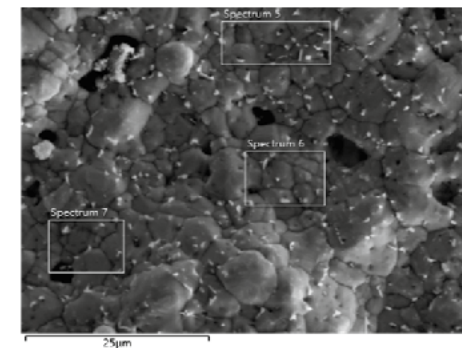

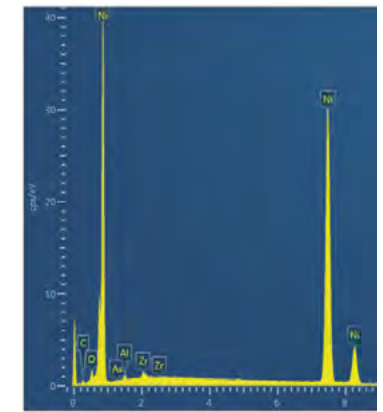Figure 8. Anode single cell seen through SEM.

Figure 9. Energy Dispersive X-ray Spectrometry (EDX) analysis of the high-lighted anode areas.

A 50 kW PEMFC pilot plant operated with industry grade hydrogen – impressions one year after commissioning

The chlor-alkali industry produces as a by product high amounts of hydrogen in their electrolytic processes. PEMFCs offer a way to improve the overall process efficiency, with a few commercial scale installations already proven viable in this niche application.

In the DuraDemo project, a 50 kW stationary PEMFC pilot plant was designed in a Finnish government funded project involving partners from different parts of the value chain. The plant, shown in Figure 1, serves as an experimental platform for evaluating stacks, balance of plant (BoP) and power electronics components, as well as monitoring hydrogen quality effects.

The plant is located at the Kemira Chemicals site in Äetsä, Finland, where around 6100 tons of hydrogen is produces as a by product per year. A portion of the by-product hydrogen is purified of chlorine traces so that it can be used in on-site processes and sold to the Woikoski gas company. This purified hydrogen also fuels the pilot plant. The 50 kW pilot plant design targets to be commercially viable when scaled up to 200 kW. The fuel cell system consists of seven 75 cell stacks in series, designed for a 150 A operating point. The BoP is divided into four subsystems presented in Figure 2.

The first successful start-up at the Äetsä site was accomplished in Jan 2014. After the first shutdown, high stack heat capacities proved problematic when running up humid stacks from room temperature. Too slow power ramp leads to condensation, while a successful start up requires rapid ramp-up to actuate stack heat production. However, during the investigations, liquid water condensation had already occurred in one of the stacks, requiring operation at partial load to evaporate water from the flooded stack, while keeping the remaining stacks sufficiently humidified.

From March 2014, the system was running at the intended 150 A operation point. In May, both recirculation pumps failed within the same week; hence the current was reduced to 90 A and operation continued in flow-through mode. In June, after 1500 operation hours, the system was shut down and closer inspection of the pumps revealed severe bearing corrosion. Operation in flow-through mode was resumed in Oct 2014. 700 hours accumulated without interruptions, until a sche-

Figure 1. Operation site of the 50 kW pilot plant in Äetsä.

duled shutdown for the hydrogen purification process maintenance. The following start-up attempts were unsuccessful as the anode pressure reducer failed to maintain sufficient flow for more than a few hours. Unstable pressure reducer performance was also evident in the previous 700 hours of recorded data.

The pressure reducer was dismounted and sent to the manufacturer, who observed a black powder-like contaminant preventing the valve poppet assembly movement. Removing the contaminant seemed to restore functionality, implying that installing a particle filter would solve this problem.

Stack voltage decay was observed during operation, but regeneration occurred after each shutdown, which suggests slow reversible accumulation of impurities. The most probable explanation is CO with trace amounts (<100 ppb) measured in the hydrogen feed.

Operation resumed in March 19th with the pressure reducer received from maintenance. Based on the field trial experience, new recirculation pump prototypes are scheduled to ship in April 2015.

When running the plant at the designed 50 kW power in spring 2014, the overall system availability was 66%, with all of the unscheduled shutdowns related to intermittent disruptions with limited hydrogen supply or electrical grid failures. ➔

➜   The stack and supply-to-grid efficiencies were 54-56% and 44-45%, respectively. In 2014, a total of 2300 operation hours were accumulated with excess of 70 MWh supplied to the grid.

The system was originally specified to operate at 4 bar hydrogen supply pressure, but on-site data has revealed that the supply pressure cycles between 3 to 6 bar, depending on the demand. Thus, uninterrupted operation would require either a hydrogen buffer or a larger valve orifice in the pressure reducer. A particulate filter would also reduce the need for pressure reducer maintenance, but would further decrease the hydrogen pressure level.

The 200 km travel distance to the site also introduces delays for mobilizing a team to run the system up after intermittent disruptions. Improved remote start-up capability could reduce the downtime, but on-site inspections are still considered essential as the reliability of all system components remains to be proven.

Pauli KOSKI*, Henri KARIMAKI, Jari IHONEN
*VTT Technical Research Centre of Finland Ltd,
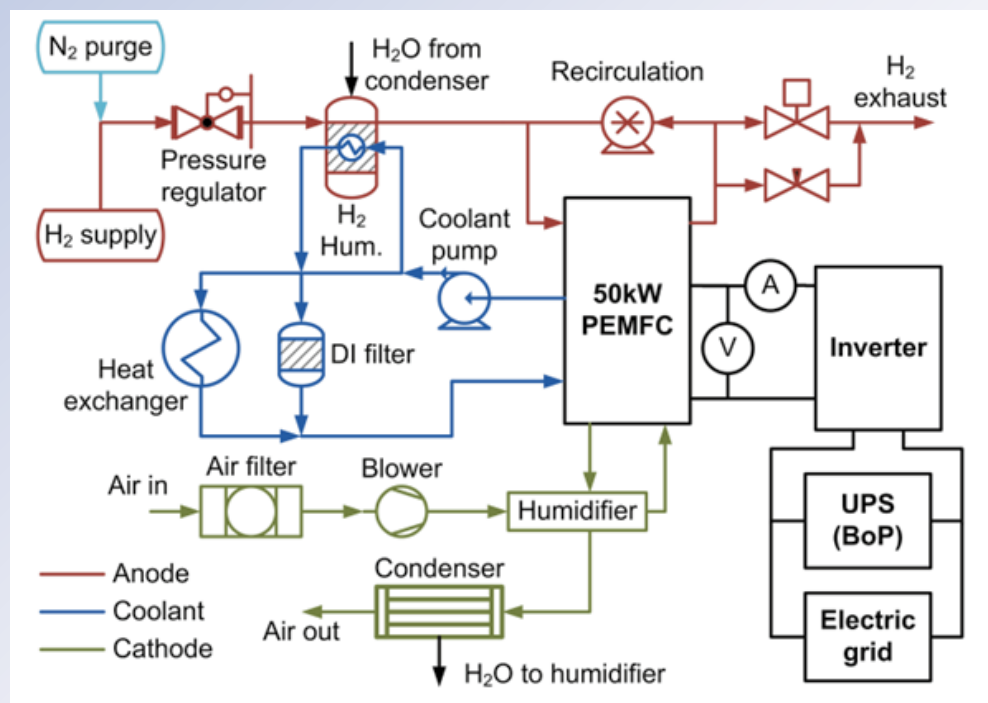**pauli.koski@vtt.fi**

Figure 2. The 50 kW pilot plant process diagram. Cathode side incorporates roots-type blower and two membrane humidifiers. Anode employs custom-made bubble humidifier, sourcing water condensed from cathode. Two scroll-type pumps recirculate hydrogen and valve assemblies enable operation in flow-through and purge modes.

Cellular structure and self-similarity of expanding hydrogen spherical flames

To perform effective hydrogen explosion risk management, consequence analysis of the possible damage induced by an accidental hydrogen explosion must be conducted. In particular, the accelerative motions in flame propagation due to intrinsic flame instabilities might cause the considerable damage in accidental large-scale hydrogen explosions, because the onset of the development of cellular structure on the surface of the expanding spherical flames leads to the increase in the flame speed. In order to ensure appropriate safety management in the event of accidental hydrogen explosions, we need to understand one of the most important mechanisms in the development of cellular structure. In addition, further studies on whether the flame acceleration could be self-similar are merited, because it is known that the self-acceleration and self-similarity definitely exist for wrinkled laminar flame propagation. In view of the above considerations, we describe the development of cellular structure and the nature of self-similar propagation in this article.

First of all, we would like to discuss the development of cellular structure of an expanding spherical hydrogen flame. In Fig. 1, the Shadowgraph images show the evolution of cellular flame structure for hydrogen/air mixtures at equivalence ratio, φ = 0.7 in a soap bubble [1]. Crack initiation on the flame surface is created by initial disturbance, which is formed by the spark. Such flame cracking propagates to form cells on the surface. The cracks propagate across the surface and the cracks start to develop along regions of high curvature. Such a mechanism of cellular flame development persists in localized regimes simultaneously and thereby the cell size on the overall flame surface also decreases. Consequently, the flame surface is fully covered by cells. As the

flame propagates, the flame is wrinkled by intrinsic flame instabilities such as diffusional-thermal instability, caused by different diffusion transports of the fuels at non-equidiffusive flames and hydrodynamic instability, caused by the expansion across the flame. The cellular structure of the flame during the initial propagation is mainly affected by the intensity of diffusional-thermal instability. For lean hydrogen mixtures, the influence of the mass diffusivity strongly dominates, the effect of thermal diffusivity is weak. Consequently a cellular shape observed. For rich hydrogen mixtures, the opposite is true, with the influence of the thermal diffusivity dominating in the propagation process, and so the flame structure is smooth and stable. Such influences of the intensity of the diffusional-thermal instability on cellular structure of the spherical flame are shown in Fig. 2. As the flame scale becomes larger, the formations of cellular structure are affected intensively by the hydrodynamic instability as shown in Fig.3. The small-scale
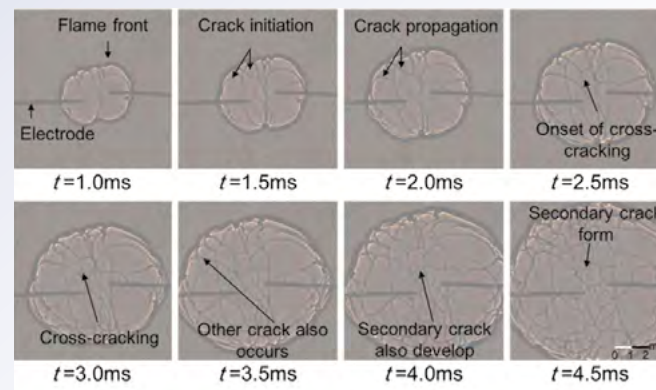
Figure 1. Shadowgraph images of evolution of cellular flame structure for lean hydrogen/air mixtures.

cell is formed by diffusional-thermal instability. As time goes on, the cell subdivides and then merges randomly. Consequently, the merged cells are finally developed as large cusps due to hydrodynamic instability [2].

Secondly, the self-similarity of expanding hydrogen spherical flames is described. Figure 4 shows the experimental acceleration exponent, α, as a function of Peclet number, (flame radius relative to the flame thickness), $(Pe-Pe_c)/Pec$ where Pec is the critical Peclet number associated with the onset of the acceleration [3]. In the initial stage of propagation (regime 1), the flame acceleration regime, which depended on the intensity of diffusional-thermal instability, exists. The values of α for lean hydrogen/air flame are higher than those for the lean methane/air flame for $(Pe-Pe_c)/Pe_c$ < 1.5. It is reasonable to assume that the acceleration exponent is affected by the intensity of diffusional-thermal instability. As the flame propagates, the value of α in this regime increases with the value of Pe. This is because hydrodynamic instability progressively dominated in the accelerating mechanism in regime 2. The present data indicate the existence of a transition period. However, the details of the transition period require further study considering the onset of self-acceleration. Then, the self-similar regime (regime 3) is observed, in which the value of α remains nearly constant with further increase in Pe. According the data, the self-similar regime is indeed observed at $(Pe-Pe_c)/Pe_c$ > 6-8. In other words, these results show that the flame accelerates with self-similarity and the structure can be attributed to its fractal nature.

In conclusion, the mechanism of the self-similar propagation can be discussed. Initially, the stretch rate is high and the →

➔ flame smoothly propagates. As the flame becomes larger, he instabilities manifest and the flame surface becomes unstable, leading to the self-acceleration. The self-accelerated speed increases as the flame propagates, and eventually the self-acceleration reaches the self-similar regime. To perform the effective risk assessment in accidental large-scale hydrogen explosions, such flame acceleration mechanism caused the considerable damages should be considered.
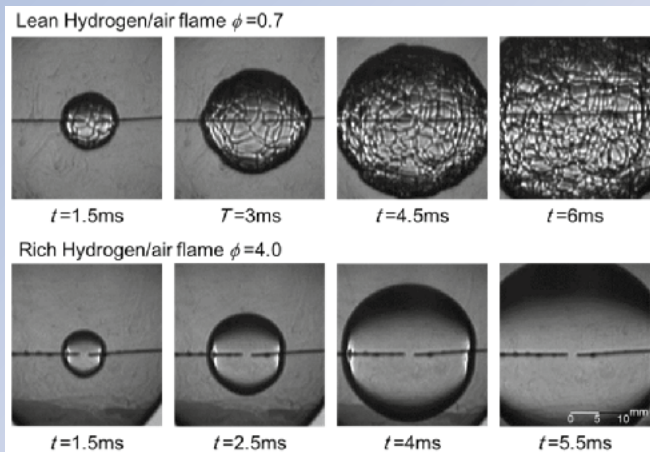
Figure 2. Schlieren images of expanding spherical hydrogen flame.
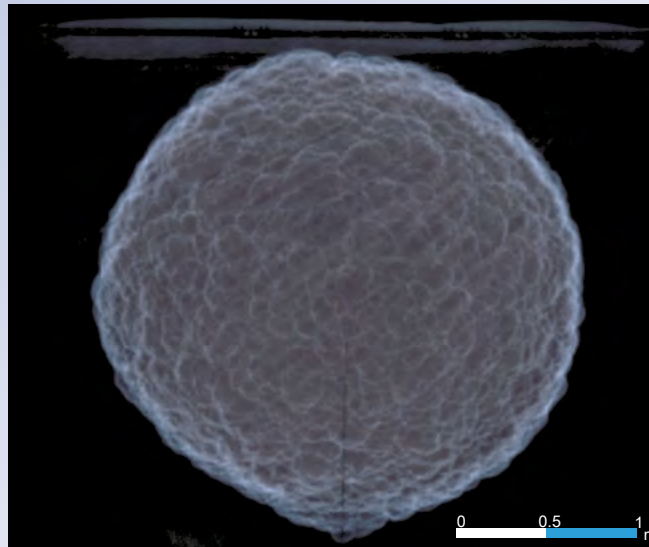
Figure 3. Wrinkled flame due to hydrodynamic instability in large scale propane/air explosion.
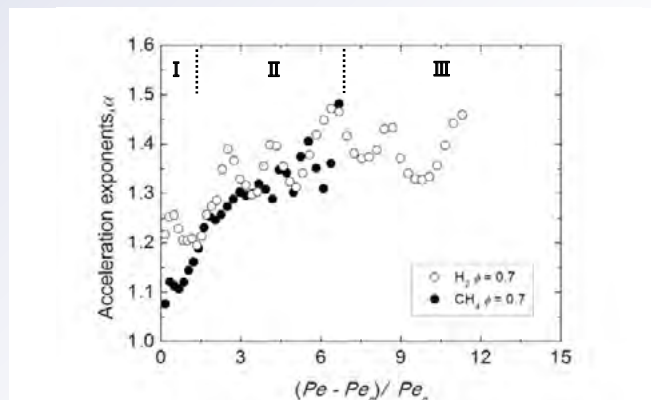
Figure 4. Acceleration exponents versus Peclet number at transition regime to self-similar propagation.

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Wookyung KIM[1]*, Toshio MOGI[2] and Ritsu DOBASHI[2]

[1] HySAFER centre, Ulster University, UK, **w.kim@ulster.ac.uk**
[2] The University of Tokyo, Japan

Quality assurance of hydrogen for fuel cell vehicles – removing the roadblock

When we talk about the current issues of rolling out fuel cell vehicles, we often mention the same problems: How do we store the hydrogen safely? Are we getting the performance we need from the vehicles? Can we build the hydrogen infrastructure quickly enough to meet user demands? It looks as though these anticipated problems are now dealt with; as of 2015 the hydrogen fuel cell vehicle market is open. There is however one issue that is quite often overlooked and this is quality assurance of the hydrogen product. It is well known that if certain impurities are present in hydrogen provided to a fuel cell vehicle it can quickly degrade the catalysts present in the system. Not only would this be very disappointing (and expensive!) for the brave few who are the first to buy the vehicles, but from 2017 it will be compulsory to perform quality assurance at refuelling stations as stated in a recent European Directive written in October 2014. This directive requires that all hydrogen refuelling stations provide high purity hydrogen as specified in ISO 14687. These specifications are given in Table 1.

Currently there are only a handful of laboratories worldwide that can perform purity analysis to the limits required by European legislation. This is because the measurements are extremely difficult; 13 gaseous impurities must be analysed ranging from 4 ppb to 300 ppm. The National Physical Laboratory (NPL) has developed high accuracy methods for measuring most of the impurities listed in ISO 14687, but this involves six state-of-the-art gas analysers and therefore analysis can be time-consuming and costly. Additionally, as some of the analyses, such as formaldehyde and total sulphur, require low level amount fraction gas calibration standards, preparation of these mixtures are certainly not straightforward and

Impurity	Amount fraction limit (ppm)
Water	5
Total hydrocarbons	2
Oxygen	5
Helium	300
Nitrogen	100
Argon	100
Carbon dioxide	2
Carbon monoxide	0.2
Total sulphur compounds	0.004
Formaldehyde	0.01
Formic acid	0.2
Ammonia	0.1
Total halogenated compounds	0.05

Table 1. ISO 14687-2 specifications for maximum allowable impurity content of hydrogen.

additionally these mixtures can degrade quickly over time. At NPL we have prepared a suite of primary reference gas standards that support the hydrogen economy by providing traceability to measurements performed during hydrogen quality assurance. This is an important aspect of hydrogen purity analysis as without traceability to the SI we cannot ensure that our measurements are accurate and comparable worldwide. In addition to providing gas standards to external laboratories, our hydrogen purity laboratory is now open for commercial work; this means that any hydrogen refuelling station can provide a sample to our laboratory in order to perform quality assurance as specified in ISO 14687-2. Our

'routine' service includes measurement of the key impurities that may be found in hydrogen produced by electrolysis or steam methane reforming, but we can additionally offer measurement of a wide range of other impurities that are not included in ISO 14687-2. ➔

Figure 1. NPL provide a wide range of primary reference gas mixtures for the energy industry – this now includes the hydrogen purity area (image courtesy of NPL).

→ As NPL have found out, to perform a full purity analysis the laboratory would need to use several expensive state-of-the-art analysers. This is mainly because some of the specifications are very low at the parts-per-billion level. If these specifications were higher, it may be possible to only use one or two more routine analysers such as a gas chromatography with mass spectrometer. Therefore at NPL we have developed a high accuracy hydrogen impurity enrichment device. This device concentrates the impurities in a sample of hydrogen to a known level by removing hydrogen through a palladium-based membrane. The enrichment factor is calculated by adding an amount of tracer gas such as krypton, and measuring the amount fraction of this gas before and after enrichment. This device has the advantage that it can also detect if an air leak or membrane failure has occurred during enrichment, which is important as this prevents obtaining incorrect results. It is anticipated that this device will help hydrogen purity laboratories in the future by lowering the costs and time taken to perform quality assurance. Figure 2 shows how the hydrogen impurity enrichment device works.

As the hydrogen economy is now starting to take off, it is clear that more work is required before laboratories can provide quality assurance of hydrogen. The main issue we face is the problem that ISO 14687-2 is most probably over-specified. In simple terms this means that it is too difficult for routine testing laboratories to follow. A method for the measurement of total halogenated compounds as specified in the ISO standard, for example, does not even exist according to the literature. The standard is also too general because it compiles all possible impurities that can derive from every known hydrogen production method (electrolysis, steam methane reforming, chloralkali process etc.). For these reasons the standard must be rethought and the ISO technical committee responsible for writing the standard is now undergoing a process to revise this standard in order to make it more fit-for-purpose. This is great news as it means that hydrogen refuelling stations in the future will find it simpler to prove that their hydrogen purity complies with the European Directive.

NPL have an experienced team of research scientists working in this area – we believe it is extremely important to carry out work in the early stages to ensure that when the large number of hydrogen refuelling stations are installed, we have the capability to perform the necessary quality assurance steps. If you would like to know more about our work please feel free to contact me. Below are links to the key papers that NPL have written in the hydrogen purity area.

Review of purity analysis methods for performing quality assurance of fuel cell hydrogen
Advancing the analysis of impurities in hydrogen by use of a novel tracer enrichment method

Arul MURUGAN*
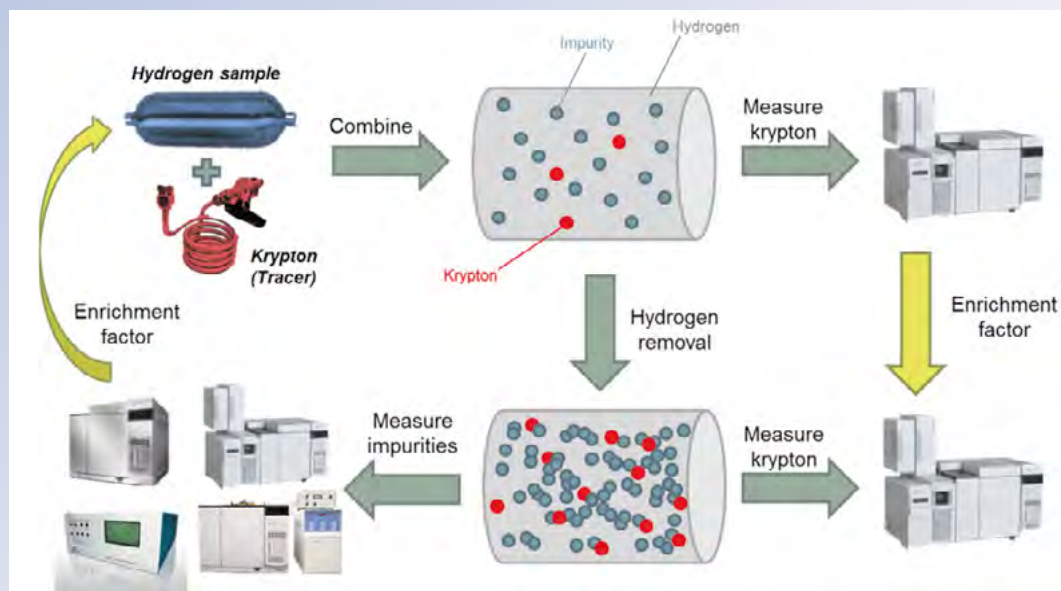* National Physical Laboratory, UK, **arul.murugan@npl.co.uk**

Figure 2. NPL's Hydrogen Impurity Enrichment Device.

Development of a premixed methane burner for bonfire-tests

The hydrogen-group of the Institute for Nuclear and Energy Technology IKET at the Karlsruhe Institute of Technology KIT received an inquiry to perform so-called bonfire-tests with hydrogen storage tanks at their hydrogen test site HyKA. At the time of the inquiry no facility dedicated to large scale fire tests was available, so the possibilities for conducting such tests at HyKA were evaluated by initially collecting information on the test regulations and the conditions to be provided in the tests.

Bonfire tests for hydrogen (H2) storage tanks are conducted to ensure a safe depressurisation of the tank when it is exposed to an external fire. In contrast to bonfire tests with gasoline tanks, where a pool of burning gasoline is placed below the tank for 2 minutes (1 minute thereof covered by some shield), bonfire tests with H2 tanks are much more challenging. Depending on the regulation applied (European Regulation [1, 2] or proposed Global UN-Regulation [3] with two possible procedures) the prescribed temperature profiles are different. However, the main test set-up is quite similar and can be briefly summarized as follows.

Prior to the test the hydrogen tank is filled to its nominal working pressure with H2 and is then positioned horizontally in a distance of approx. 100 mm above the fire source. The burner shall have a length of 1.65 m and should be able to produce a flame that encompasses the entire width of the storage system. During the test the flame temperature has to be recorded by at least three thermocouples suspended in the flame approximately 25 mm below the bottom of the tank. To pass a test successfully, the tank shall vent through Thermally-activated Pressure Relief Device(s) TPRDs to a pressure of less than 1.0 MPa without rupture.

As mentioned above different temperature profiles are prescribed in the two regulations. In the European regulation and the so-called „Engulfing Fire Test" of the UN-proposal a flame temperature of at least 590°C has to be reached by at least one thermocouple (European Regulation) and two thermocouples (as averaged over 60 s interval) (UN-proposal) within five minutes after the fire is ignited. This temperature shall then be maintained until the end of the test. In contrast to this a two-step procedure is prescribed for the UN „Fire Test". This procedure starts with the so-called „Localized Fire", where only a part of the tank (250 mm long) is exposed over its whole width to the fire that should reach a temperature of 600°C below the tank within 3 minutes. This temperature has to be maintained for 7 minutes and should not exceed 900°C, and then the „Engulfing" part of the fire test starts. Within the next 2 minutes the temperature along the entire surface of the tank shall be increased to at least 800°C but not higher than 1100°C, and the fire source is extended to produce a uniform temperature along the entire length up to 1.65 m and the entire width of the tank.

Usually bonfire tests are conducted outdoor in remote areas where nobody is endangered by the release of large quantities of hydrogen or by the consequences of an explosion in case of a tank rupture (fire, blast wave and/or missiles). At KIT such a remote site is not available. So to perform such tests at HyKA a possibility to restrict the consequences of the test to a small volume had to be found.

The test vessel V220 is HyKAs largest safety vessel. It has the dimensions of approx. 8 m x 6 m (height x diameter) and encloses a volume of approx. 220 m³. This vessel is suitable for the considered testing with respect to size and from a test infrastructural point of view. In case of a successful test the H2 released through the TPRD(s) can be easily piped to the ambience outside the vessel. The rated static pressure of the vessel is 10 bar, which is sufficient to retain the pressure wave of a bursting tank (tank pressure > 700 bar, tank volume < 50 dm³), but it might be too low to withstand a subsequent ignition of the released hydrogen inventory, which can be in the order of 3 to 7 kg.

An effective method to reduce the pressure loads to vessel V220 is to inertize it completely by replacing its atmosphere with pure nitrogen. Under such conditions hydrogen which is released from a ruptured tank is not flammable, since it lacks a reaction partner for oxidation, which usually is the oxygen fraction in air. With this concept the loads to the safety vessel are reduced to the pure expansion of the compressed tank contents. Another advantage is, that the damage to the tank is only caused by the external fire, and not due to the combustion of its contents and consequences thereof, which facilitates the post mortem analysis of the tested tank significantly.

But of course this method also has one big disadvantage: under inert conditions it is not easy to maintain a fire to provide for the prescribed temperature profiles, since again the oxidant reacting with the burner-fuel is missing. To overcome this disadvantage it was considered to design a burner that is driven with pre-mixed stoichiometric fuel-air mixture. But the use of such fuel-air mixtures leads to the next issue, since due to their low ignition energies these mixtures are quite difficult to handle. So the most important item was to ensure that the flame burns only above the burner surface and →

has no possibility to flash back into the mixing chamber of the burner.

Flame arresters are designed to separate flames from potentially flammable atmospheres. Such arresters usually consist of porous materials in which a flame has to pass through narrow channels where the heat losses to the cavity material are higher than the heat provided by the combustion. So the flame cools down and quenches when its temperature drops below the auto-ignition temperature of the burning mixture. This behavior is specific for a fuel (under given conditions) and can be described using the so-called Maximum Experimental Safe Gap (MESG) of the fuel. This measure gives the maximum gap size through which the flame of a given fuel is unable to pass.

Gaseous fuels were favored for the burner, since it is possible to generate homogeneous fuel/oxidizer mixtures, which is not possible with liquid or solid fuels. Common gaseous fuels are propane, methane and hydrogen, but despite its high heat of combustion propane was sorted out due to its tendency to liquefy already at moderate pressures (< 10 bar). Methane has a heating value of 35.89 MJ/m³ and a MESG of 1.14 mm. Compared to this the heating value of hydrogen (10.78 MJ/m³) is significantly lower, and also its MESG is quite small (in the range of 0.5 mm). So due to these differences methane was chosen as burner fuel.

On the basis of the MESG the most important part of the burner, the top plate, could now be designed. According to the burner's working principle it has two functions: provide an evenly distributed flame bed over the complete burner surface and prevent flame flash-backs into the burner body. So it has to have small pores to provide for an evenly distributed fuel flow to its upper side, but the pores have to be significantly smaller than the MESG of methane. Also it must be made from a material that withstands high temperatures. Sintered metal plates are produced in a large variety of pore diameters and materials, but due to their fabrication method only rather small tiles are available. However on request several such tiles can be welded together by the manufacturer to form larger plates in the size ordered by the customer.

To make the burner system more flexible and to reduce the manufacturing costs for the sintered metal plate it was decided to divide it into three independent but similar units. So every burner consists of a burner body for mixture distribution (dimensions approx. 58 cm x 70 cm (L x W)) that is covered with a sintered metal plate with a maximum pore size of 200 nm. It is fed by its own independent gas supply chain (methane and compressed air cylinders, flow meters, mixing vessel and piping) and can be ignited separately by its own spark discharge ignition system.

First tests with a tank mock-up showed that the required temperatures in the height specified by the regulations can be easily reached. The required minimum temperatures were reached in time and the targeted temperatures could be also well maintained within the required bounds for the whole testing time prescribed by the regulations.

In the meanwhile at KIT HyKA bonfire tests are conducted with a large burner system that has the dimensions 174 cm x 70 cm and is capable of producing a uniform maximum flame surface with the dimensions 166 cm x 57 cm, which is well in accordance with the dimensions required by both regulations (European and proposed Global UN-Regulation).
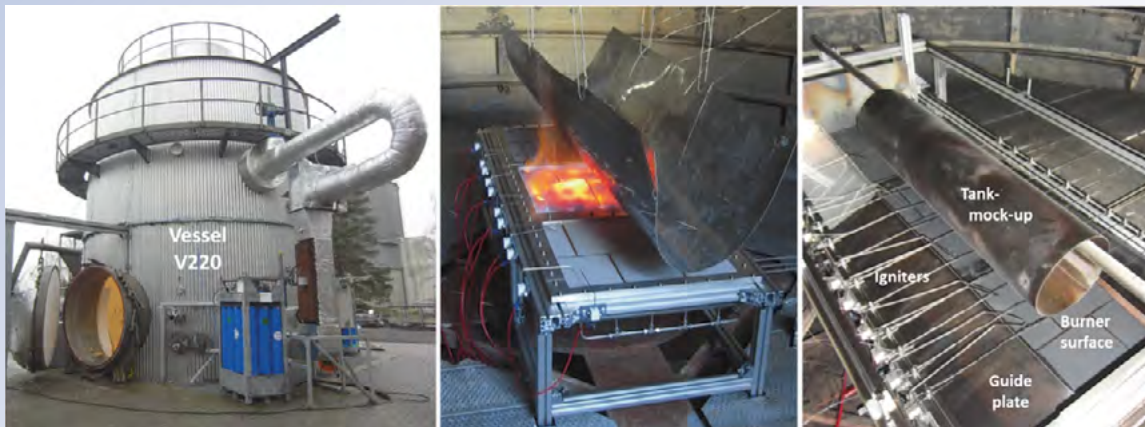
Figure 1. Outside view of safety vessel V220 (left), early performance test with ignited central burner unit (center) and assembly for tank testing with tank mock-up (right).

→ Due to its modular structure even the elaborated test sequence of the UN "Fire Test" with its localized and engulfing fire test sequences can be easily realized.

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Andreas FRIEDRICH*
* Pro-Science GmbH, Ettlingen, Germany,
friedrich@pro-science.de

Radiography and tomography:
Useful methods to investigate the structure of high pressure cylinders

On board storage of hydrogen

Nowadays almost all the main car manufactures have developed prototypes functioning with electric motors driven by a fuel system stack fuelled by hydrogen. To store hydrogen on board, almost all manufacturers have adopted the most commonly available solution, compressing hydrogen in high pressure 'vessels' or 'tanks', in the same way as it is already done for the cars fuelled with natural gas. The only difference consists in the pressure of the gas. Natural gas is compressed in cars to values of approximately 250 bar, which corresponds to 250 times the atmospheric pressure on earth. Hydrogen has a lower energy density than natural gas and must therefore be compressed to much higher pressure to guarantee an acceptable autonomy of travel, i.e. up to 700 bar. The tanks able to confine gas at such a pressure consist of an inner layer and an external shell made of carbon reinforced epoxy, many centimetres thick. The internal layer is called the 'liner'; it is made of light metal or plastics and aims at the physical confinement of the hydrogen, while the external shell delivers the required mechanical resistance, by counterbalancing the internal pressure of the gas and by protecting the liner from external forces. Hydrogen tanks are designed to resist pressure more than 2 times higher than their operative pressure, to avoid in any case any possible loss of confinement during their life.

It is however interesting to understand how these tanks behave and age during the many filling-emptying cycles they experience when installed in a hydrogen car. Interesting and important because a better insight in the degradation and rupture phenomena will allow an improved fit-for-the-pur-

pose design and tank testing procedures better considering real-life operative conditions. To this purpose, JRC studies since some years the performance of tanks by performing thousands of filling and emptying cycles under the most extreme environmental conditions. These studies are performed in collaboration with other European centres, such as the BAM in Berlin and aim at exploring the effect of cycling on the final resistance of the tank.

It is already known that the failure of structures made of carbon fibre reinforced plastics starts with the fracture of individual fibre, but the final rupture occurs only when a critical number of fibre fractures has been reached.

In the work presented here, we have investigated in how far x-ray imaging techniques can enlighten this degradation process at a microstructural level.

X-ray radiography and tomography

How do we look inside a tank without breaking it? At the Institute for Energy and Transport of the JRC in Petten, we have an x-ray radiography laboratory able to perform radiography of big (industrial) components. Figure 1 shows the radiography of a full tank, in which the liner has on purpose been damaged by means of an ultra-rapid depressurisation. The liner bending is clearly visible as well as all the other main components of the tank (the picture has been taken with a Philips MCN451 x-ray equipment).

This technique is rapid and allows for the identification of macroscopic defects and damages. However, it has also

disadvantages: its images are a projection of complex geometries onto one surface. In the case of a cylinder or tank, this means that the all cylindrical and spherical structures are flattened onto only one plane, with consequent loss of details and resolution.

On the contrary X-ray tomography (X-ray CT) illuminates the object from different angles and viewpoints and therefore allows, with the assistance of computer software, a full three-dimensional reconstruction. Figure 2 shows an example of three-dimensional reconstruction. By means of X-ray CT it is possible to characterise quantitatively micro-structural issues, such as porosity and orientation of fibre bundles. Figure 3 gives an example of identification and analysis of porosity ➜
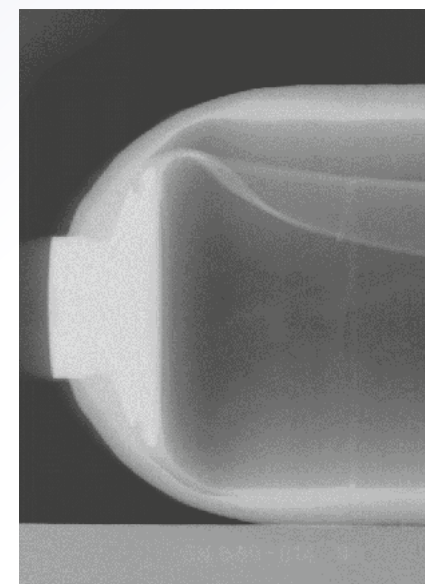

Figure 1. Full-tank radiography (only one half shown). On the left the metallic boss is visible. The internal semi-transparent structure is the plastic liner which has been on purpose deformed to test the radiography method.

→ in an annular section of a tank. The x-ray CT imaging presented here was acquired by means of a v/tome/x L300CT equipment at the General Electric Sensing & Inspection Technologies GmbH premises in Wunstorf (Germany), while the image analysis has been performed at the JRC.

The analysis of tanks by means of X-ray CT is able to identify and quantify structural defects such as major porosity, fibres bundle misalignments and macroscopic defects in general. However, it does not possess the resolution required to investigate what happens inside and around fibres, which is where the rupture of a composite structure starts.
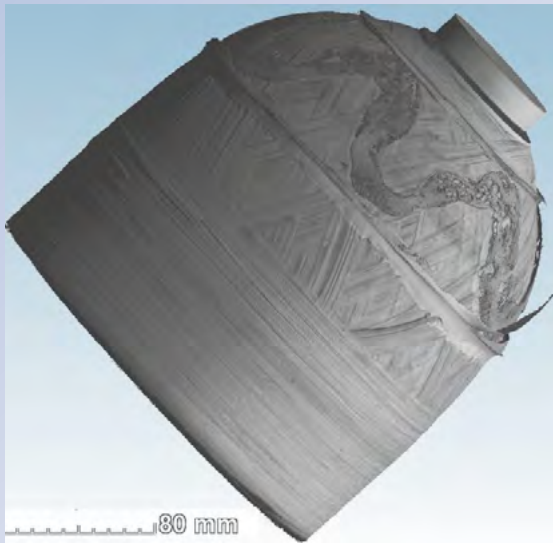

Figure 2. 3D reconstruction by X-ray CT of part of a tank, including the boss (top right). The linear structure visible on the cylindrical and spherical surface indicate the direction of the carbon fibres bundles the composite structure of the tank is made of.

For a better look into tank structures in the millimetres to micrometres range we have used an additional x-ray CT equipment able of such a resolution, a so-called micro-tomography instrument. At JRC we have a Phoenix nanotom with an ultimate resolution of few micrometres. However, contrary to the previously mentioned industrial x-ray equipment, which are able to take 'pictures' of a whole tank, this high resolution instrument requires that the tank is cut into small pieces of few centimetres.

Figure 4 shows an example of the results: epoxy, fibres and porosity are visible in the image (left picture, which shows a cross section), and the three-dimensional image analysis
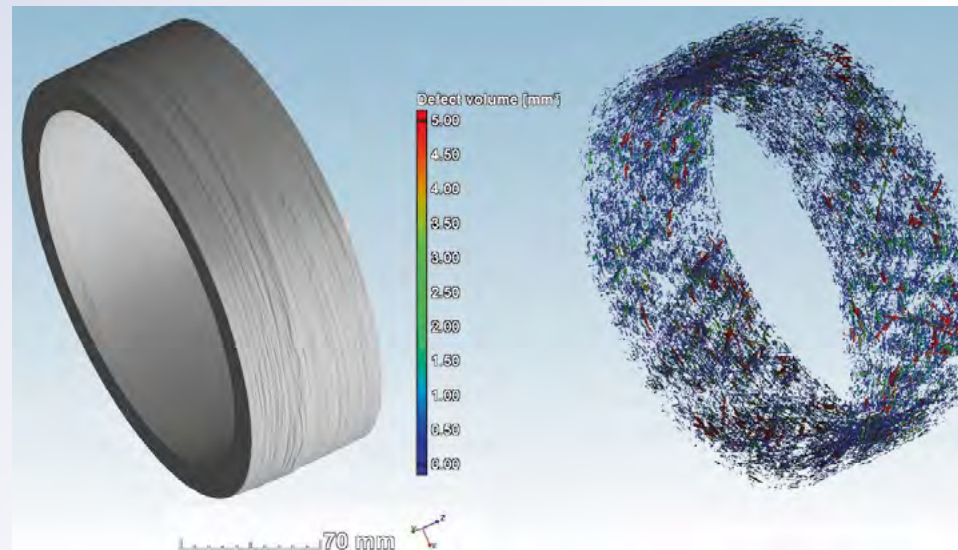
Figure 3. Annular section of a tank imaged by X-ray CT (left) and identification of its porosity (right).

allows for the identification and quantification of porosity characteristics (right picture). The very elongated voids visible in the picture occur during the manufacturing of the composite shell when the fibres are impregnated by the liquid epoxy before solidification. These voids indicate areas where the epoxy has not been able to wet the fibres.

We have applied micro-tomography to the characterisation of heavily damaged structure, a tank which is part of a breathing apparatus used by the fire brigades. This tank has experienced a pressure almost near its rupture value, and shows a fine net of superficial cracks (top-left picture of Figure 5). But how do these cracks propagate into the material? How far do they reach from surface? Only tomography can give a full answer to the questions. The bottom part of Figure 5 shows one of these cracks, and indicates that it does not penetrate deep into the composite structure. In the case shown, the full length of the crack is not greater than one millimetre. The image suggests also a reason for this early stop of cracking: the horizontal pores already existing in the composite act as stress-release: once that a crack has reached one of them, it loses its driving force and its progress comes to an end. →

→ Conclusions

This preliminary work, integrated with literature surveys, has brought us to the following conclusions:

a) the best approach to gain information on the (lifetime) damage evolution of high pressure tanks at micro-structural level is a combination of i) full component CT, for non-destructive characterisation of the tanks at selected moment of its operational life, to study their macro- and mesoscopic characteristics, ii) destructive micro-tomography, for quantitative data on microstructure indicators.

b) To directly 'see' fibres fracture, sub-microns resolution is needed. This is available only by means of synchrotron radiation. This is not easily available and required samples of millimetres dimensions. Nevertheless, micro-tomography is able to analyse damage in the epoxy matrix and delivers important information on the state of health of a tank.

c) It is not enough to study one tank only; a large set of statistically reliable data needs to be collected from the behaviour of a high number of tanks, to be able to draw conclusions on damage onset in these composite structures.

Pietro MORETTO*, Beatriz ACOSTA IBORRA, Rafael ORTIZ CEBOLLA, Nerea ECHEVARRIA DE MIGUEL

* European Commission, Joint Research Centre,
pietro.moretto@ec.europa.eu
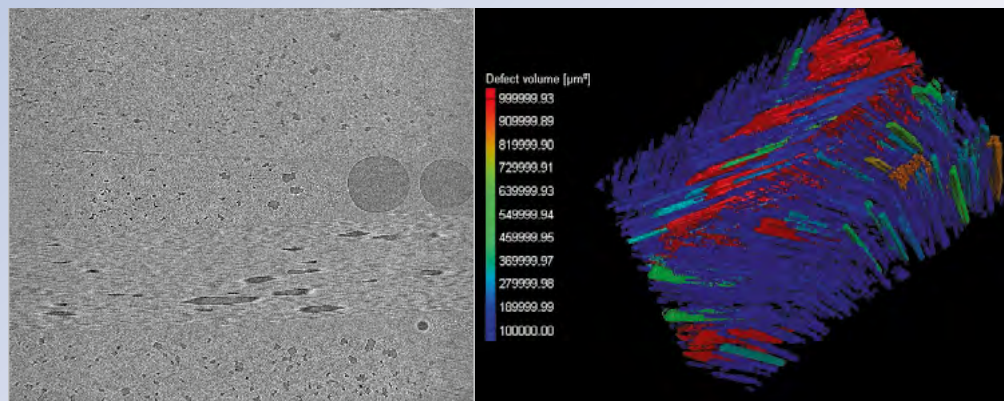
Figure 4. micro-tomography image (left) and porosity analysis (right) of a small section of a composite micro-structure. In the left picture, individual fibres are barely visible as bright spots only in central area. Darker grey areas are porosity. The two big circular pores on the left are in a zone of epoxy matrix without fibres. The picture on the right is the results of image processing of a volume from the central part of the left picture.,Tthe very elongated voids visible in the picture are typical for porosity along a cluster of fibres, the colours indicate the porosity of the individual voids.

Figure 5. Micro-tomography characteri-sation of an almost-ruptured oxygen tank. Top-left: the cracked surface of the tank. Top-tight: microstructural CT image. Bottom-left: crack identified (the top is the external surface of the tank, the crack is the purple structure, in grey porosity and fibres bundles). Bottom-right: the crack isolated from the rest, together with the final porosity where it stopped (the large horizontal structure at the botton of the picture).

HyIndoor project: Summary of research findings

Introduction

As reported in the previous e-newsletter, the HyIndoor project, sponsored by the EU Fuel Cells and Hydrogen Joint Undertaking (FCH JU) and involving ten partners, was set up to perform pre-normative research on safe indoor use of fuel cells and hydrogen systems. The partners were: L'Air Liquide SA (AL, France), CCS Global Group Ltd (UK), Commissariat a l'Energie Atomique et aux Energies Alternatives (CEA, France), National Center for Scientific Research ̈Demokritos ̈ (NCSRD , Greece), Karlsruher Institute fur Technologie (KIT, Germany), Health and Safety Executive (HSL, UK), Eurpoean Commission Joint Research Centre (JRC, The Netherlands), HyGear Fuel Cell Systems B.V. (HFCS, The Netherlands), Ulster University (UU, UK), LGI Consulting (France).

Initially the project identified representative fuel cell and hydrogen systems and their potential hydrogen leak regimes, reviewed state of the art and identified knowledge gaps and gaps in Regulations, Codes and Standards (RCS). This informed the scope and design of experimental and mathematical modelling work within the project. The project focused on four major areas: hydrogen accumulation and dispersion in enclosed spaces, vented deflagrations, hydrogen fires in confined spaces and the performance of hydrogen sensors. This article gives a brief summary of the work carried out within the HyIndoor project.

Hydrogen dispersion and accumulation in enclosed spaces

Experimental work was carried out using a 31 m^3 enclosure at HSL, investigating the relationship between hydrogen release rate and passive vent areas and location, sub-sonic and choked releases and the transient effects of wind.

Experimental work in a 1 m^3 enclosure (GAMELAN) at CEA included the investigation of more fundamental understanding of the entrainment of air in hydrogen releases. Particle image velocimetry (PIV) was used to map velocity fields – work is to continue on this subject within the H2FC project.

The performances of a number of numerical methods were tested and successes/shortcomings were identified along with requi-

Figure 1. Experimental data showing the effect wind blowing into the upper vent and overcoming buoyancy.

Figure 2. BOS image of a vented deflagration on the 1 m^3 KIT facility.

rements for simulation of light gas release and dispersion in an enclosure proposed by (UU). New predictive methods were developed and tested by UU, including performance assessment for a single passive vent, and overpressures caused by unignited hydrogen releases (̈pressure peaking ̈).

CFD modelling was carried out in order to test different modelling methods and also to test aspects not covered by practical experiments (e.g. the effect of passive vent thickness on hydrogen concentration).

Vented hydrogen deflagrations

Experimental work, carried out using the 31 m^3 enclosure at HSL and a 1 m^3 enclosure at KIT, investigated a number of parameters, focusing on relatively lean hydrogen mixtures and resulting overpressures appropriate for weak structures (typically 100 mbar): homogeneous mixtures, hydrogen →

Figure 3. Simulation, by Ulster University, of self-extinguished fire: mole fractions of H2 (left) and O2 (right).

→ layers and stratified mixtures, ignition position, relief area, the presence of obstacles, and inertia of explosion relief.

Analytical methods for predicting overpressures were tested versus the experimental data. New models for lean mixtures and for inhomogeneous mixtures, developed by UU, performed well versus experimental data from the HyIndoor tests and other sources.
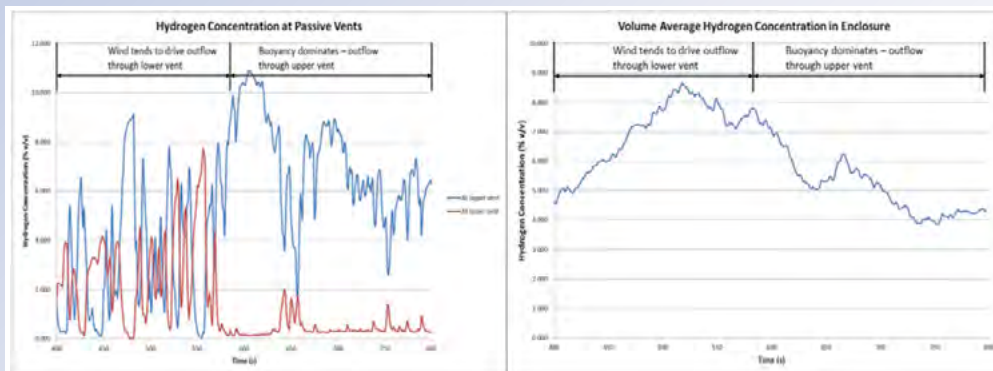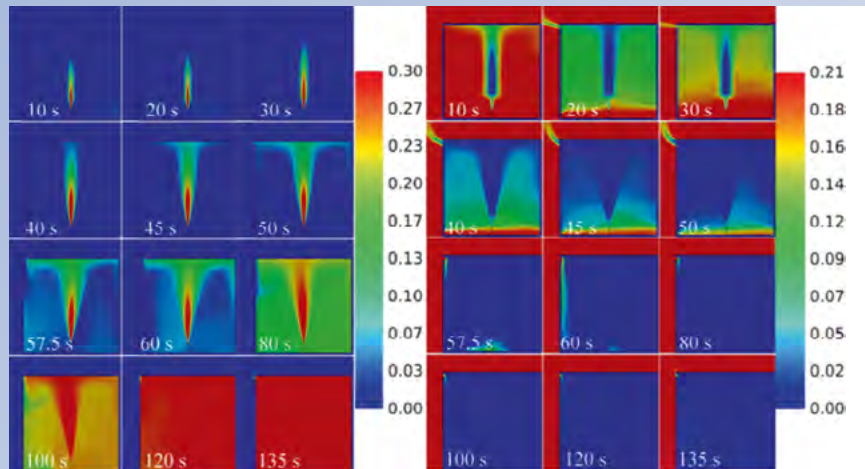
CFD modelling was capable of reproducing experimentally observed deflagration dynamics features for moderately lean mixtures, e.g. 18% v/v. The two peak structure of pressure dynamics was reproduced. The predictive capabilities of CFD models are lower for situations where instabilities have greater effect on deflagration dynamics (e.g. for mixtures close to

upward flame propagation limit). Further study is needed to develop predictive models for external explosion and to deal with flame-acoustic interactions.

Hydrogen fires in confined spaces

Experimental work was carried out using the same facilities as the vented deflagrations. Analytical and CFD modelling was also carried out by a number of partners. The project identified three indoor fire regimes: well-ventilated with no hydrogen accumulation; under-ventilated with hydrogen accumulation and either external flame at the open vent or with self-extinction of the flame. Flame oscillation in and out of the enclosure was observed in experiments at KIT. Analytical models may give an indication of whether a fire may become under-ventilated, while CFD modelling has highlighted the importance of the thermal properties of the enclosure in determining the internal temperatures.

Hydrogen sensors

A testing facility at JRC, dedicated to the characterization of hydrogen sensor performance and reliability, carried out a study that went through several steps: i) a market survey of identified commercial off-the-shelf sensors; ii) recommendations for suitable sensors based on the sensor requirements set by the consortium for indoor applications; iii) the performance of five hydrogen sensors have been tested according

to the industrial needs; iv) the experimental sensor performances were compared to Standard ISO 26142; v) recommendations and guidelines for sensor end-users were made as for the type, number and position of sensor for the target application.

Dissemination

During the project two workshops were held aimed at presenting research results and outcomes to a broad selection of researchers and industry representatives working in the field of hydrogen safety and soliciting feedback from interested stakeholders. In September 2013, HyIndoor partners led the Advanced Research Workshop (ARW) in Brussels, Belgium and the Final Dissemination Workshop (FDW) which took place in December 2014 at Les Loges-en-Josas, France.

HyIndoor project outputs

There are three public documents as outputs from HyIndoor; Guidelines, RCS Recommendations and Final Report. These are available on the HyIndoor website (**http://www.hyindoor. eu/?page_id=372**).

The guidelines on fuel cell indoor installation and use were developed based on the research outcomes of the project. The document aims to provide the course of actions and the best practices to be easily used by industry engineers for the safe indoor application of fuel cell and hydrogen systems. It includes a set of analytical models and engineering tools in the form of nomograms to address safety aspects related to mitigating the consequences of unignited releases, indoor deflagrations and jet fires.

→

➔ The regulations, codes and standards (RCS) were delivered as a roadmap for bringing of all research knowledge gathered during HyIndoor to the international RCS bodies. This document represents the consortium consensus regarding the recommendations addressed to the standard development organisations (ISO, CEN, etc.).

The HyIndoor final report summarises the scientific and engineering knowledge of the project including the full list of publications and dissemination activities in one short document.

The contents of this article, including any opinions and/or conclusion expressed or recommendations made, do not necessarily reflect policy or views of the Health and Safety Executive.

Phil HOOKER*
* Health and Safety Laboratory, UK,
philip.hooker@hsl.gsi.gov.uk

H2FC SUPERGEN: An overview of hydrogen and fuel cell research across the UK

The Hydrogen and Fuel Cell (H2FC) SUPERGEN Hub was launched in May 2012 to bring together the UK's Hydrogen and Fuel Cell research community. Funded by the Engineering and Physical Sciences Research Council (EPSRC), the Hub has an ethos of inclusiveness and openness to encourage collaboration, not only across the Hydrogen and Fuel Cell landscape, but also between academia, industry and government, linking fundamental research through to commercialisation.

H2FC SUPERGEN has around 450 members working in Hydrogen and Fuel Cell technologies. The Hub's core structure comprises a Management Board of ten academics from seven UK universities, led by Prof Nigel Brandon. They are supported by an Advisory Board of representatives from around twenty key companies and UK government departments working in Hydrogen and Fuel Cell research and development. The Hub brings together the academic community through its Science Board of around 100-based UK academics working in the area. The Hub is free to join for anyone interested in Hydrogen and Fuel Cell activities, from within the UK and internationally.

H2FC SUPERGEN disseminates academic research funding, including funding for a series of White Papers aimed at informing policy makers and stakeholders about the role of Hydrogen and Fuel Cells across a number of areas, the first of which is now publically available[1] which details the role of Hydrogen and Fuel Cells in providing affordable, secure low-carbon heat.

The Hub also supports international engagement and, for example, recently signed a Memorandum of Understanding (MoU) in the area of Hydrogen and Fuel Cells with the Republic of Korea.

The Hub strongly believes in collaboration between academia, industry and government. The UK has industrial activity across the entire Hydrogen and Fuel Cell supply chain and plays a pivotal role across SOFC (Solid Oxide Fuel Cell), PEFC (Polymer Electrolyte Fuel Cell) and AFC (Alkaline Fuel Cell) development, detailed below. The Hub's industrial Advisory Board seeks to encompass these key stakeholders and includes; Johnson Matthey, Rolls Royce Fuel Cell Systems, Ceres Power, Intelligent Energy, ITM-Power, Energy Technologies Institute, Ricardo plc, E4Tech, networks such as the Scottish Hydrogen and Fuel Cell Association, UK Energy Research Centre, and government departments and organisations including Department of Energy and Climate Change, Technology Strategy Board, EPSRC, Scottish Government and Scottish Enterprise.

For example Ceres Power specialises in SOFCs with a focus on fuel cell stack technology. In 2013 Ceres Power partnered with South Korea's largest boiler manufacturer, KD Navien, a major exporter of boilers to the USA, for initial development and product testing of a micro-CHP product for the Korean ➔
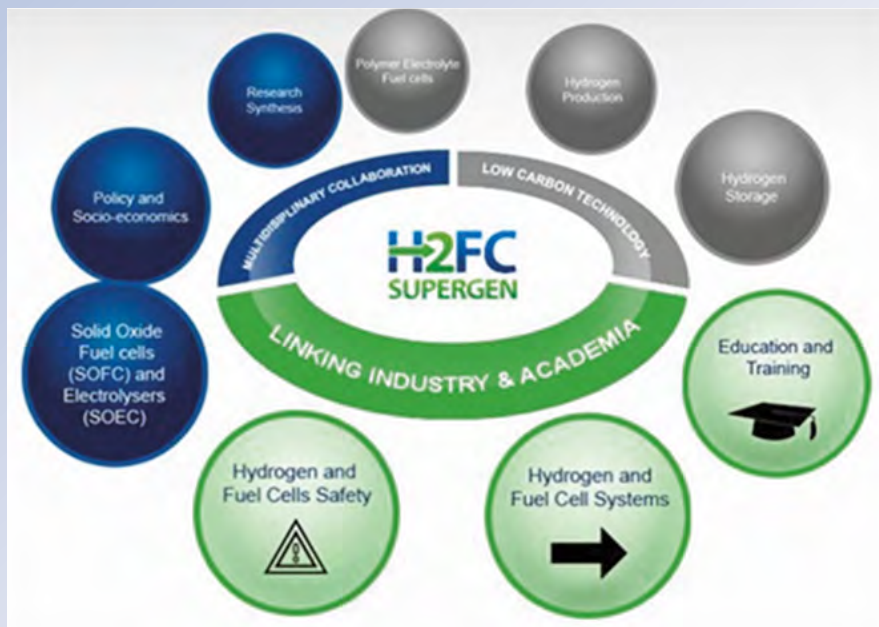
Figure 1. The research methodology within the Hub core programme consists of nine work packages and are led by the following academics: Professor Nigel Brandon, Imperial College (Director): Research Synthesis; Professor John Irvine, St Andrews, (Co-Director), SOFC/ECs; Professor Ian Metcalfe, Newcastle (Co-Director), Hydrogen Production; Dr Tim Mays, Bath (Co-Director), Hydrogen Storage; Professor David Book, University of Birmingham, Hydrogen Storage Materials /Education & Training; Professor Paul Ekins, UCL, Socio-economics and Policy; Professor Anthony Kucernak, Imperial College, (PEFCs); Professor Vladimir Molkov, Ulster, Hydrogen Safety; Professor Robert Steinberger-Wilckens, University of Birmingham, Education and Training; Professor Nilay Shah, Imperial College, Hydrogen Systems.

→ market. Intelligent Energy (IE) focuses on the development of PEFCs across the stationary power, automotive and consumer electronics sectors. IE led the HyTEC consortium to introduce a fleet of five zero emission fuel cell electric taxis that operate in London utilising a high efficiency PEFC and lithium battery powered electric hybrid with a 250-mile driving range, refuelled in less than 5 minutes at a publically accessible refuelling station at Heathrow Airport. The company also pioneered the first Hydrogen Fuel Cell motorbike and have developed fuel cell powered Upp mobile charger and are developing fuel cell back- up generators within the telecom sector in India. AFC-Energy is the world leader in Alkaline Fuel Cells and plays particular attention to stationary power markets has had considerable success in Korea and leads the FCH-JU funded project Alkamonia which looks at ammonia as a fuel source for alkaline fuel cells. ITM-Power, based in Sheffield focuses on electrolysers and has launched a first Power-to-Gas (P2G) plant to the Thüga Group in Frankfurt, Germany[3]. Hydrogen production, distribution and storage are areas that have strong industrial support presence in the UK. Air Products are building a 49 MW waste gasification plant at Teesside in the North East of England , which can produce either electricity or hydrogen from waste. Additional UK firms that are producing fuel cell products include Arcola Energy, Fuel Cell Systems, LightGreen Power and BOC. The UK has also recently seen new innovative start-up companies such as Ilika, Acal, Amalyst and Cella Energy.

UKH2Mobility is a cross cutting industry –government programme consisting of three government departments and industrial representation from the global car manufacturing, infrastructure, utility and gas sectors. In 2013, UKH2Mobility

released Phase I of their study where they explored the potential for Fuel Cell vehicles in the UK[4]. London has fuel cell buses which are part of the EU funded project, CHiC which operate the same way as any other bus in operation. A similar bus project has been launched in Aberdeen.

At the Hub's core is a research programme that spans the whole Hydrogen and Fuel Cell landscape incorporating hydrogen production, storage, and systems, low temperature fuel cells (Polymer Electrolyte Fuel Cells (PEFCs)), high temperature fuel cells (Solid Oxide Fuel Cells (SOFCs)), policy and economics, safety, and education and training with each one of these research areas having an academic lead (see Figure 1).

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Jacqueline EDGE[1]*, Nigel BRANDON[1], John IRVINE[2], Tim MAYS[3], Ian METCALFE[4], David BOOK[5], Paul EKINS[6], Anthony KUCERNAK[1], Vladimir MOLKOV[7], Robert STEINBERGER-WILCKENS[8], Nilay SHAH[1],

[1] Energy Futures Lab, Imperial College London, SW7 2AZ, UK, **h2fc@imperial.ac.uk**
[2] School of Chemistry, University of St Andrews, KY16 9ST, UK
[3] Department of Chemical Engineering, University of Bath, BA2 7AY, UK
[4] School of Chemical Engineering and Advanced Materials, Newcastle University, NE1 7RU, UK
[5] School of Metallurgy and Materials, University of Birmingham, B15 2TT, UK
[6] UCL Institute for Sustainable Resources, University College London, WC1H 0NN, UK
[7] Hydrogen Safety Engineering and Research Centre (HySAFER), University of Ulster , BT37 0QB, UK
[8] Centre for H2 & Fuel Cell Research, School of Chem. Eng., University of Birmingham, B15 2TT, UK

Center for doctoral training "fuel cells & their fuels – clean power for the 21ˢᵗ century"

The need for a CDT in fuel cells and their fuels in the UK

The Fuel Cells & Their Fuels Centre for Doctoral Training (CDT) builds on the success of The Hydrogen, Fuel Cells and Their Applications CDT which was established in 2009 and was a Midlands Energy Consortium (MEC) collaboration between the universities of Birmingham (UoB), Loughborough (LU) and Nottingham (UoN). The CDT was extremely successful, training over 60 PhD students producing its first graduates in 2013.

The success of the CDT is evidenced by the fact that all the graduating students' secured employment either prior to leaving the University or in a short time of completion (incl. positions at Intelligent Energy, MIBA and MicroCabs).

The CDT has been praised for the high standard of students recruited, for the quality of training provided, and for the multidisciplinary nature of the topics covered. The taught element of the CDT has evidenced the benefit of a structured training programme and its benefits to the students.

The inclusion of Imperial College London (ICL) and University College London (UCL) to the existing midlands based partnership of University of Birmingham, Loughborough University and The University of Nottingham brings expertise in new fields including policy and environmental studies, and advanced materials characterisation. The taught programme for PhD students includes hydrogen safety modules to be delivered by Ulster University.　➔

The name of the CDT has changed from Hydrogen Fuel Cells and their Applications to Fuel Cells and their Fuels to accommodate the wider range of fuels used in fuel cells today including direct use of natural gas, ethanol, gasification syngas, and other biomass products.

Market vision and impact

The fuel cell and hydrogen (FCH) sector is rapidly expanding and offers many opportunities for R&D and for job creation as new markets are opened. The UK is in an excellent position to capitalise on this development and reap the financial and environmental benefits by being at the forefront of R&D and commercialisation of these technologies. The Strategic Energy Technology-Plan (SET-Plan) education roadmap document estimates that the number of engineers and scientists involved in the area of Fuel Cells and their Fuels across the EU will grow from around 2000 in 2012 to 17,400 in 2020, and to over 50,000 by 2030. For the UK, independent assessment has estimated that by 2020 there will be an extra 2200 people directly employed in the FC sector and a further 2000 jobs in the related supply chain and maintenance. This rapid expansion means there will be an increasing industry need for highly trained researchers with an excellent understanding of fuel cells, related energy technologies and coupled with team leadership skills. These researchers need knowledge of the underpinning science and engineering and the wider social, economic, and policy implications.

Expanding FCH market opportunities

An example of the expanding FCH market opportunities is the announcement from major automotive OEMs (Hyundai, Mercedes, Toyota, Honda and Renault-Nissan-Ford-Daimler) of commercial roll-out of Fuel Cell Electric Vehicles (FCEV) by 2015/2016.

In order to maximise the benefit from such developments, it is critical that the UK becomes a leading player. These emerging markets are estimated at $26 billion by 2020, with growth continuing at 26% p.a.

The government supported UKH2Mobility project has unveiled plans for developing the hydrogen infrastructure (60 fuelling stations by 2015, increasing to 1000 by 2030) with an anticipated 1.5 million hydrogen powered vehicles on UK roads by 2030. This will accelerate other hydrogen and fuel cell technologies in the UK as they can take advantage of the evolving infrastructure.

Transport technologies are being developed by British companies such as Microcab, Auriga and Riversimple, whilst stationary fuel cells for back-up power and residential CHP systems are being built at Intelligent Energy and Ceres Power.

Fuel cells, as low-carbon technologies, will support the reduction of CO_2 emissions. They are essential components of the UK energy mix to support it meeting 2050 emission reduction targets. Other benefits for the UK are: the reduced need for energy imports, particularly transport fuels; decreased economic/political risk associated with energy price　➔

➔ volatility, resource depletion, and political instability of energy exporting countries; and grid stability from Grid-2-Gas concepts. Industry (incl. E.ON UK, SSE, ITM Power) has developed a keen interest for the latter idea (for instance as implemented in the TSB Ecoisland project led by ITM Power) by using electrolysers as variable loads to aid electricity grid stability and shift energy from electricity to the gas grid or providing hydrogen for FCEVs, at the same time gaining control of fluctuating renewable energy supplies.

John C HOOPER*
*University of Birmingham, UK, **j.c.hooper@bham.ac.uk**

European technical school on hydrogen and fuel cells 2015

The European Technical School on Hydrogen and Fuel Cells 2015 is funded by the European Commission under the H2FC project and coordinated by the University of Ulster. The school was held from the 22th to the 26th of June 2015 in Crete, Greece.

In 2015 the technical school gathered 93 participants, the highest number compared to the previous technical schools held in 2012 (60), 2013 (59) and 2014 (71). The participants, including academics, researchers and post-graduate students came from 28 countries around the globe. There were representatives from the EU states as well as them from Argentina, Brazil, Canada, China, Japan, Libya, South Africa, USA.

The sessions at the European Technical School on Hydrogen and Fuel Cells 2015 address the themes of hydrogen safety, storage and fuel cells. The programme includes topical lectures, outcomes of H2FC transnational access, e-infrastruc-

ture for hydrogen and fuel cell research: hydrogen safety, storage and fuel cells, hands-on training session for use of the Cyber-laboratory and poster presentations on state-of-the-art research. The detailed programme is available on the website **http://www.h2fc.eu/technicalschool**

Detailed review of the European Technical School on Hydrogen and Fuel Cells 2015 will be introduced in next issue.

Wookyung KIM*
HySAFER centre, Ulster University, UK, **w.kim@ulster.ac.uk**

Figure 1. Aquis Arina Sand hotel in Heraklion.

Figure 2. Conference room for the school 2015.

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ICHS 2015 CONFERENCE SCOPE

The 6th International Conference on Hydrogen Safety (ICHS 2015) will be held in Tokyo, Japan on October 14-17, 2015 under the auspices of the International Association for Hydrogen Safety (HySafe). The first five biennal conferences since 2005 succeeded in attracting the most relevant experts from all over the world, by providing an open platform for the presentation and discussion of new findings, information and data on hydrogen safety – covering the wide range of areas from basic research to applied research and development to standardization and regulations. As commercialization of hydrogen fuel cell electric vehicles is imminent and other hydrogen applications are being increasingly deployed globally, ICHS 2015 will focus on progress in safety of hydrogen technologies and infrastructure, as crucial/essential means to enable smart hydrogen solutions for global energy challenges. Therefore, the conference seeks papers in a wide range of hydrogen safety topics like (but not limited to) Regulations Codes and Standards, safety in H_2 infrastructure, safety solutions for the implementation of H_2 technologies, hydrogen and hydrogen blends behavior, physical effects, consequence analysis, incidents, accidents and near misses, hydrogen effects on materials and components, safety of energy storage, risk management and fuel cells related safety issues. A detailed list of ICHS 2015 Themes and Topics is shown below. All contributions to ICHS 2015 will be evaluated exclusively in the light of their scientific content and relevance to hydrogen safety.

ICHS 2015 CONFERENCE STRUCTURE

ICHS 2015 will include thematic plenary sessions, topical lectures, and parallel oral and poster sessions. The conference seeks to facilitate (enable/strengthen) the near term introduction of hydrogen technologies in the market place.

CONFERENCE ORGANIZING COMMITTEE

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CONFERENCE SCIENTIFIC COMMITTEE

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European fuel cell technology & applications Piero Lunghi conference

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Naples | **16-18** december

Topics

:: Materials
:: Modeling
:: Lab Tests
:: System Design
:: Fuels and decarbonizing society
:: Fuel Cell applications
:: Fuel Cells operated in reversed mode
:: Marketing and Policy pathways
   to full commercialization of Fuel Cells
:: Cross-cutting Issues
:: New ideas and bad ideas in FC

Special Sessions
dedicated to

:: Safety, Regulations codes
   & standards in Fuel Cells
:: Microbial Fuel Cells
:: Dissemination of European projects
   on Fuel Cells and Hydrogen

The Call for Abstracts is Open
Submit your abstract at www.europeanfuelcell.it

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"PARTHENOPE"**

The European Fuel Cell Technology & Applications "Piero Lunghi Conference", acronym EFC15, is going to celebrate its 6th edition in Naples, Italy, from 16 to 18 December 2015.

Organized by the University of Perugia and the Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) with the support of the University of Naples "Parthenope", and framed within the "H2FC European Infrastructure" project, this breakthrough conference offers three full days of intensive interaction with prominent academics, researchers, students, politicians and entrepreneurs, in the field of fuel cells. It is a major opportunity for intensifying international cooperation, expanding understanding and promoting efforts and disciplines in the area of Fuel Cells, from powder preparation to system applications. Dissemination of knowledge through the presentation of research results, state-of-the-art developments and novel concepts in this area are the key driver in the conference program.
This two-year conference has grown ever since its first edition in 2005 boasting an average of 250 participants from all over the world and 200 scientific contributions between oral and poster presentations. Several side-events normally supplement ➔

➔   the main conference and also for the 6th edition a number of thematic and dedicated workshop are foreseen. For the 2015, authors are invited to submit an abstract on the following topics:

• Materials
• Modeling
• Lab Tests
• System Design
• Fuels and decarbonizing society
• Fuel Cell applications
• Fuel Cells operated in reversed mode
• Marketing and Policy pathways to full commercialization of Fuel Cells
• Cross-cutting Issues
• New ideas and bad ideas in FC
• Safety, Regulations codes & standards in Fuel Cells
• Microbial Fuel Cells
• Dissemination of European projects on Fuel Cells and Hydrogen

Selected papers will be published in the "International Journal of Hydrogen Energy" (IJHE) and "Applied Energy".

We look forward to welcome you in beautiful Naples!
www.europeanfuelcell.it

Chiara BARCHIESI*
*University of Perugia, IT, **chiara.barchiesi@unipg.it**

Events July 2015–March 2016

30.06.–03.07.2015	5th European PEFC & H2 Forum http://www.efcf.com/	Lucerne, Switzerland
19.07.–24.07.2015	30th International Symposium on Shock Waves http://www.ortra.com/events/issw30/Welcome.aspx	Tel-Aviv, Israel
26.07.–31.07.2015	14th International Symposium on Solid Oxide Fuel Cells http://www.electrochem.org/meetings/satellite/glasgow/	Glasgow, UK
30.08.–04.09.2015	NURETH 2015 http://nureth16.anl.gov/	Chicago, USA
15.09.–17.09.2015	Critical Power Expo http://www.criticalpowerexpo.com/	Michigan, USA
11.10.–14.10.2015	World Hydrogen Technologies Convention 2015 http://www.whtc2015.com/	Sydney, Australia
12.10.–14.10.2015	F- Cell 2015 http://www.messen.de/de/11049/in/Stuttgart/f-cell/info.html	Stuttgart, Germany
19.10.–21.10.2015	6th International Conference on Hydrogen Safety http://www.ichs2015.com/	Yokohama, Japan
16.11.–19.11.2015	2015 Fuel Cell Seminar and Energy Exposition http://fuelcellseminar.com/	Los Angeles, USA
17.11.–20.11.2015	3rd Zing Hydrogen & Fuel Cells Conference http://www.zingconferences.com/conferences/3rd-zing-hydrogen-fuel-cells-conference/	Cancun, Mexico
16.12.–18.12.2015	European Fuel Cell Technology & Applications Piero Lunghi Conference http://www.europeanfuelcell.it/	Naples, Italy

→ **Events July 2015–March 2016**

11.01.–15.01.2016	1st HyResponse pilot training session http://www.hyresponse.eu/session1.php	ENSOSP, Aix en Provence, France
02.03.–04.03.2016	12th Int'l Hydrogen & Fuel Cell Expo (FC EXPO 2016) http://www.fcexpo.jp/en/	Tokyo, Japan

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