SAFETY CONSIDERATIONS FOR HYDROGEN TEST CELLS

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ABSTRACT

The properties of hydrogen compared to conventional fuels such as gasoline and diesel are substantially different requiring adaptations to the design and layout of test cells for hydrogen fuelled engines and vehicles. A comparison of hydrogen fuel properties versus conventional fuels in this paper provides identification of requirements that need to be adapted to design a safe test cell. Design examples of actual test cells are provided to showcase the differences in overall layout and ventilation, safety features, fuel supply and metering, and emissions measurements. Details include requirements for ventilation patterns, the necessity for engine fume hoods as well as hydrogen specific intake and exhaust design. The unique properties of hydrogen, in particular the wide flammability limits and non-visible flames also require additional safety features such as hydrogen sensors and flame cameras. A properly designed and implemented fuel supply system adds to the safety of the test cell by minimizing the amount of hydrogen that can be released. Apart from this the properties of hydrogen also require different fuel consumption measurement systems, pressure levels of the fuel supply system, additional ventilation lines, strategically placed safety solenoids combined with appropriate operational procedures. The emissions measurement for hydrogen application has to be expanded to include the amount of unburned hydrogen in the exhaust as a measurement of completeness of combustion. This measurement can also be used as a safety feature to avoid creation of ignitable hydrogen-air mixtures in the engine exhaust. The considerations provided in this paper lead to the conclusion that hydrogen IC engines can be safely tested, however, properly designed test cell and safety features have to be included to mitigate the additional hazards related to the change in fuel characteristics.

1.0 INTRODUCTION

The favorable physical properties of hydrogen (H_2) make it an excellent alternative fuel for internal combustion (IC) engines and hence it is widely regarded as the energy carrier of the future. Ever more stringent emissions regulations as well as efforts to further reduce fuel consumption have sparked increasing interest for hydrogen to be used in both, internal combustion engines and fuel cells. In order to safely perform tests on either system, the design and layout of the dedicated test facility has to meet certain standards and address unique requirements due to the distinct properties of hydrogen.

According to a fire hazard assessment performed in preparation of setting up a hydrogen supply system and a hydrogen test facility at the Center for Transportation Research at Argonne National Laboratory in June 2004 several codes, standards and other requirements were identified as applicable for the assessment [1]. These standards were applicable at the time of the fire hazard assessment. For performing a fire hazard assessment today the following regulations are applicable:

- National Fire Protection Association (NFPA) 13: Standard for the Installation of Sprinkler Systems, 2007 Edition.
- NFPA 55: Standard for the Storage, Use, and Handling of Compressed Gases and Cryogenic Fluids in Portable and Stationary Containers, Cylinders, and Tanks, 2005 Edition.
- NFPA 70: National Electrical Code, 2008 Edition.
- NFPA 72: National Fire Alarm Code, 2007 Edition.
- NFPA 101: Life Safety Code, 2009 Edition.

NASA has also established guidelines for hydrogen system design, materials selection, operations, storage and transportation due to their extensive use of hydrogen [2].

2.0 COMPARISON OF SAFETY RELEVANT FUEL PROPERTIES

Comparing the physical properties of hydrogen to those of more commonly used fuels allows identifying several significant differences that have to be accounted for when designing hydrogen test facilities. Table 1 summarizes some of the safety relevant properties of hydrogen as well as methane as a conventional gaseous and gasoline as a conventional liquid fuel.

Hydrogen, as well as methane, is gaseous at ambient temperature resulting in significantly lower density than gasoline. However, the density of hydrogen is still a factor of 10 lower than that of methane. At the same time the ignition limits of hydrogen are wider than any other fuel with hydrogen being ignitable in air at concentrations starting as low as 4 Vol-% up to 75 Vol-%. These extremely wide ignition limits require special precautions to avoid build-up of ignitable mixtures that could result from even small hydrogen leaks. The gravimetric energy content of hydrogen (120 kJ/kg) is more than twice that of methane and almost three times as high as gasoline. The minimum ignition energy of hydrogen at stoichiometric mixtures is a factor of 10 less than that of gasoline or methane meaning that hydrogen/air mixtures can be easily ignited from various sources including static charge. However, the self-ignition temperature of hydrogen is fairly high compared to the other fuels which is an indicator that hydrogen is not suitable for compression ignition engine operation rather than a safety relevant factor. The stoichiometric air demand of hydrogen is about twice that of methane suggesting that the same mass of hydrogen will consume twice the amount of air compared to methane. Finally, the laminar flame speed of stoichiometric hydrogen-air mixtures is a factor of five higher than methane.

Table 1: Summary of safety relevant properties of gasoline, methane and hydrogen

		Gasoline	**Methane**	**Hydrogen**
Density	kg/m^3	715 - 765	0.72	0.089
Boiling temperature	°C	25 - 215	-162	-253
Ignition limits in air Lower limit Upper limit	Vol-%	 1.4 7.6	 5.3 15	 4 75
Ignition limits in air Lower limit Upper limit	Lambda	 1.4 0.4	 2 0.6	 10 0.14
Lower heating value (gravimetric)	MJ/kg	42.7	50	120
Mass diffusivity in air	cm^2/s	~0.07	0.16	0.61
Minimum ignition energy	mJ	0.24	0.29	0.02
Self-ignition temperature	°C	228 - 501	540	585
Stoichiometric air/fuel ratio		14.7	17.2	34.3
Laminar flame speed	cm/s	~33	40	200

These significant differences in physical properties of hydrogen clearly indicate that rules and guidelines that have been established for designing test cells for conventional fuels are not directly transferable to hydrogen applications. The following sections address relevant features of engine and vehicle test cells and explain design features used for hydrogen applications based on the unique properties of hydrogen.

3.0 FUEL SUPPLY

3.1 Fuel storage

The gaseous state of hydrogen at ambient temperatures and the related low density require drastic changes in the fuel storage system. Conventional liquid fuels are generally stored in double-walled containers at atmospheric pressures; however this storage mechanism is not practical for gaseous fuels.

For most research and test applications hydrogen is either stored in cryogenic liquid form or in compressed gaseous form. Typical pressure levels for high-pressure cylinder storage range from 20 – 30 MPa for European installations and 2,000 PSI (~13.8 MPa) – 6,000 PSI (~41.4 MPa) for US installations. These pressure levels are based on the typical cylinder pressures as sold by local gas vendors. Liquid hydrogen is stored at temperatures of -253 °C generally in insulated, passive storage systems meaning that no active cooling is provided. Despite excessive insulation, the remaining heat input causes liquid hydrogen to evaporate which increases the pressure. Liquid storage systems require continuous consumption to avoid pressure build-up and ultimately release of hydrogen.

Figure 1 shows an estimate of the volumetric requirements for compressed hydrogen storage. The values result from the assumption that one would want to store the equivalent energy as contained in a 100 L (26.4 gallon) gasoline tank. At a typical compressed hydrogen storage pressure of 20 MPa one would still need to use 33 compressed 50 L hydrogen cylinders. Even at a storage pressure of 41.4 MPa storing the equivalent of 100 L of gasoline requires 16 high pressure hydrogen cylinders.

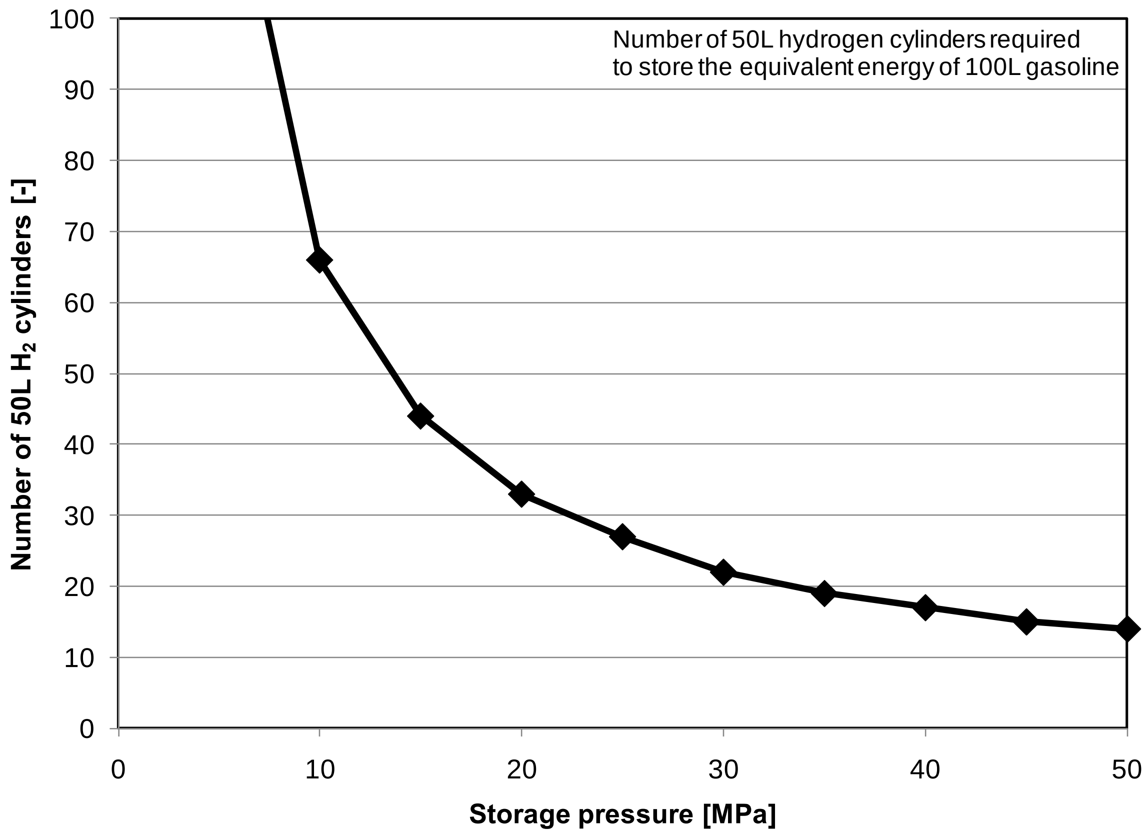

Figure 1: Estimate of compressed hydrogen storage requirements

The large volume requirements for hydrogen storage systems for both compressed as well as cryogenic setups usually result in hydrogen being stored outdoors or in dedicated fuel canopies. The hydrogen is then delivered to the test facility via hydrogen supply lines and thereby reduces the amount of energy stored inside the test facility. Also, any leaks resulting from connections of hydrogen cylinders to supply manifolds that have to be opened and re-tightened when changing high-pressure cylinders are thus located outside where natural ventilation generally decreases probability of a build-up of ignitable hydrogen-air mixtures.

3.2 Fuel delivery

Depending on the storage system as well as the application the hydrogen fuel is delivered to the test facility at widely varying pressures. The most challenging case, where hydrogen is stored in high-pressure cylinders and high delivery pressures are required, is discussed in the following example. The setup, as shown in Figure 2, was used to supply compressed hydrogen to a single-cylinder hydrogen research engine. The hydrogen was stored at pressures of up to 30 MPa with injection pressures supplied to the engine as high as 25 MPa. In order to be able to supply sufficient fuel for longer test runs, six high pressure hydrogen cylinders were hooked up to a manifold. For purging and safe leak checking of the system high-pressure helium can also be connected to the delivery system. The hydrogen or helium was passed through manual shut-off valves and check valves and supplied to a pressure regulator. Once regulated to the appropriate delivery pressure the hydrogen was fed to the engine after passing through several manual as well as solenoid-operated safety valves. These safety valves are integrated in the hydrogen supply line to minimize the amount of hydrogen that would be released into the building in case of a leak or line rupture. In close proximity to the engine a fast-acting, normally closed three-way valve is used. This valve can be remotely activated by the operator to supply hydrogen to the engine whenever needed. If the engine does not rotate or a hydrogen leak is detected, the three-way valve automatically closes. As shown in Figure 2 the normally open path of the three-way valve is connected to a purge line, thus preventing the engine hydrogen supply line from being pressurized if the engine is not operating.

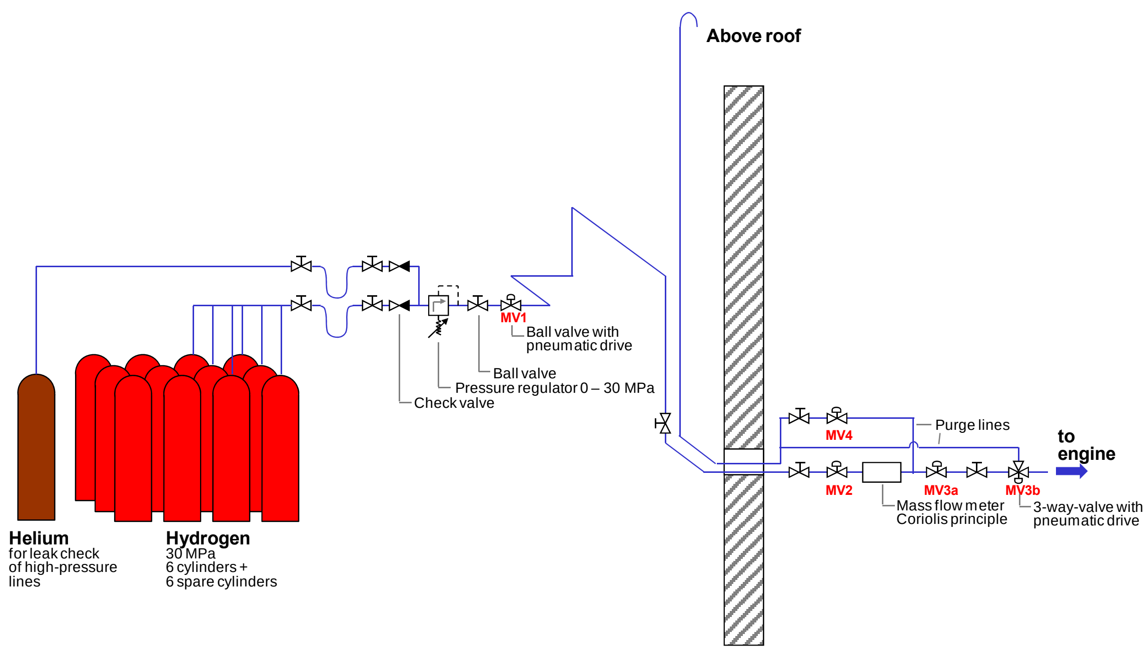

Figure 2: Sample hydrogen supply system [3]

The setup with a close-to-the-consumer three-way valve has proven to greatly reduce the risk of unintended hydrogen release into the engine through leaking injectors while minimizing the amount of hydrogen that has to be released to the atmosphere. For a long-term shut-down of the hydrogen supply system or if maintenance is required the entire hydrogen supply line can also be purged to the atmosphere using an additional solenoid valve. All solenoid valves are centrally controlled employing a logic that avoids uncontrolled release of hydrogen through the purge line.

3.3 Fuel metering

Accurate metering of the amount of consumed fuel is crucial for the quality of any engine test experiment and provides a necessary baseline for calculation of development-relevant characteristic numbers like engine efficiency or brake specific fuel consumption. Over the last couple of years a continuing transition from conventional methods including positive displacement pumps and gravimetric systems towards direct and continuous mass measurement using coriolis meters has been observed [4]. For hydrogen applications the U.S. Environmental Protection Agency (EPA) has only accepted three methods of hydrogen fuel consumption testing. These three methods are gravimetric measurement, measurement of stabilized pressure, volume and temperature (PVT), and coriolis mass flow measurement [5]. Recently another method similar to the carbon balance that is used for fuel consumption calculations for conventional vehicles based on exhaust emissions measurement has been proposed for hydrogen engines and a detailed comparison of the methods has been provided [6]. Due to the extensive measurement equipment needed for this method it has so far only found application where a direct fuel consumption measurement is not feasible [7].

Due to good accuracy over a wide flow range and the direct measurement of fuel mass, employing a coriolis meter seems to be the preferred method for hydrogen engine testing (e.g. [8]). For applications that require a range that cannot be covered by a single coriolis meter, systems that switch from a low-range to a high-range coriolis flow meter have been developed and implemented (e.g. [9]).

Figure 3 shows a schematic as well as an actual photograph of a two-stage hydrogen delivery panel that includes several functions including metering, delivery pressure conditioning, sensors for the data acquisition system, and safety control. The system is designed to deliver high flow (over 10 g/s) at delivery pressures up to approximately 2 MPa. Inside the panel, the hydrogen flows through a motorized ball valve which is controlled by the emergency stop system. The fuel is metered by either a high- or low-range mass flow sensor. The low-flow sensor is by-passed when the flow is so high that the smaller meter would create a flow restriction. The final part of the system is a pressure regulator to set the delivery pressure. Two pressure sensors are implemented in the panel and linked to the data acquisition system in the same way as the flow meters. The safety features include mechanical over-pressure and electrical over-pressure detection linked to the vent line, excess flow detection, motorized ball valve, a sprinkler and a hydrogen sensor. Due to the large number of connections that pose potential hydrogen leaks the distribution panel is located in an enclosure. The enclosure is open on the bottom and also has a small opening on the top where a sensor continuously monitors the hydrogen concentration.

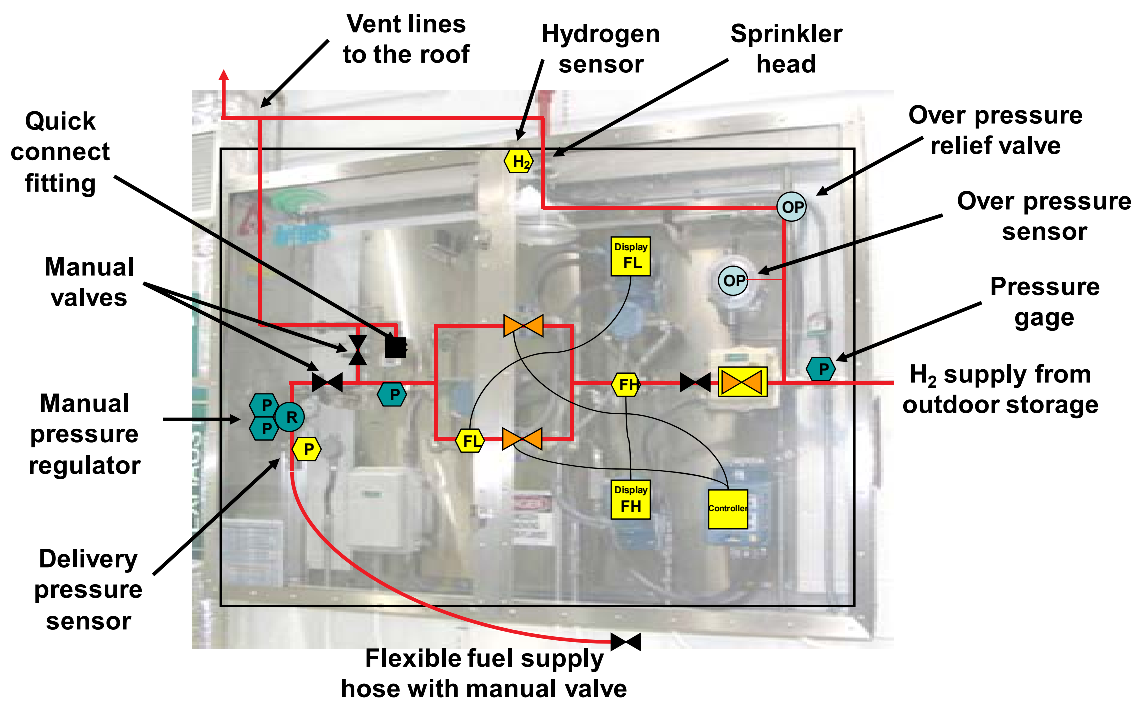

Figure 3: Hydrogen distribution panel [10]

4.0 SAFETY EQUIPMENT

The significantly different properties of hydrogen compared to conventional fuels, in particular the fact that hydrogen is a colorless, odorless, tasteless, highly flammable gas [11] require special equipment to detect hydrogen and hydrogen flames. Although there is a danger of asphyxiation in high concentration hydrogen environments because of the exclusion of adequate supply of oxygen resulting in dizziness, deeper breathing due to air hunger, possible nausea and eventual unconsciousness, the far greater risk is due to deflagration and detonation. Special precautions when dealing with hydrogen leaks and hydrogen flames include stopping the flow of hydrogen and cooling surrounding cylinders with water spray. Hydrogen burns with an almost invisible flame of relatively low thermal radiation.

For hydrogen test cell design, special emphasis on detection of hydrogen leaks and hydrogen flames is required. Detection of only gaseous hydrogen might not be sufficient for a safe test cell environment as a hydrogen leak could easily be ignited without prior detection. Once ignited a hydrogen leak would not be detected by a gaseous hydrogen detection system.

4.1 Hydrogen sensors

For detection of hydrogen several technologies are commercially available including electro-chemical, catalytic, thermal conductivity, semi-conductor based and micro electro-mechanical. An overview of sensor detection principles and comparison of sensor performance including range, cross sensitivity, accuracy, stability, and cost can be found in [12]. Recommended locations for hydrogen sensors include locations where hydrogen leaks are possible, at hydrogen connections that are routinely separated, where hydrogen could accumulate as well as in building air intake and exhaust ducts [13]. When designing a hydrogen detection system one should consider factors including detector response time, detection range, durability/lifetime of the detector, required detector maintenance and calibration, potential cross sensitivity, and area coverage [12].

A generally accepted and commonly used concentration for alarm activation is around 1 Vol-% of hydrogen in air (equivalent to 25 % of the lower flammability limit). Other hydrogen detection systems use a progressive approach with several warning and alarm limits that warn the operator at low detection limits (e.g. 10 % of the lower flammability limit) and perform automated shut-down of the hydrogen supply system and test equipment if a higher alarm limit is reached.

In addition to permanently mounted hydrogen sensors, most experimental facilities also use portable hydrogen detectors for both, personal protection and leak checking of hydrogen equipment.

4.2 Hydrogen flame camera

A hydrogen-air flame is colorless. Any visibility is caused by impurities. At reduced pressures a pale blue or purple flame may be present. Severe burns have been inflicted on persons exposed to hydrogen flames resulting from the ignition of hydrogen gas escaping from leaks. Hydrogen flame detectors can be classified in the following groups [2]:

- Thermal fire detectors classified as rate-of-temperature-rise detectors and overheat detectors have been manufactured for many years and are reliable. Thermal detectors need to be located at or very near the site of a fire.
- Optical sensors for detecting hydrogen flames fall into two spectral regions: ultraviolet (UV) and infrared (IR). UV systems are extremely sensitive; however, they are susceptible to false alarms and can be blinded in foggy conditions. Infrared systems typically are designed for hydrocarbon fires and are not very sensitive to hydrogen fires.
- Imaging systems mainly are available in the thermal IR region and do not provide continuous monitoring with alarm capability. The user is required to determine if the image being viewed is a flame. UV imaging systems require special optics and are very expensive. Low-cost systems, using lowlight silicon charge coupled device (CCD) video technology with filters centered on the 940- and 1100-nm emission peaks, have been used at some facilities.

- A broom has been used for locating small hydrogen fires. The intent is a dry corn straw or sage grass broom easily ignites as it passes through a flame. A dry fire extinguisher or throwing dust into the air also causes the flame to emit visible radiation. This technique should be used with care in windy, outdoor environments in which the light hydrogen flame can easily be blown around.

The selection of a certain detection system should be based on the ability to detect a flame at sufficient distance as well as the size of flames that can still be detected. Other selection factors include response time, insensitivity to false alarms as well as possibility to automatic periodic checkup.

4.3 Safety related instrumentation

In addition to dedicated safety instrumentation certain sensors and measuring devices commonly used in a hydrogen test cell can be included in an integrated safety system and thereby decrease the likelihood of unintended hydrogen release or accumulation. The most prominent sensors to be integrated in a safety system are the hydrogen flow measurement device in the fuel supply line as well as a hydrogen sensor in the engine exhaust.

As discussed earlier there are several EPA approved methods of measuring the fuel consumption in a hydrogen test cell including a coriolis meter, gravimetric measurement as well as measurement of stabilized pressure, volume and temperature (PVT). Due to direct measurement of actual fuel mass flow a coriolis meter is best suited as an additional safety device for detection of hydrogen leaks. Once a hydrogen engine on an engine dynamometer is motored and the hydrogen system is fully pressurized, the measured hydrogen flow should return to zero after the supply system is stabilized and all lines are filled (usually in less than 1 second). Whether automatically monitored by a data acquisition system or by observation through the operator, even small hydrogen leaks can be easily detected using an accurate fuel consumption measurement.

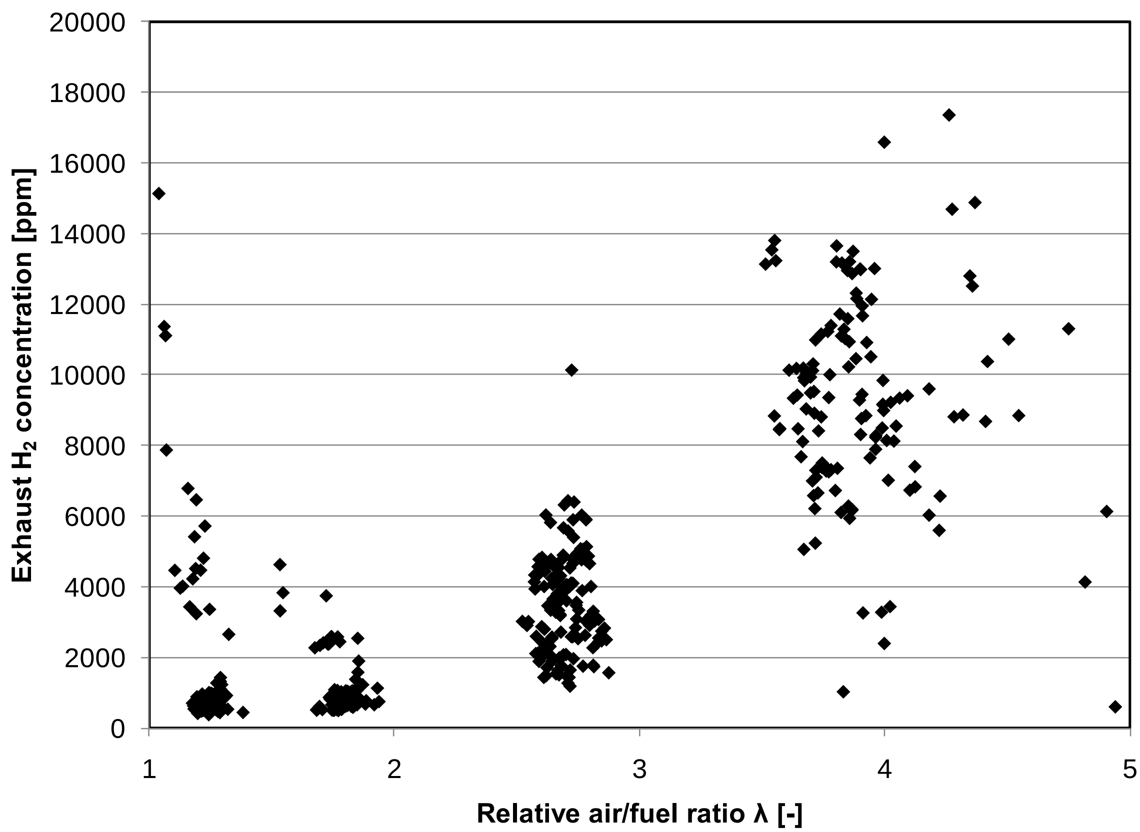

Figure 4: Exhaust hydrogen concentration versus relative air/fuel ratio

In order to calculate combustion efficiencies most hydrogen engine and vehicle test facilities are equipped to measure the amount of unburned hydrogen in the engine exhaust. Stand-alone mass spectrometer systems are widely used because standard automotive emissions measurement systems have no provisions for measurement of unburned hydrogen (e.g. [14]). During regular engine operation certain concentrations of unburned hydrogen are usually observed in the engine exhaust. These concentrations vary widely with engine load and air fuel ratio of the combusted mixture. Similar to concentration limits for facility hydrogen sensors these exhaust hydrogen sensors can be used to avoid accumulation of unburned hydrogen in the engine exhaust system. Whether or not automated monitoring of the exhaust concentrations or periodic control through the operator is required highly depends on the test application and operation conditions of the test cell.

Figure 4 shows the exhaust hydrogen concentration versus relative air/fuel ratio λ for several test runs on a single-cylinder hydrogen research engine in direct injection operation. The hydrogen content in the exhaust increases significantly and reaches levels in the range of 20,000 ppm (2 Vol-%) especially when approaching stoichiometric operation and for very lean air/fuel mixtures. For these tests 20,000 ppm was used as a threshold at which operation was stopped due to the risk of hydrogen accumulation and creation of ignitable mixtures in the exhaust.

4.4 Integrated emergency system

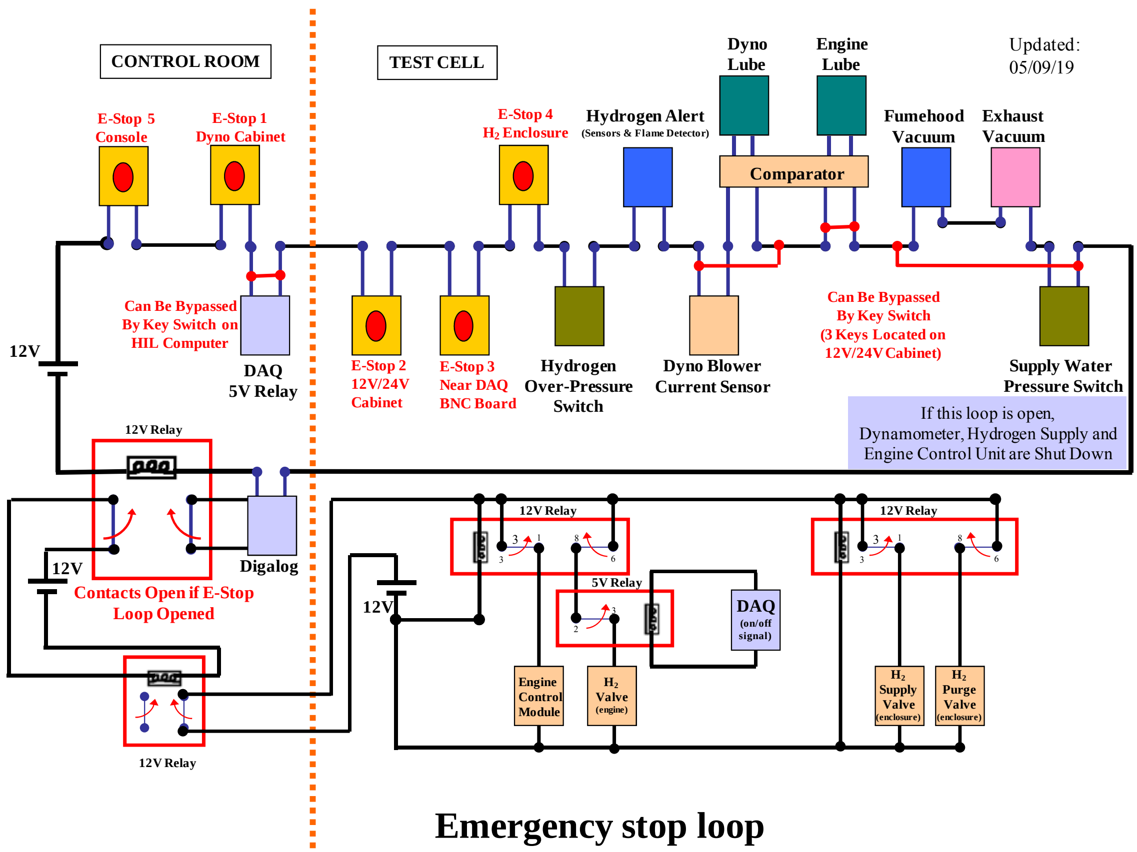

Figure 5: Sample emergency stop loop for hydrogen test cell

A schematic of an integrated E-Stop system as employed in a dedicated hydrogen engine test cell at Argonne National Laboratory is shown in Figure 5. In addition to manual E-Stop buttons located in the test cell as well as the control room several sensors are also tied into the E-Stop loop. As mentioned earlier an E-stop can be triggered if a pre-defined limit (e.g. hydrogen flow or hydrogen concentration in the exhaust) is exceeded in the data acquisition (DAQ 5V Relay), an overpressure situation in the hydrogen supply system is detected (Hydrogen Over-Pressure Switch) or a hydrogen facility sensor or camera is triggered (Hydrogen Alert). In addition to these situations with imminent threat, the E-Stop system is also triggered if relevant facility support systems fail that endanger test hardware (e.g. dyno or engine lubrication) or proper ventilation cannot be guaranteed (e.g. fumehood vacuum or exhaust vacuum).

In all cases where an E-Stop situation occurs, the dynamometer as well as the engine controller is powered down and the valves in the hydrogen supply system are closed. Due to Argonne internal safety requirements a hydrogen alert triggered by either one of the hydrogen flame cameras or facility hydrogen detectors will also notify the on-site fire department.

5.0 TEST CELL LAYOUT AND VENTILATION

5.1 Air exchange rates

Due to the low density and the gaseous state at ambient temperatures, the ventilation capabilities of hydrogen test cells are generally designed much higher than those for conventional fuels. For the layout of a hydrogen test cell, one can differentiate two cases; an enclosed engine or vehicle test cell or an open test cell located in a hi-bay building. Due to the natural convection and large amount of air available in hi-bay settings the hydrogen specific ventilation requirements are not as crucial as for enclosed test cells. As a rule of thumb for enclosed test cells, a minimum ventilation resulting in 1-2 full air exchanges per minute has been established. In order to effectively remove heat created from the test engine, as well as any hydrogen leakage, cross ventilation is usually used for enclosed hydrogen test cells. Fresh air is brought in close to the floor on one side of the test cell and removed from the test cell close to the ceiling after flowing past the experimental setup. This setup results in a controlled flow of fresh air through the test cell and also allows position of hydrogen sensors in strategic location throughout the test cell.

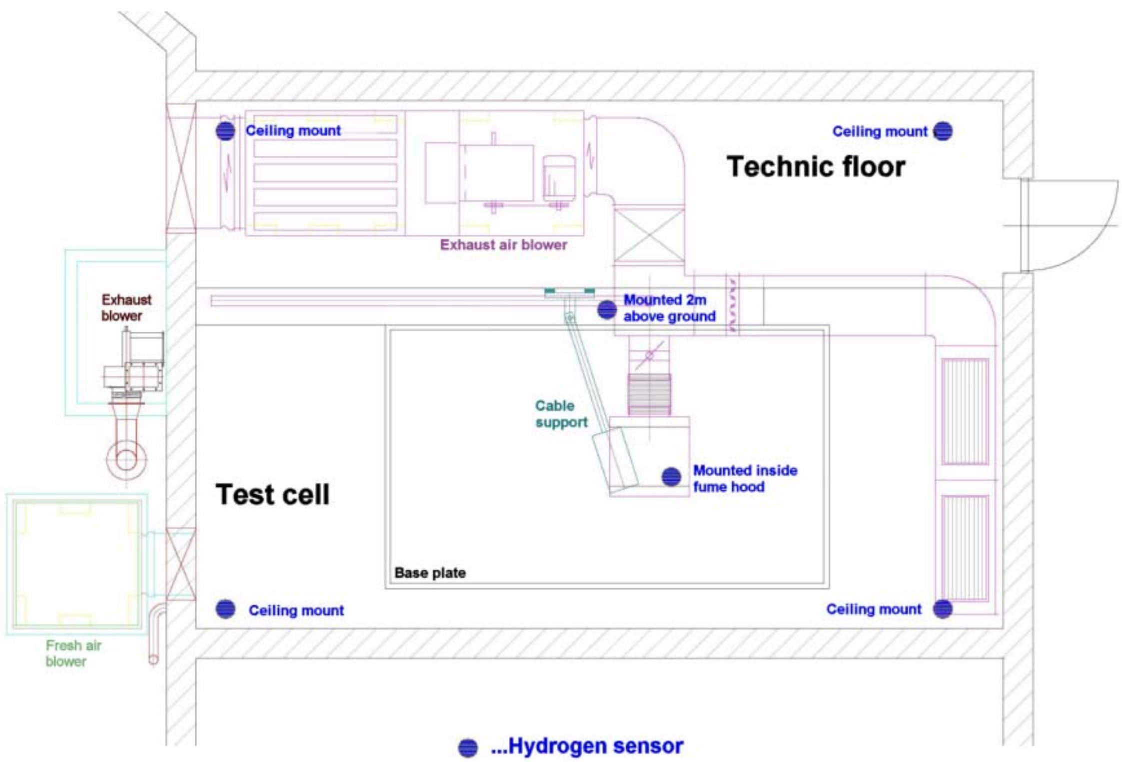

Figure 6: Sample layout of ventilation and gas monitoring system for engine test cell [3]

5.2 Sample ventilation layouts

Figure 6 shows a schematic of an enclosed hydrogen engine test cell setup with cross-ventilation and several hydrogen sensors. Fresh air is brought in from the left side of the test cell, passes by the experimental setup, which is centered just below the fume hood, and is being removed from the test cell close to the ceiling on the right side of the cell. As can be seen from the schematic, this test cell is equipped with a total of 6 hydrogen sensors strategically placed throughout the cell. Four sensors are placed in the corners on the ceiling of the cell, another sensor is placed 2 meters above ground at the hydrogen distribution panel and one sensor is placed inside a fume hood mounted directly above the test engine. This fume hood is connected to an air blower resulting in a constant stream of flow past the hydrogen sensor. Due to the number of hydrogen connections in that area and the use of prototype injection equipment one would expect that a hydrogen leak is most likely to occur in close proximity to the engine. Using a fume hood with constant flow and a hydrogen sensor inside the hood assures fast detection of hydrogen leaks and allows taking countermeasures immediately when a leak occurs.

Fume hoods are not only used in enclosed engine test cells but also in hi-bay, open test cell settings. Due to the large volume available for dilution of hydrogen leaks, detection of a potential leak could take considerable amount of time. Using hoods on top of the experimental equipment in combination with a hydrogen sensor placed inside the hood is an efficient way of detecting hydrogen leaks, especially in hi-bay settings with no defined air flow pattern.

Figure 7: Dedicated hydrogen engine test cell [15]

As an example Figure 7 shows a photograph of a dedicated hydrogen engine test cell with a double-ended dynamometer in a hi-bay location. Both engines in this test cell are designed to operate on hydrogen and therefore a fume hood connected to an air blower is located on top of either engine. As an additional design feature, these hoods are mounted on rails so they can slide easily. This feature is especially convenient and allows easy access when work on an engine is required. In this particular setup the fume hoods are equipped with a hydrogen sensor to detect any leaks occurring in close proximity to the experimental setup. In addition, both fume hoods have a water sprinkler located inside the hood that protects the experimental setup in case of a fire.

5.3 Fume hood design

In order to evaluate the effectiveness of the hood assembly used for the hydrogen test cells at Argonne National Laboratory's Center for Transportation Research, 3-D CFD calculations were performed. For these calculations the actual air flow rate through the fume hood of approximately 0.5 m^3/s (1,000 SCFM) in combination with different hydrogen leakage scenarios was simulated. Figure 8 shows the computational domain that was developed around the experimental setup covering a total volume of 10.648 m^3 which was discretisized using 150,000 pure tetrahedral cells. The side length of the square domain is 2.2 m. The actual dimensions of the fume hood and connected piping were used, the engine and engine accessories were only considered to a very limited extend. Figure 8 shows the calculation domain with the fume hood and the reduced geometry for the engine setup.

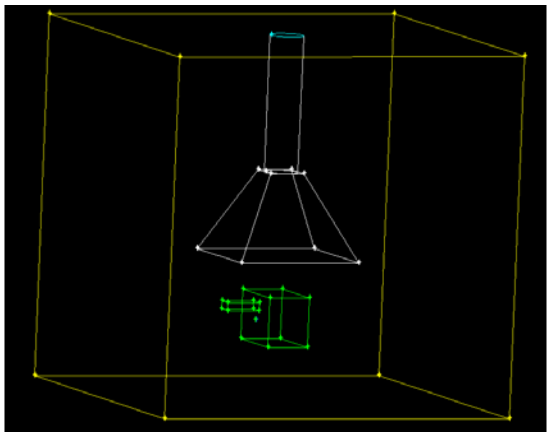

Figure 8: Domain used to calculate hydrogen release

Several hydrogen release scenarios were simulated in order to identify critical release situations. The cases varied in amount of hydrogen released as well as location and angle of hydrogen release. As an example Figure 9 shows the hydrogen concentration as well as the local velocities for a hydrogen release below the engine intake at steady flow conditions. This location would be typical for a leak on a hydrogen injector in side location. The release rate was set to 0.2 kg/h, which is similar to the actual hydrogen consumption if the engine is operated at low engine load. This case is particularly interesting because the leakage rate is low enough for it not to be detected by the operator. The velocity inside the duct connected to the fume hood is around 10 m/s. The local concentrations in close proximity to the hydrogen leak are up to 100,000 ppm and decrease rapidly with distance to the leakage point. As close to the engine as the end of the intake manifold the hydrogen concentration is already diluted to levels below the lower flammability limit (40,000 ppm). The average concentration of hydrogen in the fume hood duct at the location of the hydrogen sensor is below 2,000 ppm, hence a sensor would not trigger an alarm in this scenario.

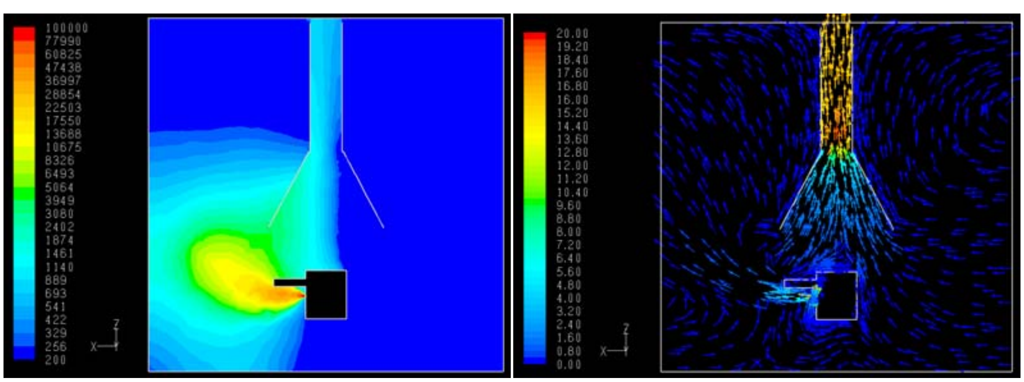

Figure 9: Hydrogen concentration in ppm and local velocities in m/s for hydrogen release scenario

5.4 Intake and exhaust system

As shown in Table 1 the ignition limits of hydrogen are extremely wide compared to other conventional fuels. This in combination with the low ignition energy requires special precautions for design and layout of intake and exhaust piping for hydrogen engines. This is particularly important for experimental work close to the rich or lean limits where unburned hydrogen could potentially accumulate and ignite in the exhaust. Hydrogen engines are also prone to combustion anomalies like pre-ignition and back-firing [16]. Both, the accumulation of hydrogen in the exhaust as well as back-firing into the intake can cause pressure waves and pressures in excess of 0.5 MPa in the intake or exhaust of hydrogen engines. In order to avoid damage to the intake and exhaust, hydrogen engine test cells, especially for basic research on single-cylinder engines, are often designed with pressure absorption and damper volumes in the intake and exhaust system. In addition to avoiding damage caused by abnormal combustion or ignition of hydrogen-rich exhaust gases, the damper volumes also help in reducing intake and exhaust pressure waves that are typical for single-cylinder setups. Figure 10 shows parts of the intake and exhaust system on a single-cylinder hydrogen research engine used for combustion system development as well as study of combustion anomalies. Both the intake and exhaust are equipped with American Society of Mechanical Engineers (ASME) rated pressure vessels.

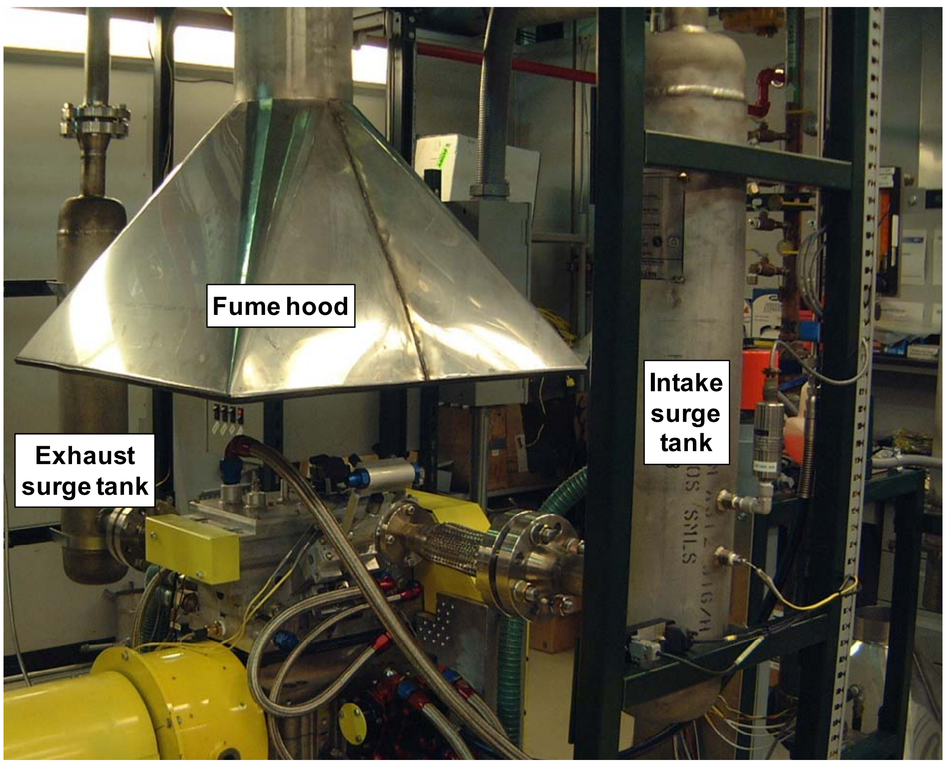

Figure 10: Pressure vessels for hydrogen intake and exhaust systems

6.0 EMISSION MEASUREMENT

The primary emissions components of interest for hydrogen engine research are oxides of nitrogen (NO_x) and excess hydrogen. The formation of carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions is negligible for hydrogen-fueled engines because the fuel source does not contain carbon. For conventional-fueled engine test cells, UHC, NO_x and soot emissions are of primary concern. The measurement of NO_x concentrations can be obtained using the same instrument as conventional-fueled test cells. The accurate measurement of hydrogen concentration in the exhaust requires a special instrument such as a mass spectrometer. Reduction in hydrogen exhaust emissions translates directly to an improvement in combustion efficiency. This is analogous to reducing unburned hydrocarbon emissions in conventional-fueled engine test cells.

7.0 CONCLUSIONS

The properties of hydrogen differ significantly from those of other conventional liquid or gaseous fuels. In particular the wide flammability limits in combination with the low ignition energy as well as the inability of the human senses to detect hydrogen leaks or flames require specific attention when designing a dedicated hydrogen test facility. Ignition sources cannot be completely excluded from a test setup; therefore a safe test cell design effectively avoids build-up of ignitable hydrogen-air mixtures. This is generally accomplished by properly designing and sizing the ventilation system according to expected leakage rates and time until a potential leak is detected. In this respect 3-D CFD simulation can be a helpful tool to quantify dilution rates and identify location for hydrogen detection devices.

The unique instrumentation in a hydrogen test environment includes hydrogen sensors to detect unintended hydrogen release as well as hydrogen flame cameras. An additional factor of safety can be achieved by integrating and monitoring safety relevant functions in an emergency system. Finally, information available in a hydrogen test setup like hydrogen fuel consumption or hydrogen concentration in the exhaust can be automatically screened for early malfunction detection.

When properly taking the unique properties into account by facility designers, engineers and operators, hydrogen can be as safe as, or safer than gasoline or diesel fuel. [9]

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ABBREVIATIONS

ASME	American Society of Mechanical Engineers
CCD	Charge coupled device
DAQ	Data acquisition
EPA	Environmental Protection Agency
ESH	Environmental Safety and Health
H_2	Hydrogen
ICE	Internal Combustion Engine
IR	Infrared
MSDS	Material Safety Data Sheet
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NO_x	Oxides of nitrogen
PVT	Pressure Volume Temperature
UHC	unburned hydrocarbon
UV	Ultraviolet

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