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Summary report for a hydrogen sensor workshop

Hydrogen safety sensors and their use in applications with hydrogen as an alternative fuel

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Contents

DEDICATION

It is with sadness that the authors learned of the death of Dr. Thomas Hübert on November 15, 2017. Dr. Hübert established, led and developed the hydrogen sensor test facility at the Bundesanstalt für Materialforschung und -prüfung (BAM) in Berlin, Germany; he researched methods for improving the safety in the areas of hydrogen production, distribution, and use. Thomas participated in the Hydrogen Sensor Workshop and made significant contributions, which are reflected in the report. He was our colleague as well as our friend. As a token of respect and recognition of his expertise in hydrogen sensors, we would like to dedicate this report and the workshop findings to Thomas. We will miss him.

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Abstract

On May 10, 2017, a Hydrogen Sensor Workshop was held in Brussels, Belgium. The workshop was jointly organised by the sensor test laboratories at the Joint Research Centre (Petten, Netherlands) and the National Renewable Energy Laboratory (Golden, Colorado, United States), with assistance from the Fuel Cell and Hydrogen Joint Undertaking. The purpose of the workshop was to bring together stakeholders in the hydrogen community with an interest in hydrogen sensors, with a special focus on the ability of existing hydrogen sensor technology to meet end-user needs in applications for hydrogen as an alternative fuel. Participants included sensor manufacturers, end-users, and experts from sensor test laboratories. The main performance gaps hindering the deployment of hydrogen sensors were discussed. From the end-user perspective, numerous gaps were identified in which existing sensor performance capability does not fully meet their needs. For most safety applications, the metrological performance of current hydrogen sensors is adequate, but improvements are still needed. The most critical metrological gap remains sensor lifetime, which includes both the functionality of the sensor (i.e., does the sensor work) and long-term signal stability (i.e., does the sensor need to be recalibrated). Also, for many applications, such as process control and critical safety scenarios, faster response times and improved sensor accuracy are necessary. Maintenance and calibration requirements were identified as a key issue. Certification requirements of hydrogen safety sensors were also identified as a critical barrier. Sensor manufacturers noted that the cumbersome certification requirements can significantly impact sensor cost, especially for a limited market. The complex certification requirements also impacted end-users who often found that sensors with required listings were not available. Simplifying and harmonizing certification requirements were identified as a critical topic requiring further attention and support. In terms of standardisation, the performance requirements for sensors for automotive applications were also mentioned as a critical gap.

The following table summarizes the high-priority gaps identified in the workshop that impact the performance and use of hydrogen sensors by end-users. A more complete gap analysis is provided in the following report. In addition to the identification of gaps and barriers, the workshop discussed strategies to address the gaps.

Metric Requirement and Gap Identification	Supplemental Comments	Application
Metrological Metrics		
Lifetime		
10-year life	Replacement cost too high, down time associated with sensor failure	Infrastructure/Automotive
Impact of chemical stressors (poisons)	Harsh chemical environment adversely affecting performance	Infrastructure/Automotive
Impact of physical stressors (T, P, RH)	Harsh environmental conditions adversely affecting performance	Infrastructure/Automotive
Accuracy		
Impact of chemical stressors (interferents)	Chemical Interferents may cause false positive or false negative alarms	
Impact of physical stressors (Environment-T, P, RH)	Environmental Interferents may cause false positive or false negative alarms	
Response Time		
General	<2 sec is desired for many applications	Infrastructure/Automotive
Flow-rate Dependence	Impact with quiescent environment vs. dynamic flowing conditions	Infrastructure/Automotive
Exhaust and process control	< 1 sec (300 ms)	Automotive
Deployment Metrics		
Cost and Availability		
Capital Cost	Need for lower cost (< 50 € for automotive; < 400 € for most infrastructure)	Automotive/Infrastructure
Codes, Standards and Regulations/Directives Issues		
Standards not always available (gaps)	No uniform set of requirements/variable requirements for different applications	Infrastructure/Automotive
Complex, costly, and often national requirements	No uniform set of certification requirements; need to simplify and harmonize	Infrastructure/Automotive
Operational Metrics		
Cost		
Maintenance and Calibration	Considered a bigger concern than capital cost; maintenance intervals > 1 year desired	Infrastructure/Automotive
Sensor Placement and Guidance	Dispersion behaviour of hydrogen plumes not fully characterized	
Location/placement of sensor	No formal guidance on sensor placement is needed	Infrastructure
Wide Area Monitoring	Need for low-cost, automated monitoring and profiling around small to large scale facilities	Infrastructure /Research

1 Introduction

A workshop on hydrogen sensors was held on May 10, 2017 at the Headquarters of the European Commission's Fuel Cell and Hydrogen Joint Undertaking (FCH JU) in Brussels, Belgium. It was jointly organised by European Commission's Directorate General Joint Research Centre (JRC), the United States' Department of Energy (DOE) National Renewable Energy Laboratory (NREL), and the FCH JU. The NREL-JRC sensor laboratories collaborate under the auspices of an agreement between DOE and JRC to encourage collaboration within the area of energy research [1].

The purpose of the workshop was to bring together stakeholders in the hydrogen community with an interest in hydrogen sensors, with a focus on the ability of existing hydrogen sensor technology to meet end-user needs in hydrogen alternative fuel applications. Participants included program administrators, sensor manufacturers, end-users, and experts from sensor test laboratories. In addition, it is noted that many of the participants were active on national and international standard development organizations. The workshop agenda is shown in Appendix 1 and covered critical topics pertaining to the use and acceptance of hydrogen sensors. Each session started with a topical talk, but the structure of the workshop was to minimize the duration of the talks, and instead to encourage interaction and input from among the participants.

Bart Biebuyck, Executive Director of FCH JU, gave the opening comments, emphasising that sensor technology is a key enabling technology for hydrogen energy infrastructure and vehicle implementation. In terms of remaining challenges, cost, performance, calibration, reliability and the supply chain were mentioned. He also stated that there are several options to support the development and deployment of hydrogen sensors within the umbrella of the FCH JU program:

1. There are two remaining calls for the FCH2 JU (2019 and 2020) for which there is be an opportunity to propose topics to bring forward sensor technology.
2. JRC sensor test facility (SenTeF) is an option to address different challenges for sensor development and deployment. JRC has a framework contract with the FCH JU.
3. Apart from call for proposals, studies launched through a call for tender are another option to support sensor technology. Tenders usually are limited in scope and only cover specific topics, but have a much shorter lead time than other funding avenues. They are launched regularly by the FCH JU

1.1 Workshop Introduction

Following the opening comments by Bart Biebuyck, William Buttner (NREL) gave the introduction to the workshop, summarizing the reasons for the workshop and identifying the main objectives. The impetus for the workshop was that it was deemed necessary to perform an updated sensor gap analysis because of recent improvements in sensor performance in some metrics (e.g., response time, robustness against poisons) coupled with a growing hydrogen market. A gap analysis of performance expectations versus capability is best based upon input from critical stakeholders in the hydrogen community. Although the primary application pertained to hydrogen as an alternative fuel, other markets are critical to support the development and use of hydrogen sensors (e.g., the nuclear industry), although input from other industries was somewhat limited because of the small number of participants representing these alternative markets. In brief, sensor performance must meet the end-user needs, and the end-user needs must be identified and documented.

The introduction was followed by an open session, in which each participant introduced him- or herself and identified their organization. The introductions included a short description of individual experiences with or interest in hydrogen sensors. The participants represented sensor manufacturers and end-users, including representatives from vehicle manufacturers, hydrogen infrastructure, and other industries. In addition, there were international representations from sensor test and evaluation facilities (NREL, JRC, and the Bundesanstalt für Materialforschung und prüfung - BAM), and project officers from the FCH JU. The list of participants can be found in Appendix 2. Feedback from the participants identified a range of expectations from the workshop, which varied by perspective (e.g., end-user vs. supplier). Desired outcomes or topics to be covered in the workshop as identified by the participants included:

Sensor manufacturers:

- Expectation of customers
- Cost and lifetime challenges
- Need for defined application-specific requirements (infrastructure)

End-User (Automotive)

- Status of technologies
- Codes and Standards—Verification technology (i.e., GTR-13 FCEV exhaust requirements)
- Leak detection at ambient conditions
- Hydrogen monitoring for FCEV exhaust
- Lifetime/cost
- Capital Cost (<50 €)
- Lifetime of 10 years without calibration/maintenance

End-User (Infrastructure):

- Simplification of Code and Standards Requirements
- Education on sensor technology, especially pertaining to different sensor platforms
- Reliability of sensors (i.e., long lifetime)
- Maintenance and recalibration of sensors
- Cost of deployment and operation
- Monitoring requirements for different release scenarios (e.g., outdoor release, semi-enclosed, wide area monitoring)
- Liquid hydrogen
- Cross-Cutting Topics and Special Applications
    - H2 in natural gas (Power to Gas)
    - Operation in harsh environments (High RH, elevated T, radiation)
- Stability more important than sensitivity (Nuclear storage)
- Certification versus other means to demonstrate that sensors work
- Improved accuracy (i.e., especially research applications)
- Platform-specific performance expectation and properties
- WAM, sensor networks

Thus, there were a significant number of topical areas of concerns identified by the participants (even before the technical discussions), affirming that hydrogen sensors are not yet simply a plug and go technology and that performance gaps exist. The subsequent technical discussions addressed many of these topics and led to a list of gaps, as presented in the overview of Session 5.

1.2 Overview of sensor testing facilities

Following introductions, overviews of the NREL, BAM, and JRC hydrogen sensor test laboratories were given. An important take-home message from this session was that the sensor test laboratories are a resource to the hydrogen community.

William Buttner described the mission and capability of sensor testing facility at NREL [2]. The NREL Hydrogen Sensor Testing Laboratory research, development, and demonstration (RD&D) effort is guided by the needs of the hydrogen community, as based upon input and feedback from stakeholders. The NREL sensor test facility assesses the performance of hydrogen sensing elements, sensors, and analysers under a variety of environmental conditions. This activity is performed for both sensor manufacturers/developers and end-users. Currently, the NREL Sensor Laboratory activity also supports deployment of hydrogen sensors for infrastructure and vehicles. The NREL sensor laboratory is also active in the development of hydrogen safety codes and standards. William Buttner also gave an overview of various on-going projects, including support of the GTR-13 (an analyser for the verification of FCEV exhaust as prescribed by GTR-13) [3], support of standard development organizations (e.g., the development of the SAE Technical Information Report TIR J3089 "Characterization of On-Board Vehicular Hydrogen Sensors", NFPA 2), hydrogen plume measurements [4] (safe use of liquid hydrogen/wide area monitoring) and guidance on the indoor deployment of hydrogen sensors.

Thomas Hübert (BAM) introduced the sensor laboratory at BAM [5]. The presentation focused on the facility for quantifying the response time for fast hydrogen sensors, and the difficulties to assess this parameter with minimal instrumental artefacts [6]. This parameter is of special relevance in automotive applications since in many scenarios a 1-second response time (or faster) is strongly desired and sometimes mandated by regulations. Characteristics of this facility include:

- Valve switching time 8 to 15 milliseconds
- 1000 data measurements per second
- Sensor signals: 0 to 50 mA, 0 to 100 mA, 0 to 10 V, 0 to 50 V

Rafael Ortiz Cebolla (JRC) gave a presentation about the testing capabilities and recent activity of the SenTeF laboratory at JRC [7]. Testing capabilities include:

- Control of environmental parameters (Pressure, Temperature, RH)
- Measurement of <1 second response time
- Lifetime and impact of deployment conditions
- Interferents/Poisoning
- Chamber and Flow-through apparatus
- Simultaneous testing of multiple sensors
- Multiple test benches for general testing (flow-through and chamber [8]), response time [9], life test, and capabilities for custom testing

There is also a proposed initiative to soon provide open access to the SenTeF laboratory for research institutions, small to medium enterprises (SMEs) and industry. The NREL and BAM sensor laboratories also have programs to provide access to their facilities to outside users.

A summary of select past SenTeF activities was highlighted:

- FCH JU project H2 Sense: Cost-effective and reliable hydrogen sensors for facilitating the safe use of hydrogen [10]
    - Assessment of the state-of-the-art hydrogen sensor technologies
    - Inventory of existing applications and identification of near-term applications

- Sensor INTER-laboratory COMparison (Sintercom) [11]:
  - Cross-validation of the NREL and the JRC sensor test laboratories and methodologies
  - Guidance to sensor development and use
- FCH JU project HyIndoor [12]
  - Assessment of several hydrogen sensors platforms for selected indoor applications
- EU FP7 capacities project H2FC European Infrastructure [13]
  - Design of a test bench to develop accelerated lifetime test methods.
- Effect of contaminants [14]
  - Study of the cross sensitivity and poisoning of hydrogen sensors to other gas species
- The Development of a Market Survey [15] and sensor data [16] for H2Sense in 2015.
  - The survey is available on the BAM website.

Current activities for the SenTeF laboratory include:

- Validation of Flow-Through method vs. Chamber method [8]
- Effect of contaminants (Continuation) [17]
- Hydrogen sensors in natural gas-hydrogen mixtures
- Intern trainee programme in place for visiting university students. The on-going internship program enables young researchers to learn about energy technologies

Several of the current and past JRC SenTeF activities were in collaboration with the NREL sensor laboratory, including this workshop.

1.3 Previous gap analysis

Thomas Hübert/BAM summarised the results from a sensor gap analysis performed by the JRC and BAM in 2010 [18]. This analysis identified performance gaps in hydrogen safety sensor technology for automotive and stationary applications. The main gaps where further research and development were required are summarised below:

- Upper limit of operation temperature (125 °C)
- Operating pressure at lower pressures (62 kPa)
- Operating at high relative humidity (<95 %)
- Shorter response and recovery times
- Life time > 5 years

Following the overview sessions on the sensor laboratories, there were a series of topical sessions, each of which included a short presentation followed by open discussions among the workshop participants. Highlights and outcomes from each of these sessions are discussed below.

2 Workshop Sessions

2.1 Session 1: Customer experiences and expectations / Manufacturer Perspective

The topics addressed in this session focused on sensor use, requirements, and issues from both the end-user and manufacturer perspectives. A short list of topics was provided in the topical talk for this session to guide the discussions and included:

Issues and Experiences from the End-User Perspective:

- Impression of sensors
- Do sensors met your needs?
- Are there shortcomings?
- Are sensors the solution?
- Availability/Performance in the field

Issues and Experiences from the manufacturer perspective:

- Market uncertainty and variability
- Application specific requirements

This session was meant to share experiences among stakeholders and to provide manufacturers with first-hand feedback from the end-users.

The **sensor manufacturers** emphasised that there is not a specific sensor that can fulfil the requirements for all applications and that requirements vary significantly among the various applications that need hydrogen sensors. Some requirements can be challenging if not fundamentally conflicting; for example, long lifetime with no maintenance and low cost. One sensor manufacturer gave specifications of their sensor that is currently deployed as a safety sensor in fuel cell electric vehicles (FCEV). The sensor was described as having a start-up time of 1 second, response time of 2 seconds (t_{90}), temperature range operation of -35°C to +85°C, relative humidity up to 95% and lifetime of 5 years. A calibration and maintenance check are recommended every year or 15000 km. In this maintenance check the sensor is exposed to 1.3 vol% H2. Some field performance data was also provided by the manufacturer. Since 2015 no failures have been reported. One representative from the automotive sector (that uses this sensor) said that, according to their experience, the performance of this sensor is satisfactory. This sensor, however, does not yet meet the cost requirement specified by the vehicle manufacturers (see Section 2.3).

Representatives from the **automotive sector** agreed about the usefulness of having specific standards for automotive applications, including sensors for on-vehicle applications. There was a suggestion that sensors be deployed in private and public garages that accommodate FCEV. However, vehicle representatives stated a strong reluctance to mandate the installation of hydrogen sensors in private garages. From their point of view, there is no safety issue when parking hydrogen vehicles in indoor garages. According to them, leaks are unlikely in normal operation and that any potential leak problem will take place when the car is running and therefore the sensors in the car will detect it and activate the safety protocol (i.e. shut-off valves). In addition, it was argued that to force the end-users to install a hydrogen sensor in their garages will increase the cost of car purchase to the costumer and also enhance a perception that hydrogen vehicles are more dangerous than conventional technologies (i.e., compressed natural gas, gasoline), the use of which do not require private installation of gas sensors. One of the infrastructure representatives however, mentioned that specific hydrogen vehicle components such as thermally activated pressure relief devices (TPRD) could fail and release hydrogen when the vehicle is parked. Also, it was pointed out that indoor fuel cells (such as those that are being increasingly installed in private homes in Japan) have hydrogen sensors installed that operate at all times.

Representatives from the automotive sector also discussed specifications for different applications. For on-board applications a measuring range up to 4 vol% with a lower detection limit at around 0.1 to 0.4 vol% was adequate. However, for the FCEV tailpipe application, a range up to 10 vol% is required with a response time of 300 ms. Conversely, for a leak detector (e.g., a "sniffer"), a much lower detection limit is necessary (< 100 ppm_v), although quantitation of the measurement is not critical.

Users from the infrastructure sector (e.g., hydrogen refuelling stations, HRS) stated that what they need from hydrogen sensor technology is reliability, accuracy, and robustness, together with low maintenance.

Specific requirements were also discussed for hydrogen sensors used in special applications such as aeronautics industry. These requirements are related to electro-magnetic fields (avoid interference with the equipment on-board) and vibrations. Similarly, the nuclear industry needed sensors with long operational lifetimes (>10 years) that will not be affected by radiation.

Representatives from research institutions had different experiences and requirements for the sensors. A strong influence of environmental parameters in the response of the sensors has been observed. Other applications were discussed, for example hydrogen–natural gas mixtures (Power-to-Gas) or storage of nuclear waste, where the sensors can be exposed a complex chemical background or to high levels of radiation. This last application can also require the use of wireless sensors, and very low maintenance frequency. A sensor for this particular application is being developed by one of the participants working in the nuclear industry, but they would like to know from sensor manufacturers if there are sensor other available.

In the past, many end-users had a preconceived perception that hydrogen sensors were not reliable, and provided minimal contribution to the overall safety of a hydrogen system. This negative attitude is not as prevalent as it had been in the past. It was, in fact, not mentioned in the workshop. In general the participants of the workshop were of an opinion that sensors are an important safety tool and necessary to assure the success of hydrogen as an alternative energy carrier.

2.2 Session 2: Sensor Analytical Performance Requirements

This session focused on the metrological (analytical) metrics of hydrogen sensors. These are related to the ability to perform the measurements. The main metrological metrics include:

Accuracy, Baseline, Cross-sensitivity (Selectivity), Drift, Environmental Effect, Final Indication, Hysteresis, Limit of Quantification, Lower Detection Limit, Linear Range/Measuring range, Noise, Operation Range (T, P, RH), Poison, Uncertainty, Response/Recovery time, Reversibility, Resolution, Saturation, Sensitivity.

A main topic of the discussion was what specification (e.g., a number) should be assigned to a specific Metric (e.g., a performance parameter). Some issues include:

- Response time
    - How is Response Time Determined (e.g., t_{90} vs. t_{67})
    - Requirements (variable, depending on applications)
    - How is the parameter measured?
- Accuracy Concerns: In laboratory performance testing, NREL found that about 1/3 models were out of specification with regard to accuracy specifications
- Selectivity (False alarms)
- Ranges/Detection Limit

- Impact of Environmental Parameters (T, P, RH)

Representatives from the automotive sector requested a higher operation temperature than infrastructure applications. It was recommended that the upper temperature limit to be expanded from the current 85°C up to 100-125°C. However, in a subsequent discussion with JARI representatives, it was argued that the upper temperature limit should be 85˚C, indicating that there is still debate among the automakers on the exact specification. Another desired requirement for *some* automotive applications was a sensor response time on the order of 1 second, or, in the case that the sensor response time does not meet this requirement, that the response time is as fast as possible. One other point of concern mentioned by a vehicle manufacturer pertained to the possible poisoning of sensors during maintenance procedures; the specific concern was that many different solvents and lubricants are used during routine vehicle maintenance and these could negatively impact performance if exposed to the sensor; an example would be silicone-based lubricants or cleaners. This is a specific example of the need for the sensor to be robust against chemical interferents and poisons,

Representatives from research institutions also provided input from their experience (this was often based on a single specific sensor platform). Sensors with higher accuracy (1% deviation of final reading) are needed. Also, the sensor response should not be affected by environmental factors as temperature and/or humidity.

There were cross-cutting comments between automotive and infrastructure applications. Flow dependence of sensor response should be reduced since sensors are often deployed without active gas transport (e.g., in rooms or containers). There were discussions related to the sensor housing design; explosion proof designs and more compact sensors are other requirements. It was also requested that some clarification be developed on the properties of different hydrogen sensor platforms and how these properties relate to the intended applications.

Representatives from infrastructure pointed out the difficulties of using hydrogen sensors in environments with high concentration of oxygen and humidity (electrolyser cathode gas streams). The high humidity concern is germane to FCEV exhaust as well. Also, some users express a need to reliably perform, in a simple manner, multiple point hydrogen measurements around fuelling stations (i.e., Wide Area Monitoring, WAM); battery power with a long-operational life (or other off-grid power sources) and remote interrogation were identified as useful design features for WAM.

2.3 Session 3: Sensor Deployment Considerations

In addition to metrological metrics, there are other factors that need to be considered when selecting a sensor for an application. These often can be described as "deployment metrics" and "operational metrics" [19]. Deployment metrics are essentially one-time considerations (e.g., capital costs) while operational metrics pertain to on-going or recurring requirements (e.g., calibration requirements). Other examples are presented below.

Deployment metrics:

Alarm Set Points, Capital Costs, Control Circuitry, Electronic Interface, Installation Cost, Commercial Maturity, Placement, Physical Size, Pneumatic Design, Power Requirements, RCS (regulations, codes & standards), Shelf Life

Operational metrics:

Calibration Requirements, Consumables, Device to Device Repeatability, Maintenance Matric Effects, Mechanical Stability, Minimum Analyte Volume, Operation Lifetime, Orientation Effect, Warm-up Time

The open discussion during this session was focused on the identification of the most important deployment and operational requirements, which was cost, which is comprised of both capital and operational costs. However, the complex certification requirements were also a major concern and topic of discussion. Thomas Hübert provided a rather lengthy but still partial list of standards that a sensor may need to be certified to (14 individual standards were identified, see Appendix 3). A manufacturer representative noted that the cost to obtain certifications to all standards is prohibitive and asked for clarification as to what is actually required. Regrettably, there was no easy concise answer to this question; certification requirements will remain application and jurisdiction dependent. The cost of certification is further exacerbated by the need to use national standards. This thus may require multiple, possible redundant certification (and the related costs) for international markets. For example, in Great Britain, as it was pointed out, some industries require certification to standards from Great Britain. In the case of a limited market, the cost of certification would be spread over a small number of unit sales. Manufacturers pointed out that certification can be too costly for the current market size. It was suggested that the database developed by the JRC for H2Sense [16] should be upgraded to include the certifications for the sensor. End-users, especially from the infrastructure sector, noted that their equipment must be compliant to a range of standards (i.e., performance, electrical); it is necessary that components in such equipment, including sensor, are compliant to those standards.

End-users strongly desire cheaper sensors. In automotive applications, , the price of all their components needs to be low in order to be competitive. It is considered that 50 €/pc would be a competitive price for sensors in hydrogen vehicles (which was coupled with a 10-year, maintenance free lifetime). Manufacturers stated that sensors for 50 euros are not impossible, but it will depend on implementing sensor designs amenable to advance manufacturing methods that can properly exploit economy of scale manufacturing.

There were also concerns related to calibration and maintenance costs. Regular routine calibration and maintenance activity will likely remain mandatory for many infrastructure applications. Depending on the frequency of maintenance and the specific training required for this activity, the total cost of the sensor could increase to levels not acceptable for many of the end-users; this expense is further increased when facilities use many sensors. Some automotive manufacturers have staff in their repair facilities trained to check the functioning of the sensors, but this will not necessarily be universally true for all OEMs and other infrastructures.

2.4 Session 4: Sensor Lifetime

Sensor lifetime is one of the most important metrological parameters. Depending on the application there are different lifetime requirements. For instance, DOE set a life-time target minimum of 5 years for stationary applications. Conversely, in the DOE Fuel Cell Technology Multi-Year plan, a 10-year lifetime was identified as a critical target for hydrogen sensors [20]. In transport applications lifetime requirements can be around 6000 hours (StorHy) [21]. Some other specific applications can require lifetimes of up to 9000 hours.

Lifetime of sensors can be affected by a variety of factors, including stressors such as chemical contaminants or environmental factors (physical stressors). Several questions were raised during this session. For instance, it was discussed if self-diagnosis of sensors would be possible or, in case this option is not possible, if the sensor could include a safety failure mode so it would be able to communicate to the user that something is not working properly.

The effect of vibration on lifetime is a matter of concern for users in transport applications. To a lesser extent, this was also a concern in infrastructure since vibrations will be induced by mechanical components such as compressors.

There was also a discussion about lifetime vs. replacement cost. It may be that increasing the lifetime of the sensor could be more expensive (research and development costs) than replacing it for a new one with less lifetime (maybe a 10-year lifetime sensor could be more expensive than two 5-year lifetime sensors).

The importance of the development of accelerated lifetime test (ALT) protocol was highlighted. However, it is difficult to correlate the test results with real world performance. A proper ALT must model or mimic fundamental root causes for sensor failure, and presently, this is still a gap. Support from the end-users is necessary to identify real-world root causes of failure.

3 Gap and Barrier Summary

This session was intended to be a wrap-up of all the topics discussed in the previous sessions and to attempt to establish priorities in the different gaps and barriers identified. The following tables list the hydrogen sensor gaps and issues identified in the workshop, with an emphasis on hydrogen as an alternative fuel. The discussion for the alternative applications (e.g., the aerospace and nuclear industries) was brief owing to the small number of representatives at the workshop in these alternative fields. However, it is recognized that cross-cutting applications is one means to increase market size for hydrogen sensors and thus ultimately reduced cost, and thus addressing these market needs can support the hydrogen as an alternative fuel industry. The tables are separated into gaps pertaining end-user metrological, deployment, and operational requirements. Tables 1 through 3 focus on sensors for hydrogen as an alternative energy, while Table 4 gives a short summary of gaps for alternative industries (e.g., aerospace and nuclear). In addition, Table 5 provides a summary of market barriers for hydrogen sensors from a manufacturer perspective is provided.

A short-list of the most critical gaps is provided in Table 6.

Table 1: Hydrogen Sensors Gaps and Barriers--Metrological Metrics and Considerations

Metric Requirement and Gap Identification	Supplemental Comments	Application
Lifetime / Reliability		
5-year life / 10 year life	Minimal acceptable sensor life is 5 years, longer is better, sensing element replacement.	Infrastructure
10-year life; maintenance free	Possible routine midlife replacement at 5 years	Automotive
End of Life Indication	Fault indication on a non-functional sensor	Infrastructure /Automotive
Maintenance/calibration requirements	Quarterly to annual calibrations are costly	Infrastructure
Self-testing sensors/Auto Calibration	Need for automatic maintenance indication and procedures	Infrastructure
Drift during deployment	Must be below level that leads to false positive-negative alarms	Infrastructure /Automotive
Impact of Drift	More frequent calibration, may not be known that drift is occurring	Infrastructure
Impact of chemical stressors (poisons)	Silianes, CO, NOx, Sulphur compounds (H2S, SO2), lead	Infrastructure /Automotive
Impact of Physical Stressors (environment)	Infrastructure: T to -40 $^{\circ}$C up to +85 $^{\circ}$C, high humidity / Automotive: -	Infrastructure /Automotive
Operation in harsh environments	Infrastructure: T, P, RH extremes, rapid changes, Measuring H2 in O2 at high RH. Automotive: T ('-40 to +125 $^{\circ}$C) and RH (condensing) extremes; thermal jumps.	Infrastructure /Automotive
Impact of physical stressors (Shock and Vibration)	Affect electronic circuit boards and interconnects and physical structure of sensing element	Infrastructure /Automotive
Development of protective measures	Infrastructure: Robust Hardware-interconnects Automotive: Robust hardware and interconnects	Infrastructure /Automotive
Impact of EMI/Radiation	Interference with electrical equipment (permanent damage), incomplete characterizations	Infrastructure /Automotive
Development of validated Accelerated Life Tests	Need root cause of failure and drift	Infrastructure /Automotive
Accuracy		
Performance specification	5 to 10% of full scale or reading is typical and not a gap, but 1% accuracy can be required	Research
Selectivity to chemical interferences	CO, CO2, NO2, H2S, Methane, Propane, Butane, Methanol	Infrastructure /Automotive
Stability to T, P, RH fluctuations	-40 to +80 $^{\circ}$C, 0.6 to 1.1 Bar, dry to 95% (in general)	General
Impact of EMI/Radiation	Interference with electrical equipment, Incomplete characterizations (permanent damage)	General
Flow Dependence	Reading with quiescent environment vs. dynamic flowing conditions	Infrastructure /Automotive
Lower Detection Limit		
Leak Detection (sniffer)	200 ppm or better	Research/ Automotive/ Infrastructure
General leak	Infrastructure (general indoor safety):0.1 vol% to 1.0 vol% / Automotive: 0.4 vol% to 4 vol%	Infrastructure /Automotive
Process control/exhaust monitor	0.1 vol% to 10 vol%	Automotive
Response Time (variable with application)		
Flow-rate Dependence	Impact with quiescent environment vs. dynamic flowing conditions	Infrastructure /Automotive
General	Infrastructure: 5 sec; not really a gap with many commercial sensors /Automotive: 2 sec	Infrastructure /Automotive
Exhaust and process control	< 1 sec (300 ms)	Automotive

Table 2: Hydrogen Sensors Gaps and Barriers--Deployment Metrics and Considerations

Metric Requirement and Gap Identification	Supplemental Comments	Application
Codes, Standards and Regulations/Directives Issues		
Standards not always available (gaps)	No uniform set of requirements/variable requirements for different applications	Infrastructure /Automotive
Cost and complexity of certification	Many standards, costly for certification	Infrastructure /Automotive
Lack of international harmonization	Standards not harmonized or accepted internationally	Infrastructure /Automotive
Requirement to use specific standards	Mandated use of regional or national codes	Infrastructure /Automotive
Cost and Availability		
Capital costs	Automotive: < 50€ at full market scale (10^5 sales/year); Infrastructure: < 400 € for sensor and system integration	Infrastructure /Automotive
Assurance of sensor supply	Scalability of production to meet demand, concerns about unavailability of qualified sensor	Automotive
Sensor Availability		
Scalability of production	Growing markets may demand significant number sensors; economy of scale for cost	Automotive
Assurance of supply	Product line discontinuation, supplier may go out of business	Automotive
Proper Use of Sensors		
Limits/features of different platforms	Knowledge gap among general users	Infrastructure /Automotive
Deployment guidelines	Often placement is by intuition	Infrastructure /Automotive
Packaging		
Physically small	Limited space for some applications	Infrastructure /Automotive
Explosion proof/electrical safety	Not available in all models, cost impacts	Infrastructure /Automotive

Table 3: Hydrogen Sensors Gaps and Barriers--Operational Metrics and Considerations

Metric Requirement and Gap Identification	Supplemental Comments	Application
Cost and Availability		
Maintenance (calibration) requirements	Automotive: Maintenance free for life of sensing element Infrastructure: No more frequent than annual verification checks	Infrastructure/Automotive
Validation for application		
Device to device repeatability	"Plug and Go" replacement will lower cost	Automotive
Inadequate sensor field performance data	Impact of local environment on lifetime	Infrastructure/Automotive
Expedited sensor test and validation protocols	Expedited sensor test protocols will save time and money	Infrastructure/Automotive
Deployment in Harsh Condition		
Operation Temperature Range	-40°C to + 85°C	Automotive
Sensor Knowledge/Expertise		
Sensor Database	Availability and updated for new sensors and certification status	
Sensor types	Features and limitation of various sensor types	
Communication and Data Management Issues		
Wide Area Monitoring	Large facilities (H2@Scale)	Infrastructure/Research
Stand-off detection	not yet common; poor detection limits	Infrastructure
wireless/remote operation	not yet common	Infrastructure
Proper electrical interface	Controller Area Network (CAN)	Automotive
wireless power	not yet common	Infrastructure

Table 4: Hydrogen Sensors Gaps and Barriers--Alternative Markets and Applications

Metric Requirement and Gap Identification	Supplemental Comments	Application
Lifetime		
10-year life	Long life time required	Nuclear Industry
Impact of chemical stressors (poisons)	Harsh Chemical Environment	Nuclear Industry
Impact of physical stressors (T, P, RH)	Harsh Chemical Environment	Nuclear/Aerospace Industry
Impact of EMI Radiation	Interference with electrical equipment, Incomplete characterizations (permanent damage)	Nuclear/Aerospace Industry
Impact of vibrations	Affect electronic circuit boards and interconnects and physical structure of sensing element	Aerospace Industry
Accuracy		
Impact of EMI Radiation	Interference with electrical equipment, Incomplete characterization	Nuclear Industry
Communication and Data Management Issues		
Wide Area Monitoring	Nuclear waste storage	Nuclear
Stand-off measurements	not yet common; poor detection limits with most technologies	Nuclear
wireless/remote operation	not yet common	Nuclear
wireless power	not yet common	Nuclear

Table 5: Hydrogen Sensors Gaps and Barriers--Manufacturer Perspective

Metric and Gap Identification	Supplemental comments
Metrological Issues	No uniform set of end-user requirements
Non-uniform Specifications	variability among end-user applications
Inadequately Defined end-user requirements	vague requirements from many end-users
Deployment/Operational Issues	
Market Sustainability	Large potential market, but customer base is not guaranteed
Access to other markets (nuclear, petroleum)	Cross-cutting markets one strategy to lower cost
Manufacturing cost	Current market precludes full exploitation of economy of scale production
Complicated costly C&S requirements	A large number of standards (electrical safety, performance, etc.), costly for certification

Table 6: Hydrogen Sensors Priority Gaps and Barriers

Metric Requirement and Gap Identification	Supplemental Comments	Application
Metrological Metrics		
Lifetime		
10 year life	Replacement cost too high, down time associated with sensor failure	Infrastructure/Automotive
Impact of chemical stressors (poisons)	Harsh chemical environment adversely affecting performance	Infrastructure/Automotive
Impact of physical stressors (T, P, RH)	Harsh environmental conditions adversely affecting performance	Infrastructure/Automotive
Accuracy		
Impact of chemical stressors (interferents)	Chemical Interferents may cause false positive or false negative alarms	
Impact of physical stressors (Environment-T, P, RH)	Environmental Interferents may cause false positive or false negative alarms	
Response Time		
General	<2 sec is desired for many applications	Infrastructure/Automotive
Flow-rate Dependence	Impact with quiescent environment vs. dynamic flowing conditions	Infrastructure/Automotive
Exhaust and process control	< 1 sec (300 ms)	Automotive
Deployment Metrics		
Cost and Availability		
Capital Cost	Need for lower cost (< 50 € for automotive; < 400 € for most infrastructure)	Automotive/Infrastructure
Codes, Standards and Regulations/Directives Issues		
Standards not always available (gaps)	No uniform set of requirements/variable requirements for different applications	Infrastructure/Automotive
Complex, costly, and often national requirements	No uniform set of certification requirements; need to simplify and harmonize	Infrastructure/Automotive
Operational Metrics		
Cost		
Maintenance and Calibration	Considered a bigger concern than capital cost; maintenance intervals > 1 year desired	Infrastructure/Automotive
Sensor Placement and Guidance	Dispersion behaviour of hydrogen plumes not fully characterized	
Location/placement of sensor	No formal guidance on sensor placement is needed	Infrastructure
Wide Area Monitoring	Need for low-cost, automated monitoring and profiling around small to large scale facilities	Infrastructure /Research

4 Conclusions and Path Forward: Strategies to address gaps

The Sensor Test Laboratories in Europe (JRC and BAM) and in the United States (NREL) will continue to support the implementation of hydrogen infrastructure and vehicle deployment by addressing the needs of the hydrogen community. The workshop, with input from a cross-section of stakeholders in the hydrogen community, represented an important first step in developing an updated gaps and barriers analysis with regards to the performance and use of hydrogen sensors. The critical research gaps, as identified from this workshop, which warrant further support and includes the following critical subjects:

- Sensor lifetime
  - Impact of chemical and physical stressors on lifetime (fundamental failure mechanism)
    - Support development of accelerated life test
    - Indication of (pending) sensor failure
- Selectivity (robustness against chemical and physical interference)
- Sensor Placement and Wide Area Monitoring
- Simplify and Harmonize Codes and Standards
- Wide Area Monitoring
  - Monitoring for verification of safe operations for small to large scale facilities
  - Research tool to validate models
  - Review strategies (point detection vs. standoff measurements)

The sensor laboratories will continue to maintain close interaction with the hydrogen community to provide further input into the gap analysis. Current on-going activity within the NREL and JRC Sensor laboratories address some of the gaps identified in the workshop, including investigating the impact of chemical poisons and interferents on sensor performance. NREL is also regularly interfacing with code and standard development organizations, which will help assure harmonization and codes and standards. This would, however, not have significant impact on national regulations requiring the use of domestic standards, which will have to be addressed by national regulatory agencies.

More importantly, these interactions will facilitate partnerships with stakeholders to more effectively address the gaps. Specific strategies for moving forward include:

- Formation of strategic partnerships to address topical issues pertaining to sensor gaps and performance. For example, such partnership can address various issues
  - Develop validated expedited sensor test protocols.
  - Correlate deployment conditions to lifetime
- Continued investigation into impact of chemical and physical stressors on sensor performance (accuracy and lifetime)
- Follow-up Workshop and/or topical Webinars for the hydrogen community.
  - Periodic topical Webinars for automotive applications (members of the SAE FCSC and JARI have already requested more support from the Sensor Laboratories).
  - Topical Webinars can be held for infrastructure
    - Electrolyser Safety

- Hydrogen in Natural Gas (safety and performance)
- Wide Area Monitoring
- Codes and Standard Requirements/alternative strategies

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APPENDIX 1

(Workshop Agenda)

HYDROGEN SENSOR WORKSHOP

Hydrogen Safety Sensors
and Their Use in Applications with Hydrogen as an Alternative Fuel
“End User Needs vs. Capability of Current Technology”

May 10, 2017
Jointly organized by
EC DG JRC, US DOE NREL and FCH JU

Agenda

8:30	**Sign in, coffee**	
9:00	**Welcome**	**Alberto Garcia, FCH2 JU**
9:15	**Introduction to workshop**	**William Buttner, NREL**
9:30	**Round table discussions** *(Introduction of participants, expectation of workshop)*	**ALL**
10:00	**Overview of the Hydrogen Sensor Test Laboratories**	**Rafael Ortiz Cebolla, JRC** **William Buttner, NREL** **Thomas Hűbert, BAM;**
10:20	**Previous Sensor Gap Analysis**	**Thomas Hűbert, BAM**
10:40	**Session 1: Customer experiences and expectations / Manufacturer Perspective** **(***Disparity between specification and performance, barriers to use)*	**Chair and Introduction:** **William Buttner, NREL;** **ALL**
11:20	**COFFEE BREAK**	
11:45	**Session 2: Sensor Analytical Performance Requirements** *(Priority metrics and specifications for sensors)*	**Chair and Introduction:** **William Buttner, NREL;** **ALL**
12:30	**LUNCH**	
13:30	**Session 3: Sensor Deployment Considerations** *(Operation and maintenance of sensors, placement of sensors)*	**Chair and Introduction:** **Thomas Hűbert, BAM;** **ALL**
14:15	**Session 4: Sensor Lifetime** *(Operational Lifetime, stability and robustness of sensors)*	**Chair and Introduction:** **Eveline Weidner, JRC;** **ALL**
15:00	**COFFEE BREAK**	
15:30	**Session 5: Summary** *(Identification and ranking of critical gaps)*	**Chair and Introduction:** **William Buttner, NREL;** **ALL**
16:15	**Session 6: Way forward—Strategies to address gaps**	**Chair and Introduction:** **Eveline Weidner, JRC;** **ALL**
17:00	**Adjourn** Informal gathering for further discussion (until 18:00)	**ALL**

NREL
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APPENDIX 2

(Participants and Organizations)

Name	Surname	Institution
Hideaki	Akahane	FIS/Nissha
Stewart	Anderson	Haskel
Johan	Bertrand	Environmental and Disposal Monitoring Dept
Bart	Biebuyck	FCH 2 JU
Christian	Bonato	European Commission
Stefan	Boneberg	Daimler
William	Buttner	National Renewable Energy Laboratory
Angélique	D'Agostino	Engie
Franziska	Fricke	Audi AG
Giacomo	Frigo	Sensitron
Alberto	Garcia Hombrados	FCH 2 JU
Nick	Hart	ITM Power
David	Hedley	HSL: HSE’s Health & Safety Laboratory
Deborah	HOUSSIN	Air Liquide
Thomas	Hübert	BAM
Vincent	Mattelaer	Toyota Europa
Ralf	Mueller	Daimler
Rafael	Ortiz Cebolla	European Commission
Gareth	Powell	Haskel
Sander	van Herwaarden	Xensor
Eveline	Weidner	European Commission

APPENDIX 3

(Standards for sensor certification)

ISO 26142:2010	Hydrogen detection apparatus - Stationary applications
SAE TIR J3089	Characterization of On-Board Vehicular Hydrogen Sensors
EN 60079-29-1:2007	Explosive atmospheres - Part 29-1
EN 60079-29-2:2013	Explosive atmospheres Part 29-2
EN 60079-29-3:2013	Explosive atmospheres - Part 29-3
EN 60079-29-4:2011	Explosive atmospheres - Part 29-4
EN 50194–1:2009	Electrical apparatus for the detection of combustible gases in domestic premises - Part 1: Test methods and performance requirements
EN 50194–2:2017	Electrical apparatus for the detection of combustible gases in domestic premises - Part 2
EN 50244:2017	Electrical apparatus for the detection of combustible gases in domestic premises - Guide on the selection
UL 2075:2004	Standard for Safety Gas and Vapour Detectors and Sensors
JIS M 7626:1994	Stational Type Combustible Gas Alarm
UL 913 UL:2002	Standard for Safety Intrinsically Safe Apparatus and Associated Apparatus for Use in Class I, II, and III, Division I, Hazardous (Classified) Locations
CSA 22.2 n. 30	Explosion-proof enclosures for the use in hazardous locations
CSA 22.2 n. 157	Intrinsically safe and non-incentive equipment for the use in hazardous locations

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