Process Safety in Automotive & Transportation R&D Testing – Basis of Safety for a 700 bar Hydrogen Tank Test Bench & Demonstrator Filling Station

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Fuel cell vehicles represent an alternative powertrain technology with filling times and ranges comparable to conventional petrol and diesel driven cars. Onboard hydrogen storage is generally achieved by high pressure carbon fibre polymer cylinders with a gas tight lining. In order to achieve Type approval for the cylinders a number of leak, permeation and pressure cycling tests with high pressure inert gas and hydrogen must be passed. The facility required to carry out the tests is based on SAE filling protocols used in the automotive industry but with additional essential functionality to determine the consequence of excursions outside of standard protocols.

The paper details the practical key process design requirements and approach to developing the basis of safety, showing how process engineering and process safety approach is valid for automotive and transport applications. Major accident hazards, worst credible events and the resulting basis of safety developed for the operation of the test bench is presented, with key procedural controls, occupancy factors, and secondary containment options for the worst case scenarios shown.

Keywords – Hydrogen Safety, Hazard Studies, Basis of Safety.

Background

The automotive and transportation industries are in a period of change from hydrocarbon based petrol and diesel cars and lorries, to alternative electrified vehicles. The diesel scandal and resulting increasing public and political pressure about the impact of vehicular emissions has led countries such as the UK and France to announce plans to cease the sale of petrol and diesel driven cars by 2040. Currently battery and battery/petrol hybrid powered vehicles have the major share of the alternative powertrain market, but hydrogen fuel cell powered vehicles remain in development and being produced on a small commercial scale by Toyota, Hyundai and Honda, and Mercedes Benz have announced a pre-production battery-fuel cell hybrid vehicle in September 2017. (1)

Automotive applications are not the only application where hydrogen powered vehicles are used in transportation applications. In November 2017 Alstom, Linde and the German state of Lower Saxony announced the order of the first 14 hydrogen fuel cell powered trains, replacing diesel trains on local lines from 2021 onwards (2). The trains have a range of 1000 km and a top speed of 140 km/h.

Current production cars have a range of approximately 300 miles, and the refuelling process takes 3-5 minutes with a 5kg payload, which is a significant advantage compared to electrically charging battery systems. Infrastructure remains a challenge, with limited but rapidly increasing numbers of hydrogen refilling stations available, but with a joint venture and roadmap in Germany to expand the network to 100 stations in 2018 and to expand this to 400 stations by 2023 (3) – the refilling station project is a joint venture between Air Liquide, Daimler, OMV, Shell and TOTAL.

Hydrogen is traditionally produced in steam reforming processes, however, increasingly larger amounts of renewable electrical energy are being generated by wind and solar power, electrolyser technology is available to generate “green” hydrogen, a potential end use is compression and storage for use in fuel cell transportation applications. H&R refinery in Hamburg announced the inauguration of the world’s largest dynamic electrolyser in November 2017 (4).

Hydrogen Storage Tanks & Filling Protocols

Cylinder Design

Hydrogen is stored in the vehicles in high pressure storage cylinders - either single or multiple cylinders mounted in a skid with integrated delivery valves mounted directly on the cylinder inlets. For mobile applications 350 bar and 700 bar cylinders are available. In terms of physical size and volume, the cylinders range from 60 to 200 litres, diameter approximately 30-40 cm, length up to 2-2.5m. Vehicle range depends on hydrogen payload and weight.

In order to achieve high range and good fuel economy in transportation applications weight of the cylinder is a critical parameter, therefore Type III or IV storage cylinders constructed from a carbon fibre composite liner which provides mechanical strength with an aluminium (III) plastic (IV) liner for gas tightness are the preferred technology. In addition to the low weight compared to metal designs, the cylinders offer a high resistance to fatigue, corrosion resistance and no issues with hydrogen embrittlement.

Standards & Type Approval

Current standards/regulations used in the EU relating to type approval for automotive applications include EC79/2009, EC406/2010, and UNECE R134.

EC79 specifies the testing requirements for components and cylinders used in gaseous applications, including those relevant to the cylinder design, EC406 provides more detail on test procedures. A comprehensive range of hydraulic, leak and process gas tests must be passed to gain type approval for the cylinder design, a summary is listed below:

- Hydrostatic Testing – Burst Testing, Ambient Pressure Cycling to failure or specified cycle number is reached, leak before break performance test to provide evidence that the container fails by leakage before rupture, composite flaw tolerance test, accelerated stress rupture test at the limit of the allowable operating range with subsequent burst test
- Torque testing followed by burst test and leak testing
- External impact, bullet penetration and chemical exposure testing (including acids, bases & hydrocarbons)
- Leak testing with leak testing inert gases (H_2/N_2 or He/N_2 mix) at nominal working pressure
- Hydrogen permeation testing – the test cylinder is pressurised to the nominal working pressure and monitored for permeation in a closed chamber for a specified time under specified temperature conditions.
- Hydrogen gas cycle test – the container is subjected to a number of pressure cycles using hydrogen gas and a leak test. The container must meet leak test requirements, and be free of any deterioration e.g. fatigue cracking or electrostatic discharge.

Standard Hydrogen Filling Protocols & Filling Station Standards

Hydrogen filling protocols for use in vehicle filling stations are defined in the Society of Automotive Engineers Standard SAE/J2601, which was issued in 2010 and revised in 2014 (5). It is the de facto standard for hydrogen fuelling worldwide, and is based on fuelling simulation models which have been validated through a mixture of real world and lab testing.

The filling rate of the container must be controlled so that the design temperature of the vessel is not exceeded during the fast fill process. The gas present in the cylinder heats up during the filling process, when cooling down to ambient temperature the pressure in the cylinder falls from 875 bar to 700 bar.

Variables that affect the process include ambient temperature, dispenser pressure class, fuel delivery temperature, starting temperature and pressure of the installed vehicle in the container, dispenser to vehicle pressure drop and heat transfer considerations. The goal of J2601 is to fuel the vehicle as fast as possible – target time 3 minutes - while staying inside the design limits of the fuel tank. For a 700 bar nominal rated vessel the temperature and pressure limits are minus 40 - 85°C and 5 to 875 bar.

The fuelling station control system must adjust the gas flow rate depending on the initial conditions, e.g. on a hot day the station must fuel more slowly to ensure that the vehicle tank does not exceed its maximum operating temperature. The control system measures the pressure and ambient temperature during fuel startup, protocols exist for vehicles with and without communications interfaces between the vehicle tank and filling station.

The standard details a range of lookup tables which specify a target filling rate, in bar per minute, which depends on initial tank pressure and ambient temperature. Maximum permissible fill rate is limited to 60 g/s H_2.

A technical ISO standard exists for hydrogen fuelling stations, ISO TS 19880 (6), which specifies the minimum design characteristics for safety of public and non-public fuelling stations that dispense gaseous hydrogen to light duty land vehicles. The standard recommends a quantitative or semi-quantitative risk assessment process to be carried out on the hydrogen filling station and a safety system which is conform to IEC61511, use of the SAE J2601 or equivalent fuelling protocol.

In addition to those standards listed above, guidance from the EIGA/BCGA on the storage and use of high pressure gas cylinders and fixed storage facilities applies.

Gas Testing Facility Design Requirements

Dedicated testing & development facilities are required to be able to carry out the required range of hydraulic and gas tests during the cylinder R&D development cycle in a safe manner.

Handling significant quantities of hydrogen and inert gases at high pressure presents an obvious process safety/major accident hazard from fires, deflagration and detonation of hydrogen, the potential energy in the system from the high pressure of gas in use is a hazard in itself.

For the gaseous leak testing procedure one cylinder must be tested for type approval, a specified number per batch, and all finished containers in production testing. The cylinder must be pressurised for at least 3 minutes to nominal working pressure with leak test gas, with leakage through cracks, pores or similar defects causing the tank to be rejected.

Hydrogen permeation testing must be carried out on one type IV container only for type approval, hydrogen diffuses slowly through the cylinder liner, the cylinders have a permissible permeation rate which may not be exceeded. The container must be pressurised with hydrogen gas up to nominal working pressure and placed in a climate controlled chamber for 500 hours or until steady state leak rate is achieved for at least 48 hours. The EC406/2010 maximum leak rate is 6 nml/hr per litre of internal volume of the container at 15°C.

Hydrogen gas cycling must be performed – according to EC406/2010 between less than 20 bar to greater than or equal to the nominal working pressure for 1000 cycles – beyond the lifetime of the vehicle (approx. 300,000 miles) - with the standard 5 minute maximum filling time as achieved in a filling station – the test facility must be able to fill the cylinder identically to the full scale filling station, and depressurise the cylinder in a controlled manner in the shortest practical time possible. Excessive depressurisation rates cause thermal damage to the cylinder, in particular to the liner which can become detached from the carbon fibre body.

The permeation testing according to the R134 protocol differs slightly, and is performed at a temperature above or equal to 50°C and at 95% relative humidity, the permissible global leak rate is 46 ml/hr/l water capacity of the storage system during the test. Pressure cycling and permeation are carried out as part of one larger test, permeation measurements are carried out for 30 hours.

To be able to measure the leak and permeation rate the test specimen is located inside a secondary vessel to allow for precise temperature control and accurate measurement of hydrogen concentration. The secondary test chamber is inerted with N_2 prior to starting work with hydrogen, and on completion of the test an air atmosphere is restored prior to opening.

Additional Testing Requirements

In addition to tests required for Type approval of the cylinder and fulfilment of the industry standard hydrogen filling protocols for the vessel manufacturer it is important to know the safety margins within the existing design, and be able to answer the question – what is the consequence of a failure in the process control and inbuilt safety system when the filling rate specified is exceeded, and what is the consequence of a rapid, essentially uncontrolled, depressurisation of the tank.

Common to other R&D facilities in the process industry, additional functionality, flexibility and protective systems are required in comparison to a standard hydrogen filling station.

Process Design

The basic process flow diagram & example physical layout of the test bench is shown in Figure 2.

Hydrogen process gas is supplied from 300 bar cylinder packs and compressed from around 20 to maximum 950 bar with a dual stage piston compressor package (Hofer). In order to achieve the 3-5 minute filling times the compressor does not directly fill the cylinder, a cascaded fill from a high pressure bank (1034 bar, 4x300l) of cylinders is used. The complex fuelling protocols are integrated within the control system, manual filling is not possible without appropriate access levels. Overall system throughput is limited by the delivery rate of the hydrogen compressor, the high pressure storage banks must be refilled between cylinder or vehicle fuelling.

Hydrogen is precooled to -40°C using a heat exchanger downstream of the storage vessels, the cold hydrogen is fed either to the test specimen in the climate controlled test chamber or directly to a vehicle via a standard SAE conform hose fuel dispensing system.

On completion of a pressure cycle or permeation test the hydrogen in the sample is reused by recycling to the compressor inlet, keeping overall system hydrogen consumption to a practical minimum. Depressurisation end pressure is limited by the inlet pressure of the hydrogen compressor and pressure drop in the lines. Residual cylinder content is vented to atmosphere via a stack system with vent tip above the apex of nearby structures.

Leak testing gas (He or 5% H_2 in N_2) is fed in a partially separate circuit from cylinder supplies and dedicated air driven compressor. Fast filling is not required, inert gas leak testing is a relatively infrequent event. The largest assemblies in use take about 5 hours to fill to test pressure. Leak test gas is also recycled via intermediate cylinder buffer storage system to the gas compressor inlet.

Climate Controlled Secondary Chamber Design

To cover the required operating temperature window - between -40 and 85°C, relative humidity to 95%, and to be able to measure leak and permeation rates accurately, the sample cylinder is housed in a climate controlled sealed chamber, and secured against movement. Manual handling is carried out via a trolley and roller bed system. Temperature control of the chamber is carried out using an external circulating low temperature oil/thermal fluid circuit. The entire vessel and sections of feed lines are insulated with low temperature insulation to maintain the required temperature and for personal protection against hot and cold surfaces.

The chamber is effectively a moderately sized horizontally mounted double jacketed process vessel with one flanged end for opening and closing the system, with instruments and process feed lines installed/fed through from the other end. In order to accommodate the largest cylinders which are produced, internal diameter is 1.3m, length 3.5m to match the full spectrum. Analytical instruments are located inline in an external ring line remote from the main chamber to enable ease of calibration and maintenance.

The required vessel wall thickness is normally not determined internal overpressure, but by the external overpressure imposed by the thermal fluid jacket and potential vacuum which can be generated caused by cooling down of a closed vessel. The vessel is designed for full vacuum.

High Pressure Pipework & Fittings

A key inherent safety design requirement is for an inherently leak tight design and using the narrowest bore tubing practical to assist in reducing the inventory and maximum hydrogen release. High integrity fittings (welded or compression type) are preferred to flanged connections wherever possible.

For high pressure systems the flows (60 g/s max) are such that a relatively small pipe diameter can be used with the appropriate pressure rating. High pressure (20,000 psi) SS316L 3/8" or 9/16" tubing and valves with coned and threaded connectors are available as standard, and for "low" pressure sections (300 bar max) Swagelok® type connections and tubing are used.

All lines are leak tested with 5% H_2 in N_2 prior to use at the full system operating pressure, a short “bump” type test is carried out and recorded by the operator when connections are made and broken in normal operation. With leak testing procedures in place and repeated leak testing after maintenance and regular intervals most of the components and valves in use do not present a credible hydrogen leak source for area classification purposes.

Facility Layout Considerations

Standard layout for the test bench is shown in Figure 3. Key to the layout is the separation of operating personnel from the hazards wherever possible– access control on entry points to limits access to operational personnel only. The control room is remote from the rest of the facility, similar to on process plants. A high degree of automation is implemented in order to reduce operator occupancy in and around hazardous areas.

Where possible hydrogen containing parts and storage are located outdoors in open structures. Ancillary equipment such as compressors hydraulic motors are housed outside of hazardous areas in plant room containers.

Control of ignition sources as per area classification requirements, zoned areas are present in and around the hydrogen compressors, and around flanges where hydrogen may be present.

In the automotive/OEM tank manufacturing environment testing facilities and plant layouts are different to those seen in the process industries for valid historical reasons, high process hazard facilities are seldom present, construction of suitable dedicated areas remote from the rest of the facility is an integral part of the project.

Major Accident Hazards Inherent to the Process – Hydrogen, High Pressure and Inert Gas

Overall hydrogen inventory of the test bench is around 75 kg, stored in situ at pressures of up to 900 bar – release of hydrogen and immediate ignition, leading to a jet fire, or delayed ignition, leading to deflagration or detonation is an obvious hazard. Rapid release of large quantities of gas with no ignition is a major hazard due to the high potential energy of the pressurised gas.

The Type IV cylinders are not 100% leak tight, permeation rates of up to 46 ml/hr/l of hydrogen can be expected based on the maximum permissible leak rate in the R134 standard. For the largest cylinders in the 200l range this equates to 9.2 l/hr hydrogen which can leak into the secondary chamber of approx. $4m^3$. For a test lasting around a day the amount of hydrogen which can conceivably leak into the chamber could easily be in the % range during normal operation, ignition sources in the chamber cannot be excluded (moving parts), so inertisation of the chamber reducing the oxygen content to below the LOC of 5% is therefore required.

A large inertised vessel is used, which must be opened and closed at the end of each test, resulting in an asphyxiation hazard.

Two separate modes exist for the test bench – testing with 350 bar and 700 bar test vessels – using a 350 bar design pressure cylinder with a 700 bar fill protocol can credibly cause a rapid failure of the test cylinder with associated gas release.

Hazard Studies During Design Process

The basis of safety for the operation of the test bench has been developed by following the multistage hazard study process commonly used in the process industries – process engineering and process safety input is essential.

Initial Safety Review (HS1)

Hazid (HS2)

Hazop (HS3)

Commissioning Startup reviews (HS4, HS5)

Associated studies are performed as required and specified during the initial stages of the project– machinery risk assessments according to EN12100 for non-process hazards, consequence estimation/modelling, SIL classification LoPA, Area Classification.

HS2 and use of a risk matrix with agreed has been particularly effective in identifying the required basis of safety, major accident hazards and additional necessary layers of protection to reduce risks to a tolerable level. Hazard Study 2 using the PFDs takes typically one or two days for a typical test bench.

Hazop/HS3 is effective in identifying specific weaknesses in the design. The full P&ID for the test bench runs to 8 A3 pages and typically takes up to a week -20 nodes - depending on the amount of pre-work carried out. Separate small studies have been carried out on the interfaces between the system and vendor packages, including cooling systems, circulating thermostats and compressor skids.

Introductory sessions had to be arranged for participants who had never participated in Hazard Studies 2 & 3 previously.

A risk matrix has been used to assess consequence and frequency of events with and without protective systems in place. Use of a risk matrix was new to operating customers and was approved by the operating customer at the corporate level prior to use.

Large parts of the technical standard ISO/TS 19880 relating to hydrogen fuelling are relevant to the test bench design, and the standard itself refers to many process industry standards, including recommendations that a semi-quantitative or quantitative risk assessment is carried out, and the functional safety of the control and safety system is determined using IEC61511 and relief stream/device design is carried out according to EN4126.

Handling large inventories of high pressure hydrogen is not common practice in the automobile industry compared to traditional high hazard process industries, hazards associated with machinery, hydraulic and pneumatic systems are, however, familiar and well understood. While hydrogen inventory is significant, it is worth noting that it is not even close to the COMAH lower tier threshold limit of 5 tons.

Here, for the test bench application for gaining Type Approval of new cylinder designs it is important to differentiate between type approved and “not yet” type approved cylinders during testing. For tanks with type approval – successfully passed the tests specified in the EC regulations - and used within their design specifications with established fuelling protocols credit has been taken that the likelihood of burst failure before leakage is not credible, providing positive identification of type approved tanks is in place.

Worst Case Scenario(s)

Worst case scenario associated with the facility is a multiple fatality event caused by a detonation of hydrogen caused by a sudden cylinder rupture, loss of hydrogen contents in a short period with delayed ignition, resulting in structural damage and destruction of non-blast proof buildings in a ~ 30m radius, structural damage and destruction of windows in a wider radius. Ignition within the detonation limits for hydrogen in air (18.3-59%) ref can’t be excluded. Consequence modelling was carried out on a first pass basis using the ALOHA® software package, the MARPLOT® tool which plots the threat zones generated on a map is a highly effective method to draw attention of senior management to the worst case consequence.

As with any other process handling significant quantities of high pressure hydrogen, there are a number of other initiating events which can result in a hydrogen leak and explosion, and when dealing with large inerted vessels fatality from nitrogen asphyxiation must be assessed..

Burst failure of a tank, it should be noted, is not an occurrence which is reasonably foreseeable for a fully type approved design, and is not by any means an expected occurrence during the developmental process, since hydraulic testing and verification is required but cannot be entirely excluded. Worst case event initiating frequency is driven by procedural error and use of a 350 bar cylinder with a 700 bar fuelling protocol. A commonly heard statement is “if one bursts that means the end of the programme”, manufacturers are acutely aware of the business and reputational consequences of a major accident associated with their products.

Deflagration of hydrogen has a lesser, but still serious consequence, a number of experimental and modelling studies (7,8) have been carried out as part of the HYSEA project on hydrogen safety on the consequence of explosions inside container type structures typically used in hydrogen fuelling applications.

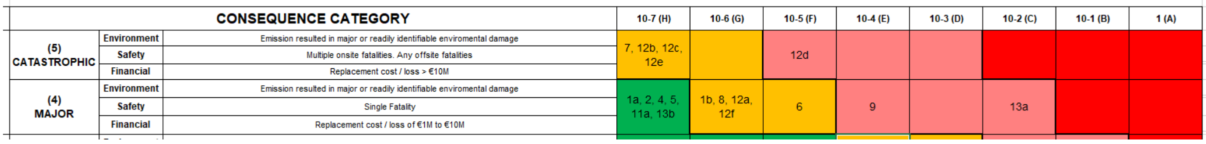
Secondary Containment

For permeation and hydrogen cycle testing of uncertified containers, secondary containment of the test specimen was considered to be reasonably practical in view of the high health and safety and financial consequence of a hydrogen detonation when taking surrounding buildings and occupancy levels into account.

There are two options which have been implemented and in development in differing designs – containment of hydrogen within the secondary test chamber (high design pressure), and consequence mitigation provided by explosion proof reinforced bunker which contains the test specimens and secondary chamber (s). Failure of the secondary chamber without ignition results in a pressure wave of ~1 bar inside the bunker, and with ignition results in a hydrogen explosion inside the bunker, requiring a design pressure in the region of 7-8 bar. Other overpressure scenarios are catered for with a design pressure of 2 bar (g) and a suitably designed relief stream.

Design of the climate chamber to withstand loss of a full test cylinder or internal explosion is also possible, the increased design pressure is calculated based on the maximum inventory of hydrogen and the volume of the chamber. Inertisation is a key control in preventing a hydrogen/air ignition inside the chamber A high mechanical strength Duplex steel can be used for such applications whilst maintaining reasonable wall thicknesses for ease and cost of vessel manufacturing. From a project management perspective custom pressure vessels have their own implications relating to the capital cost and delivery time of the project.

Highest Residual Hazard Scenarios from Haz Studies Performed



CONSEQUENCE CATEGORY			10-7 (H)	10-6 (G)	10-5 (F)	10-4 (E)	10-3 (D)	10-2 (C)	10-1 (B)	1 (A)
(5) CATASTROPHIC	Environment	Emission resulted in major or readily identifiable enviromental damage	7, 12b, 12c, 12e		12d					
	Safety	Multiple onsite fatalities. Any offsite fatalities								
	Financial	Replacement cost / loss > €10M								
(4) MAJOR	Environment	Emission resulted in major or readily identifiable enviromental damage	1a, 2, 4, 5, 11a, 13b	1b, 8, 12a, 12f	6	9		13a		
	Safety	Single Fatality								
	Financial	Replacement cost / loss of €1M to €10M								

Figure 3 High Hazard Scenarios

For communication purposes scenarios from the hazard studies are displayed on a summary sheet in the report graphical form on the risk grid.

Highest hazard consequences stem from either failure of the tank, or asphyxiation of the operator when opening a large inerted vessel in an essentially closed space.

Scenario 12d is failure of a 350 bar tank when used with a 700 bar filling programme, highlighting the need for positive identification of test cylinders, and management of change procedure relating to changed test campaigns with different vessel designs.

Scenario 13a above is asphyxiation of an operator, the initiating event is failure of the purge system and oxygen detection system inside the tank, which initially are part of the control system. Further procedural controls, additional independent monitoring via different sensor types (flow, pressure, concentration), and integration of these in the safety system in addition to the standard control package.

Scenario 9 is vehicle/forklift collision with high pressure hydrogen storage, highlighting the need for barrier protection around vulnerable items.

Notably, process design hazards generally resulted in lower residual risk than organisational and human factors initiating events, highlighting the need for a broad spectrum of expertise in the design process.

Overpressure Protection

The test chamber is equipped with a burst disc for the following overpressure scenarios

- Line break of the feed line to the chamber (also covers leaks from the test specimen up to the line internal diameter)
- Human error when connecting the test cylinder resulting in full flow from an open connection and failure of the initial leak test
- TPRD failure of valve assembly leading to activation – during the risk assessment process estimated as 0.1/year event as a conservative estimate

High pressure/low pressure interfaces are a classic overpressure scenario and present downstream of regulators or control valve within the system, particularly in gas recycle lines. Failure of a non-safety rated control system or regulator failure is assessed as a 0.1/year initiating event. Consequence of 900 bar on valves and tubing which are not rated is in all likelihood a line or valve failure with large hydrogen leak are equipped with a relief valve (PFD 0.01) and a high pressure trip (PFD 0.1) on the regulator outlet.

Relief stream design was carried out using the PEL software package from ABB – a 6” nominal bore burst disc provides adequate relief capacity for full flow from the TPRD and full flow from both sides of a 5mm i.d. line break at maximum operating pressure, which is the governing relief case.

Required Procedural Controls During Operation

Controlled Access to Test area via access card controls. Entry to the bunker is only permissible when the hydrogen flow is stopped and isolated.

Process isolations have been implemented as per HSE guide HSG/253 “The Safe Isolation of Plant and Equipment”. Manual double block and bleeds with Lock Out Tag Out (LOTO) is applied on key process and inert gas isolations.

Management of change procedures, with appropriate signoffs by competent personnel, are necessary when switching between 350 and 700 bar vessel testing, different control modes are used, which must be changed by authorised personnel only. Campaigns Test specimens are clearly marked to avoid the chance of mix-up. Different fittings are used on the connecting pieces of the tanks in the test bench as an additional control, analogous to different cylinders

Functional Safety & LoPA

The test bench is equipped with a PLC based control system and safety system which is conform to IEC61511. High hazard, low demand, scenarios subject to a LoPA assessment. Some high demand systems are integrated in the safety system for safety critical control sequences e.g. filling rate control are implemented in a safety control system with a higher degree of reliability than a standard control system.

LoPA scenarios have been carried out after Hazard Study 2 where possible and where further clarification is required on whether residual risk for high consequence events, where necessary further assessments are carried out after HS3.

The preferred process control system is based on Siemens PLCs and safety PLCs which are compliant with IEC61511.

Alarms & Alarm Response

A number of alarms are implemented with operator required alarm response as per EN62682. However, the system is designed for unmanned operation with no 24/7 shift cover as in many R&D facilities so no credit was taken for operator response to an alarm.

Conclusion

Type IV hydrogen storage tanks for use in fuel cell vehicles – light duty, heavy duty and rail applications - require a range of tests with high pressure hydrogen and leak testing gas to be successfully passed to achieve type certification. The manufacturers and end users of the tanks are primarily based in the automotive sector, on sites which are not traditionally associated with the process industries, with limited process safety expertise. The test facility is similar to a demonstrator hydrogen filling station in terms of scale but not throughput, with extra functionality required which is not covered by existing automotive industry standards and protocols.

In terms of process design and inventory of hazardous materials the test bench equivalent to a process industry pilot plant. Therefore, a traditional multistage Hazard Study and associated semi-quantitative Risk Assessments has been used in the design and construction of the facility. Pressure overprotection is provided using burst discs and relief valves, instrumented safety systems conform to IEC61511 are implemented.

Major accident hazards associated with the facility include hydrogen explosion (detonation and deflagration), asphyxiation from using inertised vessels which house the test specimens, and from human factors issues related to different pressure ratings of tanks which must be tested, and ensuring that a robust management of change when using test cylinders of lower design pressures than the maximum delivery pressure of hydrogen in use.

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Figure 2 – Process Flow Diagram

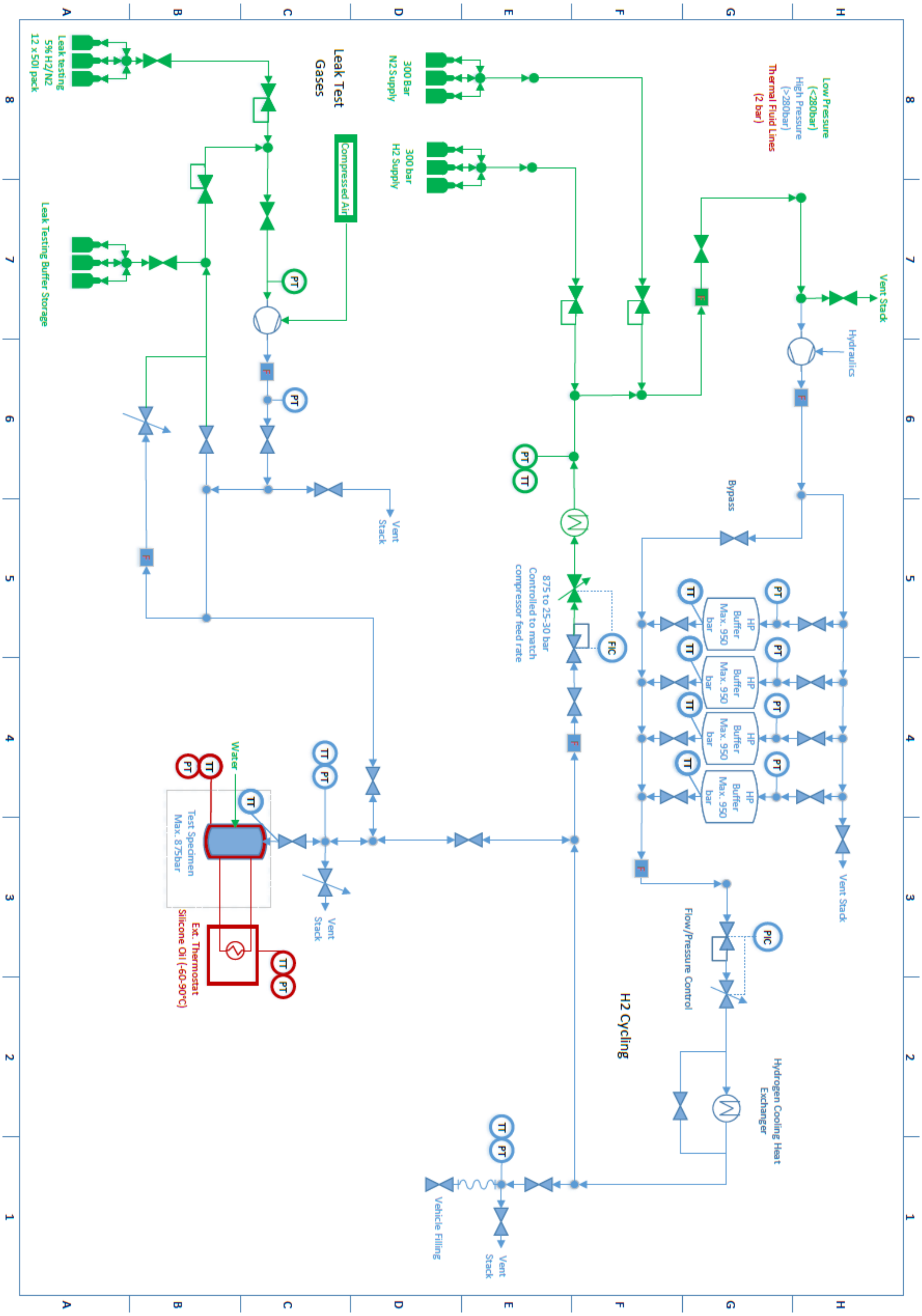

Figure 3 Simplified Test Bench Layout