

Automotive Production of Liquid Hydrogen Storage Systems

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LIQUID HYDROGEN STORAGE, SERIES PRODUCTION

Summary

Liquid hydrogen takes up less storage volume than gas but requires cryogenic vessels. State-of-the-art applications for passenger vehicles consist of double-wall cylindrical tanks with a hydrogen storage mass of up to 10 kg. The preferred shell material for the tanks is stainless steel, since it is very resistant to hydrogen brittleness and shows negligible hydrogen permeation. Therefore, the weight of the whole tank system including valves and heat exchanger is more than 100 kg. The cavity between the inner and outer vessel is mainly used for thermal super-insulation. The remaining heat in-leak leads to a boil-off rate of 1 to 5 percent per day. Car storage systems require a fail-safe design since drivers are usually not experienced in handling hydrogen. Therefore, Failure Mode and Effect Analysis (FMEA) performed on critical components shall minimize the occurrence of malfunctions of the system. The production of several liquid hydrogen tanks which fulfill the draft of regulations of the European Integrated Hydrogen Project (EIHP) is being prepared. Cars represent the ultimate market for manufacturers of hydrogen storage systems due to the quantities involved worldwide. They also pose some of the greatest challenges to commercialization, including their relatively small size, the vast fuelling infrastructure required, and the inconsistent maintenance habits of the public at large. In addition, performance and reliability expectations are high. Cost issues will be addressed by selecting automated production technologies and scaling effects in mass production.

1 Introduction

What motivates the development and propagation of hydrogen as an energy carrier is the imminent exhaustion of oil reserves as well as the alarming increase of air pollution and global warming effects. Hydrogen-powered vehicles, no matter if they are powered by electrical engines via fuel cells or by internal combustion engines, have to successfully compete with conventional gasoline- or diesel-powered vehicles. Main criteria are the driving range, maintenance, and price. Within the next decades, hydrogen-powered vehicles are predicted to remain niche products. Since vehicle and component costs in the automobile industry are mainly reduced in high volume production, hydrogen-powered vehicles will be more expensive than diesel-powered vehicles. Generally, on-board hydrogen can be stored as compressed gas up to about 70 MPa, as a liquid at about 20 K, or in solid media. The first two methods are rather established technologies, whereas solid media are still under investigation. Thanks to the low working pressure in the case of cryogenic storage, this storage option enables tank geometries that can be adapted to the vehicle space available.

MAGNA STEYR is convinced that liquid hydrogen storage is the most efficient system for automotive applications. In order to offer an added value to the automotive OEMs, MAGNA STEYR aims to build a team of experts and accumulate hydrogen-specific knowledge and expertise in-house. Moreover, our focus on liquid hydrogen constitutes a considerable competitive advantage over other automotive suppliers. This strategy paves the way for receiving future development and production contracts in that field from the OEMs.

In the next few years, our main goal is to set up a production area, in which we can guarantee an automotive production process for very small and medium-size production volumes. In the medium term (10-15 years), we will establish a production area for higher quantities. This is in line with strategic goals of important OEMs like GM and BMW. GM, for instance, plans to build up to 100.000 fuel-cell vehicles until 2010.

2 State-of-the-art design

State-of-the-art mobile liquid hydrogen storage systems, as shown in Fig. 1, consist of double-wall vessels of cylindrical shape. Depending on the clearance, the hydrogen mass ranges up to 10 kg for passenger vehicles. Preferred shell materials are stainless steel or aluminium alloy, since they are very resistant to hydrogen brittleness and show negligible hydrogen permeation. For stainless steel, the minimum wall thickness for cryogenic vessels is at least 2 mm. The weight of the whole tank system including valves and heat exchanger is above 100 kg. The space between the inner and outer vessel is mainly used for the thermal insulation. Several layers of insulation foils reduce the heat entry by thermal radiation. The high vacuum with a pressure of less than 10^{-2} Pa (at about 20 K) reduces the thermal convection. The insulation consists of reflective foils (aluminium or aluminised polymer) separated by spacers (glass fibre or polymeric). Support structures, which keep the inner tank in position to the outer tank, are made of materials with low thermal conductivity (e.g. glass- or carbon fibre reinforced plastics). After about three days of not using the vehicle, the heat entry leads to a boil-off rate of 1 to 5% per day.

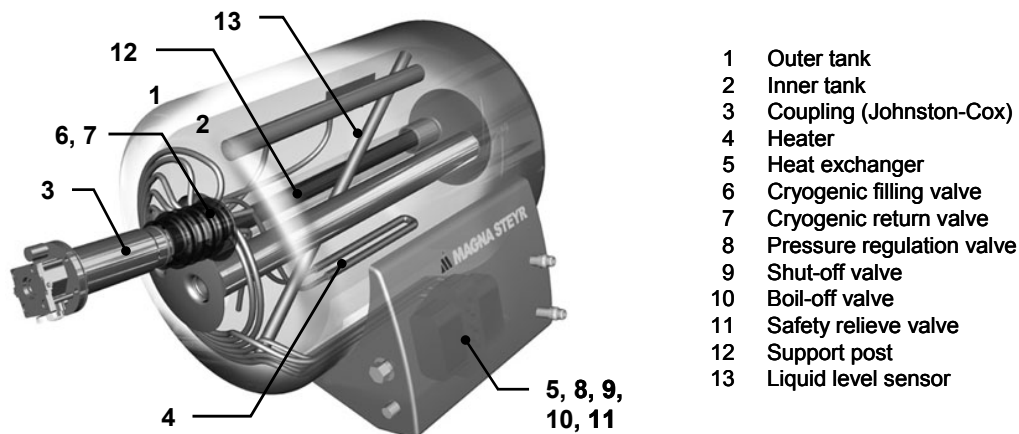


Fig. 1: Liquid hydrogen storage system

3 Requirements

Today there are more than 800 million passenger cars and commercial vehicles worldwide. Safety and durability standards for these vehicles have been developed within one century. New hydrogen-powered vehicles have to follow in the footsteps conventionally powered vehicles by fulfilling the same quality standards. As long as just a few hydrogen-powered vehicles exist, lifetime forecasts for hydrogen-specific components can be evaluated only with difficulty. Predictions for the next decade show that car bodies will still be adapted from gasoline- and diesel-powered vehicles. Therefore, the entire on-board hydrogen infrastructure, composed of the hydrogen storage system, the piping, a fuel cell, and the engine, must fit into the vehicle package.

Hydrogen is an odourless gas, which is flammable. Mixtures with oxygen can be explosive. Because of the small molecules, hydrogen has a high leak rate, diffuses rapidly and embrittles certain materials. The component design of liquid hydrogen storage systems depends on the safety concept for hydrogen-powered vehicles.

3.1 Quality requirements

Mobile storage containments for liquid hydrogen are mainly a spin-off from the air and space industry. Space applications are designed for a short lifetime of a few minutes and low-volume production, whereas the lifetime for vehicle applications in high volume production ranges between 10 and 15 years. For use in alternatively powered vehicles, most components of the storage system have to be redesigned in order to become affordable to consumers. This redesigning must not influence the reliability and safety of any specific component.

The development process of liquid hydrogen storage systems may follow the V-Model (see Fig. 2) based on the functional safety process according to the standard IEC 61508. The two branches symbolize the requirements and the realization.

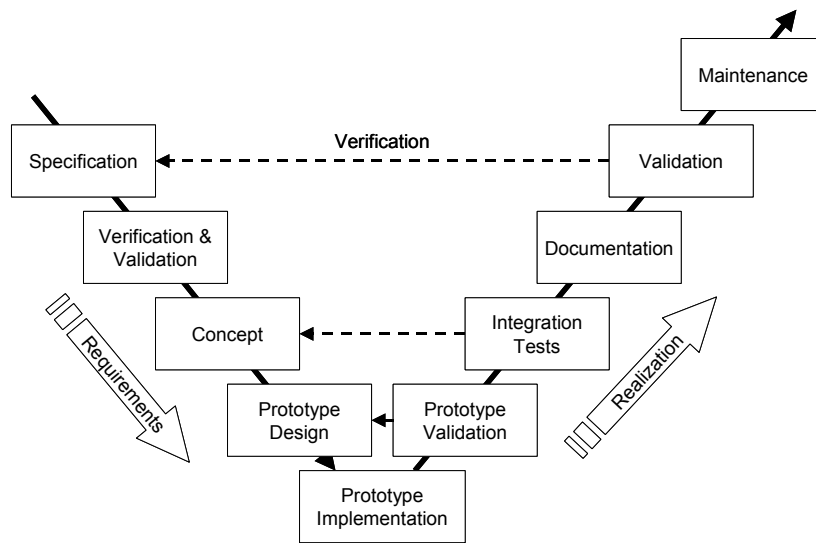


Fig. 2: Development process as described by the V-Model

The “specification” is based on the requirements defined by the automobile industry. It includes vehicle-specific (i.e. package geometry, fuelling and re-fuelling procedures) and environmental requirements (i.e. operational temperature, ambient pressure range) as well as the EIHP draft of regulations for cryogenic vessels. In addition, it defines the safety integrity level of the storage system. In “verification & validation”, specified data and proposed functions are tested and proven. The “concept” visualizes functions and hardware. Safety analyses, like the Failure Method and Effect Analysis, shall discover hidden risks. “Prototype design”, including calculation, material selection, and drawings, is the next step. First prototypes are built during the “prototype implementation” phase. The “prototype validation” gives a feedback to prototype design. Within this loop, the prototype will be modified until most of the requirements are fulfilled. After passing the prototype phase, the storage system must succeed in different “integration tests”. The test results shall be verified by means of the concept. The safety process requires a complete “documentation”, including test records, material and welding certificates. The “validation” of the system verifies the specification and entails extensions of some requirements. For high volume products, the feedback from “maintenance” activities is important.

As soon as a tolerable risk is achieved, the safety integrity level (SIL) can be defined according to Tab. 1. The use of redundant systems and functions reduces the risk.

Tab. 1: Failure margins for safety functions (IEC 61508-1)

Safety Integrity Level [SIL]	Mode of Operation with high demand rate or continuous demand [Probability of a dangerous failure per hour]	Typical effects
4	$\geq 10^{-9}$ to $< 10^{-8}$	death of a lot of persons
3	$\geq 10^{-8}$ to $< 10^{-7}$	death of some persons
2	$\geq 10^{-7}$ to $< 10^{-6}$	significant injury, death of one person
1	$\geq 10^{-6}$ to $< 10^{-5}$	insignificant injury, loss of function

Typically, safety-related components in liquid hydrogen storage systems are defined by SIL 2 or 3, because in case of a dangerous failure of a specific component one or more people can die. Hence, when designing the component a meantime between a dangerous failure greater than 10^7 hours (1140 years) between two dangerous failures must be considered.

As a consequence, the number of components which may cause a dangerous failure has to be minimized. The risk must be predictable. Failure Mode and Effect Analysis (FMEA), performed on the functional concept as well as on component design, shall minimize the occurrence of malfunctions of the system. To achieve that, the system is divided into main functions, as shown in Fig. 3. A team of specialists considers possible failures for the specific functions or components and proposes methods to prevent or minimize them. Moreover, they weight the remaining risks in relation to their priority.

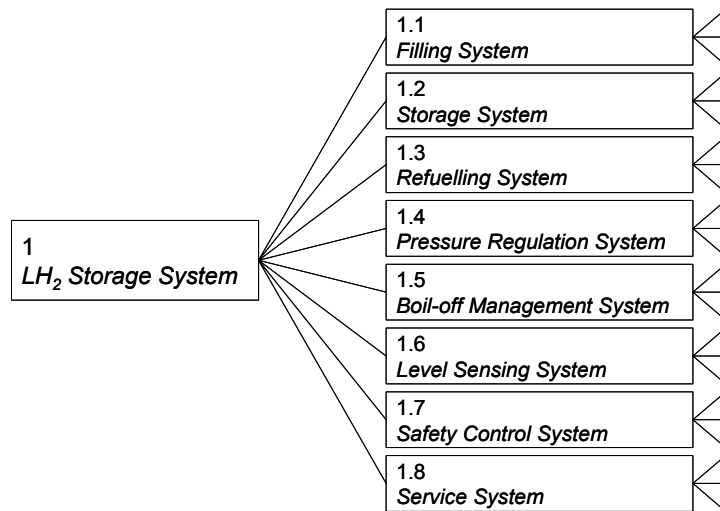


Fig. 3: Basic structure of the FMEA

The proposal for new draft regulations for uniform provisions concerning the approval of “Specific components of motor vehicles using liquid hydrogen” and the “Vehicle with regard to the installation of specific components for the use of liquid hydrogen”, revised by EIHP, defines standards for the design and testing of specific components of a liquid hydrogen storage system. The current revision deals with metallic vessel materials. The performance of hydrogen containers made from other materials than metals has to be demonstrated to fulfil the requirements according to existing standards. The hydrogen container including the safety devices affixed to it must be mounted and fixed in a way that the acceleration of at least 200 m/s² in the direction of travel and at least 80 m/s² horizontally perpendicular to the direction of travel can be absorbed in case of an accident with a full hydrogen tank without damage to the safety-related parts. No uncontrolled release of hydrogen is allowed.

Operational excitation frequency ranges between 0 and about 30 Hz. Therefore, the natural frequency of safety components has to be above 40 Hz in order to avoid damage due to resonance effects. Durability and lifetime expectations depend on the strategy of the car manufacturer.

The design and validation plan (DVP) for liquid hydrogen storage systems includes all test and approval procedures necessary for releasing the system. This comprises thermal and pressure tests of hydrogen-specific components, durability and lifetime tests for the liquid hydrogen storage system as well as misuse investigations with the whole system in the vehicle.

In the automobile industry the procedural instruction VA 9 controls procedures and competences of the quality management for purchasing and procuring vendor parts. It includes the supplier selection, project estimates, supplier product and process development, process series, first-time production qualification, and procedures for escalation.

3.2 Production requirements

First prototypes are built to validate the required functions, the quality of the thermal insulation, the pressure-rise time, and the boil-off rate. In parallel to the prototypes, production devices are designed, built, and adjusted. They are necessary to produce liquid hydrogen storage systems with similar characteristics. Furthermore, an A-B-C analysis identifies cost-effective components of the system, since all components and procedures are validated with known or estimated costs. Necessary modification procedures shall reduce the costs.

Fig. 4 shows the cost distribution of the main functions of a liquid hydrogen storage system. Costs are mainly determined by storage, filling, refueling, and safety aspects. Depending on the safety integrity level, up to 100% of welding seems have to be tested.

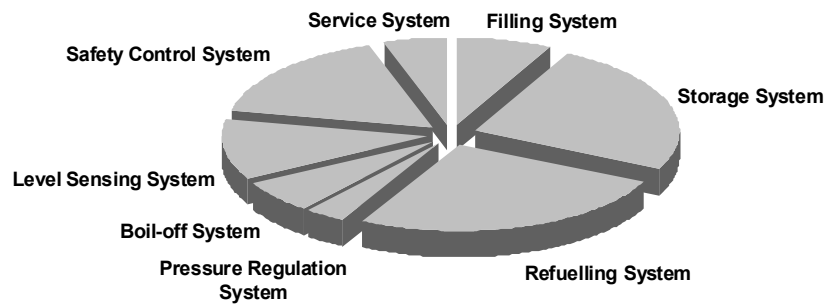


Fig. 4: Cost distribution for a liquid hydrogen storage system

Reducing the costs is strongly linked to the degree of automation due to the use of efficient mounting devices. Hence, it should be pointed out that moderate investments will already increase the degree of automation substantially from currently 3%. As shown in Fig. 5, doubling the produced units per year entails a reduction of production costs by about 20%.

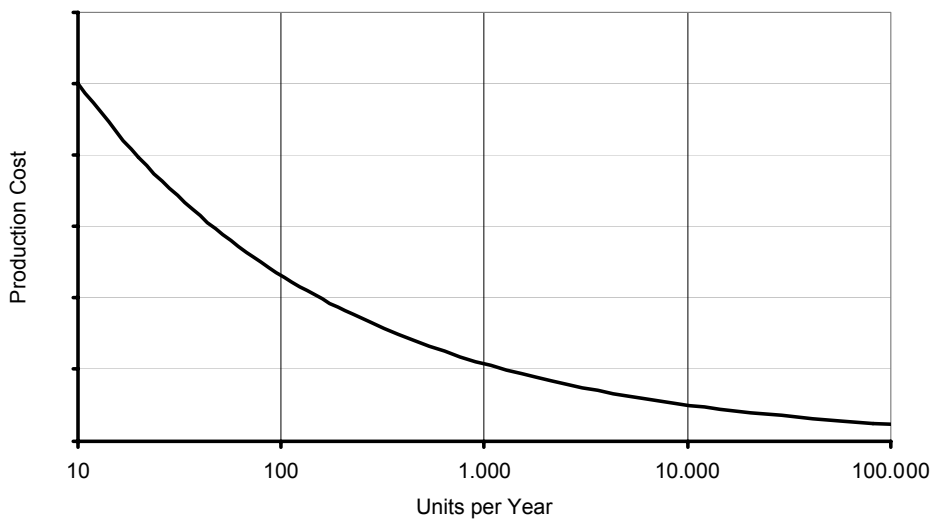


Fig. 5: Reduction of production costs (Source: Integrierte Produktentwicklung, K. Ehrlenspiel)

4 Assembly procedure

The design of the liquid hydrogen storage system is divided into two sub-modules, the container and the system box (see Fig. 6). The container is composed of inner vessel, pipes, thermal insulation, and outer vessel. The inner vessel and all hydrogen-containing pipes are designed according to the pressure vessel standards and have to fulfill a pressure test after assembly, which is then followed by a visual inspection. After the inner vessel is surrounded with thermal insulation foils and the getter material is installed, the inner vessel is inserted into the outer vessel. The getter is one of the essential components for a static vacuum-insulated hydrogen storage system as it allows maintenance-free use. The bottleneck during the production process is the evacuation of the space between the outer and inner vessel down to a residual pressure of about 10^{-2} Pa. In order to reduce the time for evacuation to a few days, the container has to be heated above 370 K.

The system box is built parallelly to the container. It mainly contains valves and sensors, which are fixed in valve blocks. Since hydrogen has to be delivered to the propulsion system as a gas at a temperature above 300 K, a thermally isolated heat exchanger is located in the system box. The system box and the container are connected via a multiple Johnston-Cox coupling.

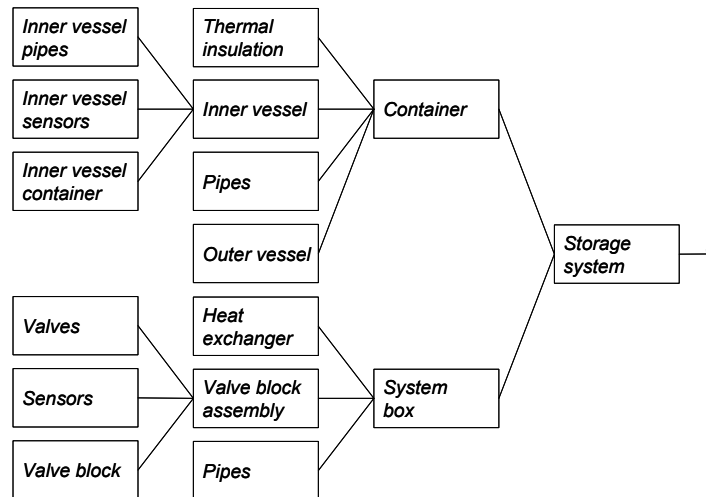


Fig. 6: Assembly steps of a liquid hydrogen storage system

5 Conclusions

A high volume production of liquid hydrogen storage systems requires major adjustments in design and assembly. Production technologies have to be certified according to safety and quality requirements. Hence, technology spin-offs from air and space applications have to be adapted for automotive processes. A considerable reduction of costs can be achieved by using tools and rigs suitable for high volume production. Main development activities for a cost-effective production focus on the fields of thermal insulation and the thermodynamic design of piping, valves, heat exchangers, and sensors. Several materials are under investigation. In addition, the application of casting and brazing at low temperature and in contact with hydrogen has to be verified. Future liquid hydrogen storage systems will have shaped geometries made of lightweight materials.

6 Bibliography

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