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70 MPa Fueling Station for Hydrogen Vehicles

Joe Wong[a], Livio Gambone[b]

[a]*Powertech Labs Inc, 12388 88th Avenue, Surrey, B.C., Canada, joe.wong@powertechlabs.com*
[b]*Powertech Labs Inc, 12388 88th Avenue, Surrey, B.C., Canada, livio.gambone@powertechlabs.com*

ABSTRACT:

To achieve sufficient driving range for fuel cell powered vehicles, automotive companies have developed on-board fuel systems capable of storing hydrogen compressed to 70 MPa (10,000 psi). Fueling infrastructure was required to support the effort of these car manufacturers. This paper describes a demonstration project to design and construct 70 MPa fueling station facilities at Powertech Labs in Surrey, B.C., Canada. The station was part of a government and industry funded co-operative project called "Compressed Hydrogen Infrastructure Program (CH$_2$IP)". Filling a fuel cell vehicle to 70 MPa necessitates a hydrogen fueling station working pressure of 87.5 (12,500 psi). The biggest challenge of the project was to source components capable of withstanding hydrogen compressed to 87.5 MPa. Key components were developed by a number of suppliers to accommodate the higher pressure requirements (cylinders, valves, fittings, flow-meter, dispenser, and fill nozzle). Prior to installation, the new components were extensively tested at Powertech to ensure they could be operated safely and reliably under normal and abnormal fueling station service conditions.

KEYWORDS: *70 MPa compressed hydrogen fueling station*

Introduction

In current years, the technology of using 35 MPa compressed hydrogen gas storage systems has become widely accepted and adopted by most automotive original equipment manufacturers (OEMs) for fuel cell powered vehicles. In order to gain market acceptance, the driving range of hydrogen vehicles must increase to match the performance of conventional vehicles. In a Powertech program supported by automotive OEMs (Hydrogen 700), the technical feasibility of 70 MPa (10,000 psi) high-pressure gaseous hydrogen storage for fuel cell vehicle applications was demonstrated. Since that time, automotive companies have developed vehicles with on-board fuel systems capable of storing hydrogen compressed to 70 MPa. As a result, the development of cost effective and safe infrastructure for fueling hydrogen vehicles is of equal importance to support the effort of these car manufacturers. This paper describes a demonstration project to design and construct 70 MPa fueling station facilities located at Powertech in Surrey, Canada.

Figure 1: Fueling of a Nissan 70 MPa Vehicle at Powertech

This fueling station was part of a government and industry funded co-operative project called "Compressed Hydrogen Infrastructure Program (CH$_2$IP)". This Program, managed by Powertech, demonstrated the following important advances which will promote the use of compressed hydrogen as a fuel for vehicles:

- Fast filling hydrogen vehicles at 35 MPa (5,000 psi).
- Demonstrating lightweight mobile trailers for transporting hydrogen.
- Fast filling vehicle storage systems to 70 MPa (10,000 psi).
- Demonstrating a hydrogen generator/compressor package.
- Supporting testing of prototype 70 MPa vehicle storage systems.
- Providing data to produce safety standards for hydrogen fueling stations.

The purpose of the project was to demonstrate a low cost method of establishing a hydrogen station infrastructure. The initial phase of the project, completed in 2002, focused on the construction of a 35 MPa fueling station. An on-site electrolyser produced approximately 24 kg of hydrogen per day based on a 24-hour operation. The electrolyser also contained two small compressors that provided hydrogen at 35 MPa. The compressed hydrogen was stored in light weight, aluminum lined carbon fibre reinforced cylinders at a pressure of 43.8 MPa. The hydrogen was dispensed through a 35 MPa dual hose hydrogen/compressed natural gas (CNG) dispenser. In 2003 the existing 35 MPa fueling station was upgraded to dispense hydrogen at 70 MPa (10,000 psi).

The third phase of the program, completed in 2004, consisted of the construction of a 70 MPa hydrogen satellite station. The satellite station demonstrated the concept of generating hydrogen at a central facility and transporting it to supply a remote fuel station location. The concept is similar to existing liquid petroleum fueling stations, where the liquid fuel is transported by truck. The hydrogen is transported in high-pressure cylinders installed in a trailer mounted ISO container unit. A small booster compressor was used to transfer compressed hydrogen between the cylinders to maintain a high pressure for fast filling operations. The container unit was parked at the satellite site at Powertech and was connected to a fueling dispenser which was permanently mounted on a fueling island

Filling Station Design

The 700 bar station at Powertech was designed to fuel light duty fuel cell vehicles requiring approximately 3 to 5 kg of hydrogen per fill. Figure 2 shows a schematic of the major components in the station. The 43.8 MPa storage bank provides hydrogen to the 87.5 MPa compressor.

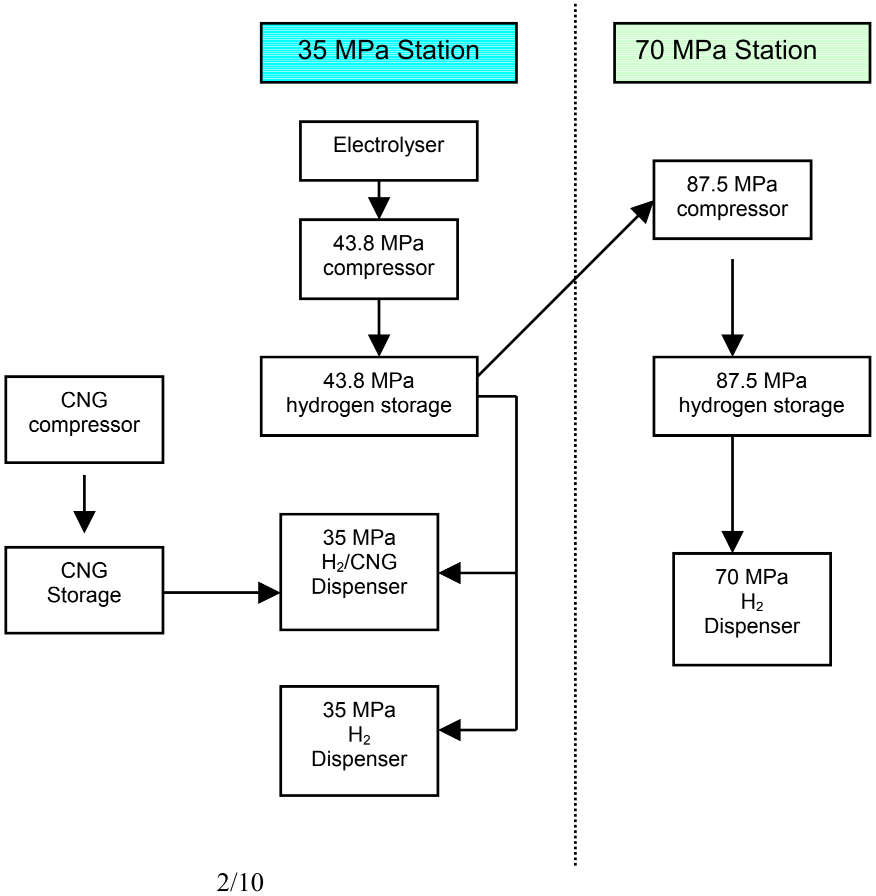

Figure 2:

Schematic of hydrogen fueling station at Powertech

High Pressure Station Components

Filling a fuel cell vehicle to 70 MPa necessitates a hydrogen fueling station working pressure of 87.5 MPa (12,500 psi). The biggest challenge of the project was to source components capable of withstanding hydrogen compressed to 87.5 MPa. Key components were developed by a number of suppliers to accommodate the higher pressure including: compressors, storage cylinders, valves, fittings, flow-meter, dispenser, and fill nozzle. Prior to installation, the new parts were extensively tested at Powertech to ensure they could be operated safely and reliably under normal and abnormal fueling station service conditions.

Compressors

The factors in choosing a compressor for a specific application included:

- Inlet and outlet pressure/compression ratio
- Variable inlet pressure
- Maximum outlet pressure
- Flow rate
- Purity of hydrogen
- Reliability
- Cost

A number of different types of compressors for hydrogen were utilized in this project: The basic types included:

Reciprocating piston – oil lubricated
The disadvantage of a reciprocating piston – oil lubricated compressor was the large amount of continued maintenance required to prevent contamination of the hydrogen. Special care and attention was required to maintain the purification system. In addition to the maintenance of the purification system, the compressor itself required replacement of valves and other parts at regular intervals. While this maintenance was manageable for 35 MPa systems, it would not be feasible for 70 MPa systems.

Oil free non-lubricated gas piston
The oil free non-lubricated gas piston prevented oil carry-over contamination of the compressed hydrogen. The main advantage of this compressor was the simplicity of the packaging. It can also use a variable suction pressure and thus it is often used as a gas booster.

Diaphragm
The main difference between piston and diaphragm compressors was the manner in which the gas was compressed. The metal diaphragm compressor completely isolates the gas from the displacing element during the entire work cycle. The discharge gas was as pure as the gas entering the compression head. If the integrity of diaphragm or seal is breached, a pressure switch will shut down the compressor.

A diaphragm compressor with a capacity of 0.71 m3/min (25 scfm) was used to compress hydrogen to 85 MPa. The compressor package used hydrogen from the 43.8 MPa storage bank as suction and boosted it to 85 MPa. This was much greater than the capacity of the electrolyser, which fed the 43.8 MPa storage bank. As a result, the compressor had a fairly complex starting and stopping control algorithm to avoid compressor dead band. For the compressor to start, the compressor discharge pressure must be depleted below the start set-point of 76 MPa (11,000 psi) and the suction pressure must be greater than 15 MPa (2200 psi). During normal operation the suction pressure will be depleted to 14 MPa (2000 psi) at which point the compressor will stop. As the electrolyser / compressor replenishes storage (on suction), the compressor will again start when the inlet pressure reaches 15 MPa. Regardless of inlet pressure, the compressor will stop when the discharge pressure reaches the stop set point of 85 MPa. If the inlet pressure depletes to 12 MPa (1700 psi), the compressor will shut down on a low inlet pressure fault.

Over-pressure protection on compressor discharge was accomplished by the PLC stopping the compressor at a maximum pressure set point. In addition, a discharge relief valve was set to discharge at the maximum allowable working pressure (MAWP) of the system. This relief was set to vent into a vent header equipped with a pressure switch to shut down the compressor in the event of a relief valve actuation.

To prevent over heating (and damage) of compressor components the inlet gas temperature must be limited to less than 100ºF. Depending on ambient temperature and the extent of depletion of the inlet storage pressure, there was a wide variation in inlet gas temperature. A heat exchanger was installed to maintain low inlet gas temperatures

Overall, a diaphragm compressor was more expensive to package due to the large number of sensors and alarms required to protect the compressor.

Figure 3: 25 scfm diaphragm 87.5 MPa compressor

87.5 MPa Hydrogen Storage

One of the most important aspects of a hydrogen fueling station is the storage of gaseous hydrogen. Steel tanks, traditionally used for ground storage are very heavy and difficult to manufacture when designed to 87.5 MPa. Therefore, lightweight carbon fiber composite storage tanks were designed and built for use in this project.

Over the last ten years, the composite cylinder design has proven to be robust and weight efficient in many transportation applications. The design was manufactured in accordance with CSA B51-03, Part 2 covers "High-pressure Cylinders for the Onboard Storage of Natural Gas as a Fuel for Automotive Vehicles", and Part 3 covers the ground storage cylinders used in fueling stations. This standard was modified to include hydrogen as a fuel for automotive vehicles and was one of the first published standards for high pressure composite cylinders. In British Columbia, the BC Safety Authority (BCSA) has used this standard to register composite cylinders for use in hydrogen vehicles and fueling stations. The cylinder manufacturer has registered designs in British Columbia for both 45 MPa and 85 MPa type 3 composite cylinders.

Figure 4: Comparison of wall thickness between a 200 bar and a 700 bar rated Type 3 composite cylinders

The CH2IP project has provided a unique worldwide opportunity to demonstrate the use of high-pressure composite cylinders for hydrogen storage in fueling stations. Many other jurisdictions and countries require storage cylinders to be designed to ASME codes. However, the ASME code does not include high pressure composite cylinders. ASME has started a new working group to address this issue. The results from experience gained on composite cylinders during this project will be shared with the ASME working group.

The hydrogen storage cylinders are designed to withstand the service conditions of vehicle applications. The cylinders have to meet a stringent set of performance tests as outlined in CSA B51-Part 2.

Performance Tests included:

- Materials verification tests (includes hydrogen embrittlement tests)
- Burst – minimum burst ratio 2.25 times service pressure
- Simulated fueling/defueling cycle test
- Damage tolerance due to surface flaws

- Damage tolerance due to handling impact
- Stress rupture of fibres
- Fatigue cracking of fibres
- Damage tolerance due to environmental effects
- Damage tolerance due to fire damage

The minimum requirement for the burst ratio in the cylinder standards was 2.25 times the service pressure. For a cylinder designed to 85 MPa, the required burst pressure was 192 MPa. This was quite a substantial margin of safety since the cylinder would have to be over pressurized by 107 MPa (15,500 psi). By comparison, a cylinder designed to 43.8 MPa only has a margin of safety of 54.7 MPa (7900 psi). Another observation during a burst test was that carbon fibre behave elastically prior to failure (i.e. there is very little damage to the cylinder fibres until the pressure reaches close to the final burst pressure).

Another requirement of the cylinder standard was that a finite element analysis (FEA) was performed on every cylinder design to verify the maximum allowable stresses. The following figure shows the cylinder model and the stresses in the metal liner and the composite laminate as a result of an internal gas pressure. These calculations become very important in thick wall designs where stress concentrations may occur.

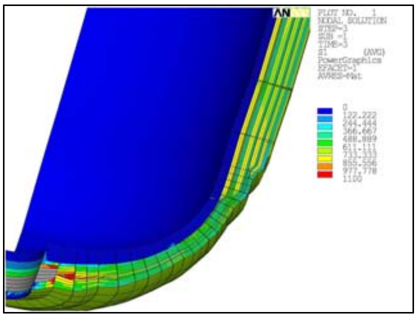

Figure 5: FEA of composite laminate

Nondestructive testing (NDT) was performed on every cylinder as another method to ensure safety. A NDT scan is performed on the liner to detect any flaws in the metal. The finished cylinder is hydrostatically proof tested to 1.5 times the service pressure.

Destructive batch tests (pressure cycling and burst) were performed after every 200 cylinders produced to ensure that quality was maintained to meet the requirements of the original design.

The 438 bar hydrogen storage unit consisted of 16 type 3 aluminum lined carbon fiber wrapped cylinders mounted in stackable steel racks. Each cylinder had an internal water volume of 150 litres. The current storage holds approximately 68 kg of hydrogen.

Ten tanks were used in the station as ground storage tanks holding approximately 59 kg of hydrogen. Each cylinder was 58 cm in diameter and 95 cm long and had a maximum allowable service pressure of 85 MPa. Since these were the first cylinders approved to this pressure, BCSA has given these cylinders a registration period of six years.

With a station storage capacity of 127 kg, there was a potential to fill a large number of light duty fuel cell vehicles each requiring approximately 5 kg of hydrogen per fill. However, in order to achieve a full fill, during consecutive fast filling of vehicles the storage bank has to be maintained at a high pressure. In order to optimize the fast filling capability without requiring continuous replenishment by the compressor, a "cascading" method was used to fill the vehicles. The storage bank is divided into three banks. Filling of a vehicle starts with the low bank. When the pressure in the vehicle is equalized with the pressure in the low bank, the filling is switched to the medium pressure bank. The high-pressure bank tops off the fill once the medium bank equalizes with the vehicle. This method allows a greater number of full fills compared to single-bank system.

Tubing

Most of the tubing used for the project was Type 316 SS bright annealed seamless ASTM A213/A269 tubing at 0.120'' wall. This tubing is not susceptible to hydrogen embrittlement. Another advantage of using this tubing was its availability in continuous lengths of up to 200 feet. The flow rate through the tubing was adequate for all the required applications.

Fittings

All fittings used in this project were made from 316 stainless steel. There were existing fittings available that were rated to over 140 MPa (20,000 psi). The principle of operation for this type of fitting was a reverse threaded collar and gland system with coned sealing faces. The disadvantages of using these types of fitting were that the tube wall thickness was reduced and that amount of tube preparation was required.

One supplier produced a new line of fittings rated to 100 MPa utilizing a nut and dual ferrule system. The advantages of this system were; no tube preparation was required, the wall thickness was not reduced.

Other Components

Powertech worked with a number of suppliers worldwide to provide components for the hydrogen station capable of withstanding pressures of 85 MPa. In many cases, prototype parts were supplied for the project. These parts were tested in Powertech's high pressure testing facilities prior to their installation in the station. These parts include fittings, tubing, valves, relief valves, pressure relief devices (PRDs), check valves, and regulators.

A number of different valves from various manufacturers were used throughout the station. The ultra high pressure rated valves did not encountered problems, however expensive adapters are required when cold drawn tubing is used. Some needle valves were found to leak internally over time. Additional development work was required to produce reliable valves rated to 100 MPa.

70 MPa Dispenser

An automated hydrogen dispenser was developed to dispense hydrogen at 70 MPa. Several suppliers offered flow-meters for 700 bar service. The flow-meter chosen for the dispenser was a Coriolis style mass flow-meter with a pressure rating of 86.8 MPa. The flow-meter can measure up to 7 kg/min and was calibrated to 7 kg/min with less than 1% error. Calibration was performed using a test cylinder filled with hydrogen. The cylinder was weighed before and after filling using a 150 kg scale accurate to 1 gram.

The dispenser fills the vehicles by first sensing the initial pressure and temperature. Then a set mass of hydrogen was dispensed and the cylinder pressure was re-measured. The filling algorithm then calculates the target fill pressure based on the ambient temperture. The only problem with this type of filling method was that the temperature in the vehicle system may significantly increase exceeding the design temperature of the on-board storage system. The filling rate was sufficiently decreased to avoid the high temperatures. Testing is performed to ensure these temperatures are not exceeded. The graph below shows a vehicle test system filled using the station dispenser. Temperatures were monitored in the test tank, at the end connections and on the exterior tank surface. The ambient temperature was approximately 10°C. The cylinder was filled to approximately 81 MPa. The gas temperature reached approximately 75°C. After the system returned to the ambient temperture, the settled pressure in the cylinder was 66.2 MPa (96% of the target pressure of 70 MPa).

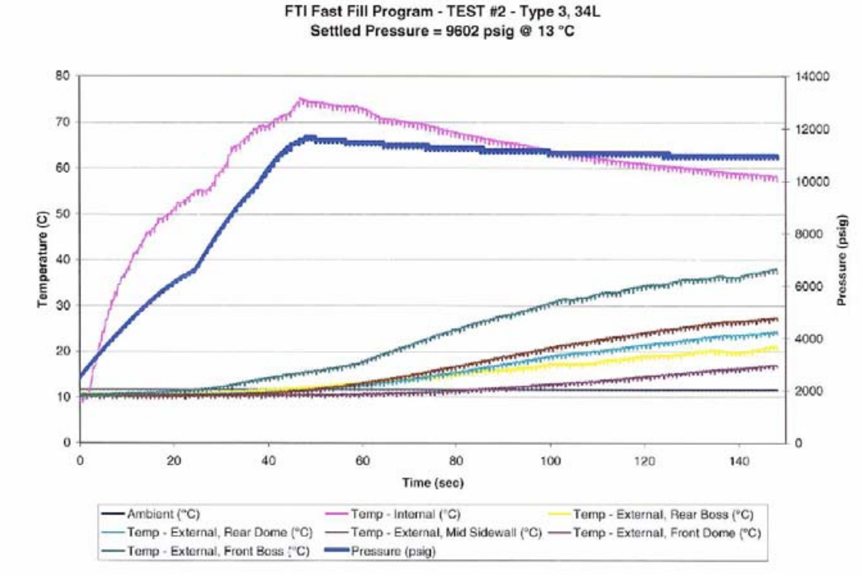

Figure 6: Vehicle fill test data

Fast Fill Testing

The fueling objectives were to transfer the maximum amount of hydrogen to the vehicle in the shortest amount of time, without overfilling or exceeding the maximum allowable gas temperature. A facility was constructed at Powertech to study the effects of fast filling of fuel storage systems to 70 MPa. The facility consists of a high-pressure storage bank mounted inside a hydrogen safe environmental chamber, capable of conditioning the gas temperature from -40°C to +50°C. The storage is divided into three banks to allow filling by cascading. Each storage bank was monitored using pressure and temperture sensors. A flow-meter was connected in line with a manual control valve.

Figure 7: 70 MPa fast fill facility

The SAE J2601 Standard is being developed to recommend practice for gaseous and liquid hydrogen vehicle fueling with respect to vehicle-to-dispenser communication, temperature compensation, and fueling targets and protocols. This working group performed an evaluation of fueling performance targets for onboard 70 MPa gaseous hydrogen storage containers[1]. As part this study, Powertech provided a data set of 25 fill tests to 70 MPa using the fast fill test facility. The study examined the effects of:

- initial ambient storage temperatures
- cylinders with plastic or metal liners
- large or small cylinders
- different filling algorithms or flow control schemes
- pre-cooling of gas

The study provided valuable data for optimizing fill strategies. It also showed that more investigations was required to control the effects of heat of compression.

70 MPa Satellite Station and Transport Facilities

The third phase of the program consisted of the construction of a 700 bar hydrogen satellite station. The purpose was to demonstrate a low-cost method of establishing a hydrogen station infrastructure. The concept of the satellite station was to have the hydrogen trailer brought onto the filling station site, and parked in an enclosed compound. The storage would be connected on site to a gas booster and a PLC control box located inside the compound. The control box would automatically manage the gas by constantly replenishing the high bank cylinder using the low and medium bank as suction. The connections would supply a sequencing panel to fill cars through the 700 bar dispenser (see figure 8). When the cylinders were depleted, the trailer would be transported to a central location for filling.

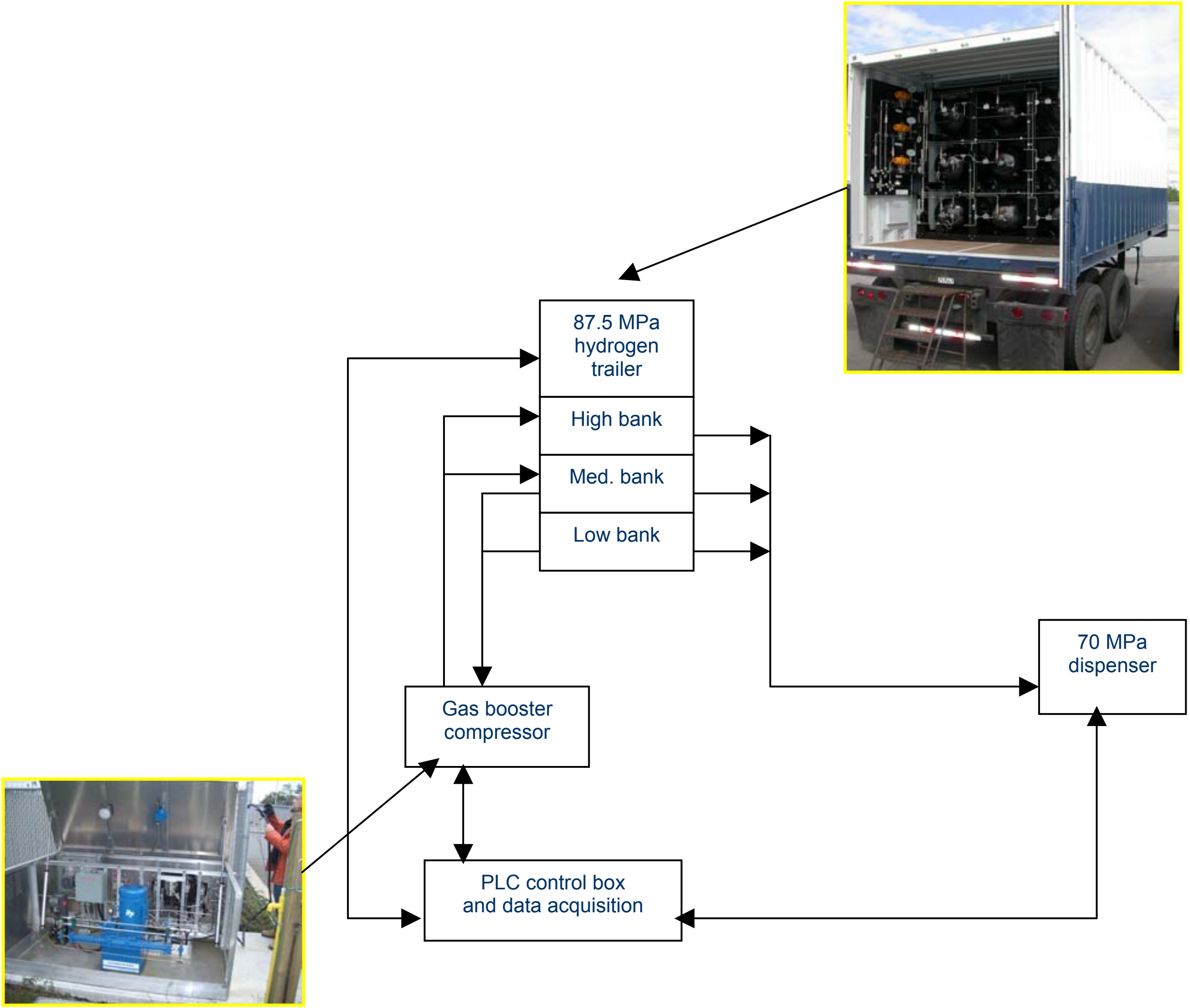

Figure 8: Schematic of the satellite station.

The key aspect of this technology was the use of high-pressure, light-weight storage cylinders for transporting hydrogen. Convention tube trailers made of steel were quite heavy. The table below shows that the composite cylinders were only 1/3 of the weight of the steel cylinder that carried approximately the same amount of hydrogen.

Tube type	No. of tubes	Service pressure (MPa)	Tube OD (mm)	Tube length (m)	Tube weight (kg)	Hydrogen stored per tube (kg)	Total weight of tubes (kg)	Total hydrogen stored (kg)
Steel - DOT 3AAX	1	16.55	559	6.10	1280	15.52	1280	15.52
Composite- Type 3	3	86.19	580	0.95	127	5.90	381	17.70

The cylinders were mounted on to a steel frame that fit into a standard ISO container. The frame was designed to withstand all the required vehicle loading.

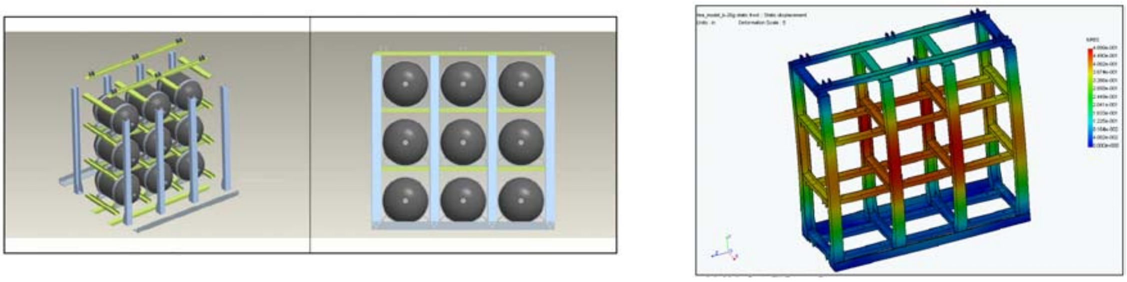

Figure 9: Finite element modeling of the trailer cylinder frame subjected to a 20 g load

Safety of 70 MPa Systems

Powertech's engineering staff performed extensive safety reviews of the hydrogen filling facilities with input from external expertise in the area of compress gas stations. Since there are currently no standards covering hydrogen filling stations, the design closely conformed to standards developed for compressed natural gas filling stations. Powertech also worked with the Gas Safety Branch of the British Columbia Safety Authority to review the station design. They have registered the design base on deviations to the natural gas codes. Information from this demonstration project will be used to support new standards for hydrogen installations.

Hydrogen safety evaluations were performed through testing the various components to study the effects of fire, effects from impact/collision, and management of leaks/releases. Materials verification tests were also performed (includes hydrogen embrittlement tests at 100 MPa).

A Hazard and Operability Study (HAZOP) was performed which involved systematically questioning every part of the process to establish how deviations from the design intent can arise. The deviation and its consequence were rated based on the severity of the deviation and the frequency of it. If necessary, action was taken to remedy the situation.

An Emergency Response Plan for the hydrogen storage and dispensing facility at Powertech was prepared to provide a course of action to follow should an emergency event occur on site or in the surrounding retail business or community area. The plan outlined the procedures and personnel responsible for executing the plan.

Conclusions

The CH_2IP program has demonstrating a number of important advances to promote the use of compressed hydrogen as a fuel for vehicles and have shown:

- It is technically feasible to compress, store, and dispense hydrogen to vehicles at 70 MPa.
- Manufacturers have developed components critical to support building of 70 MPa fueling stations.
- The use of light weight composite cylinders will facilitate the efficient distribution of hydrogen with transport trailers.
- The continued operation of the 70 MPa station will provide valuable data for developing installation and component standards.
- Further work is required in developing dispensing strategies to optimize the transfer of hydrogen to the vehicle.

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