SAFETY DEMANDS FOR AUTOMOTIVE HYDROGEN STORAGE SYSTEMS

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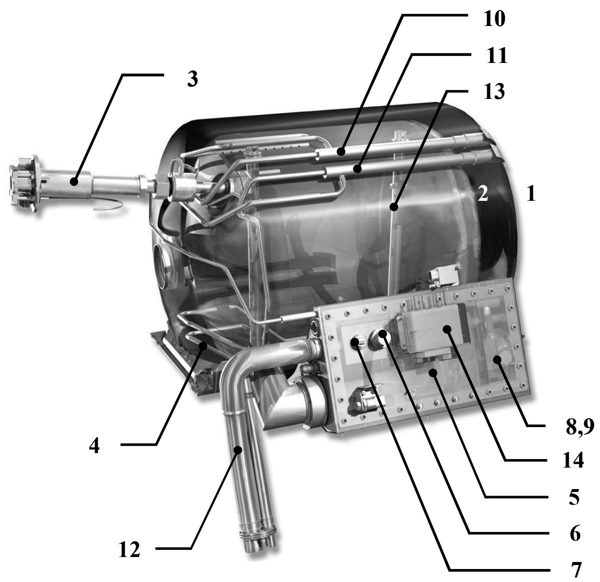
ABSTRACT

Fuel storage systems for vehicles require a fail-safe design strategy. In case of system failures or accidents, the control electronics have to switch the system into a safe operation mode. Failure Mode and Effect Analysis (FMEA) or Failure Tree Analysis (FTA) are performed already in the early design phase in order to minimize the risk of design failures in the fuel storage system. Currently, the specifications of requirements for pressurized and liquid hydrogen fuel tanks are based on draft UN-ECE Regulations developed by the European Integrated Hydrogen Project (EIHP). Used materials and accessories shall be compatible with hydrogen. A selection of metallic and non-metallic materials will be presented. Complex components have to be optimised by FEM simulations in order to determine weak spots in the design, which will be overstressed in case of pressure, thermal expansion or dynamic vibrations. According to automotive standards, the performance of liquid hydrogen fuel tank systems has to be verified in various destructive and non-destructive tests.

1 INTRODUCTION

Onboard hydrogen storage in vehicles is a key enabling technology essential for realising a hydrogen based economy. It also constitutes a major challenge and technical hurdle on the road to this goal. The main costumer requirements for future hydrogen powered vehicles are mainly derived from their experience with petrol or diesel powered vehicles. Hydrogen stored in its liquid phase has the highest energy density and therefore the longest range compared to high pressure and solid hydrogen fuel storage systems.



1 Outer jacket
2 Inner tank
3 Refueling coupling
4 Inner tank heater
5 Cooling water heat exchanger
6 Pressure control valve
7 Shut-off valve
8 Boil-off valve
9 Pressure relief valves
10 Cryogenic inlet valve
11 Cryogenic outlet valve
12 Hydrogen pipes
13 Liquid level system
14 Electronics

Figure 1: Liquid hydrogen fuel tank

The liquid hydrogen fuel tank, according to Figure 1, is a stainless steel dewar consisting of an outer jacket (1) and an inner tank (2) with thermal insulation in between to keep the temperature of hydrogen in the inner tank near 20 K. The heat entry by thermal radiation is reduced by about 40 layers of highly reflective aluminium foils separated by glass fibre spacers. A vacuum pressure below 10^{-2} Pa reduces thermal convection to a minimum. The support structure, which keeps the inner tank in position to the outer jacket, is made of carbon fibre reinforced plastics and has to withstand an acceleration of 20 g in direction of travel and 8 g horizontally perpendicular to the direction of travel. When the car is parking, the finite heat in-leak to the stored hydrogen of about 2.5 watts leads to an increase of pressure in the inner tank and therefore to a system autonomy time of about one day. Then the hydrogen boils off at a rate of around 4 percent per day. It passes a boil-off conversion system and leaves the vehicle as water.

Refuelling: During refuelling both valves, the cryogenic inlet valve (10) and the cryogenic outlet valve (11), are opened. Liquid hydrogen can flow from the filling station via a Johnston-Cox coupling (3) and the cryogenic inlet valve into the inner tank (2). In order to keep the inner tank pressure low, evaporated gaseous hydrogen leaves the inner tank via the cryogenic outlet valve and flows back to the filling station. When the refuelling procedure is finished, both cryogenic valves are closed.

Operation: For tapping hydrogen from the inner tank the cryogenic outlet valve is opened. Gaseous hydrogen flows from the inner tank to the cooling water heat exchanger (5). It heats up above ambient temperature and flows through the pressure control valve (6) and the shut-off valve (7) via the hydrogen pipes (12) to the connected combustion engine or fuel cell. If the inlet pressure drops down to the lower margin of the set pressure of the pressure controller, a partial flow inlet of the pressure control valve will open to let part of the warm hydrogen gas pass through the inner tank heater (4). Due to heat transfer, the liquid hydrogen around the inner tank heater evaporates. Thus the pressure in the inner tank is kept at a constant level. When the engine is switched off, both cryogenic valves and the shut-off valve are closed.

Boil-off and safety: During long-term parking the hydrogen pressure in the inner tank rises until the boil-off valve (8) opens to limit the boil-off pressure. Overpressure in the inner tank must not open the cryogenic valves. If the boil-off conversion system cannot manage the incoming hydrogen, i.e. in case of a degraded thermal insulation, the pressure in the inner tank increases until the first pressure relief valve (9) opens. Malfunction of the first pressure relief valve provokes the opening of the second pressure relief valve. In case of an accident or a loss of vacuum, the pressure relief devices shall release the evaporating hydrogen by keeping the inner tank pressure at an acceptable level. The specified pressure levels for the liquid hydrogen fuel tank are listed in Table 1.

Table 1: Pressure levels of the presented liquid hydrogen fuel tank

Description	Pressure [MPa]
Inner tank test pressure	1.19
Opening pressure of 2nd pressure relief valve	0.97
Maximum allowable working pressure (MAWP)	0.82
Opening pressure of 1st pressure relief valve	0.74
Opening pressure of boil-off valve	0.61
Nominal operating pressure	0.40

2 FAIL-SAFE DESIGN STRATEGY FOR LIQUID HYDROGEN FUEL TANKS

Today hydrogen is mainly used in the chemical, electronic and metallurgical industry. As opposed to industrial applications, in which hydrogen plants are operated by highly skilled individuals, future hydrogen powered vehicles will be driven by people who are not especially trained in handling hydrogen. The European Integrated Hydrogen Project (EIHP) [1] was established to draft new regulations related to hydrogen fuel tanks based on the consisting UN-ECE regulations for compressed natural gas and liquid petroleum gas [2]. The technical content of the current Draft UN ECE Regulation has wide support from authorities and the industry in Europe. The development of the state-of-the-art automotive liquid hydrogen fuel tanks, as shown in Figure 1, is based on Draft UN ECE Regulation revision 14 and 14 add. 1. The goal of a safety related design is to keep the probability of critical failures at an acceptable level. The common risk of hydrogen powered vehicles must not exceed the risk of conventional vehicles for passengers or other persons. Every failure must be detected and critical situations must be prevented by adequate measures or minimized by redundant safety devices.

While the Draft UN ECE Regulation is focussed on uniform provisions concerning the approval of specific components for motor vehicles using liquid hydrogen, a valid standard for safety related design has been found in the IEC 61508 about functional safety of safety-related systems [3]. This standard looks at the whole safety life cycle, starting with the concept, implementation, servicing, modification, retrofitting up to de-installation / shut down. The safety life cycle is shown in Figure 2.

Step 3 to step 5 describe the most important aspects for classification into safety integrity levels (SIL). This classification shows the impact of each part on the safety of the whole storage system. To that end, a risk analysis (step 3) has to be done, to assign the separate parts to SIL 1 to SIL 4. SIL 1 represents a small accident and SIL 4 a very bad accident with very high body count. The highest level for the liquid hydrogen fuel tank system is SIL 3.

This classification is the basis for all efforts for the next steps. The demands for each SIL level is also an input for the safety system. Parts classified as SIL 3 need a verification that the probability of a dangerous failure is lower than 10^{-8}. The probability that a failure is not dangerous must be higher than 99%. With one safety device, it may be between 90 and 99% and if the storage system is secured by a redundant safety system, failure tolerance is between 60 and 90%. So the use of a redundant safety system is recommended for SIL 3.

The demands for an approval also increase with the SIL classification. For SIL 1, verifications are required, for SIL 2 more stringent tests are necessary. For a SIL3 approval, an external assessor is necessary. This assessor has to be independent as far as the project is concerned but may be an employee of the same company.

Due to the fact that the IEC 61508 is a standard for functional safety of electrical / electronic / programmable electronic safety-related systems, it is also used for mechanical parts “in according to”. But implementing this standard for mechanical parts causes some difficulties because the definition for the appliance “in according to” is not defined. Many questions are still to discuss. In particular, the failure probability of complete new design parts is unknown so that in some cases a statistic verification is not possible. For mechanical stress, statistic tests like the hydro-pulse test are available, but for thermal tests, statistic results are hardly achievable. Since quantitative statements are unavailable, the approval has to be based on qualitative statements. The IEC 61508 is very useful from the point of view of safety but for mechanical parts, some further definitions are necessary.

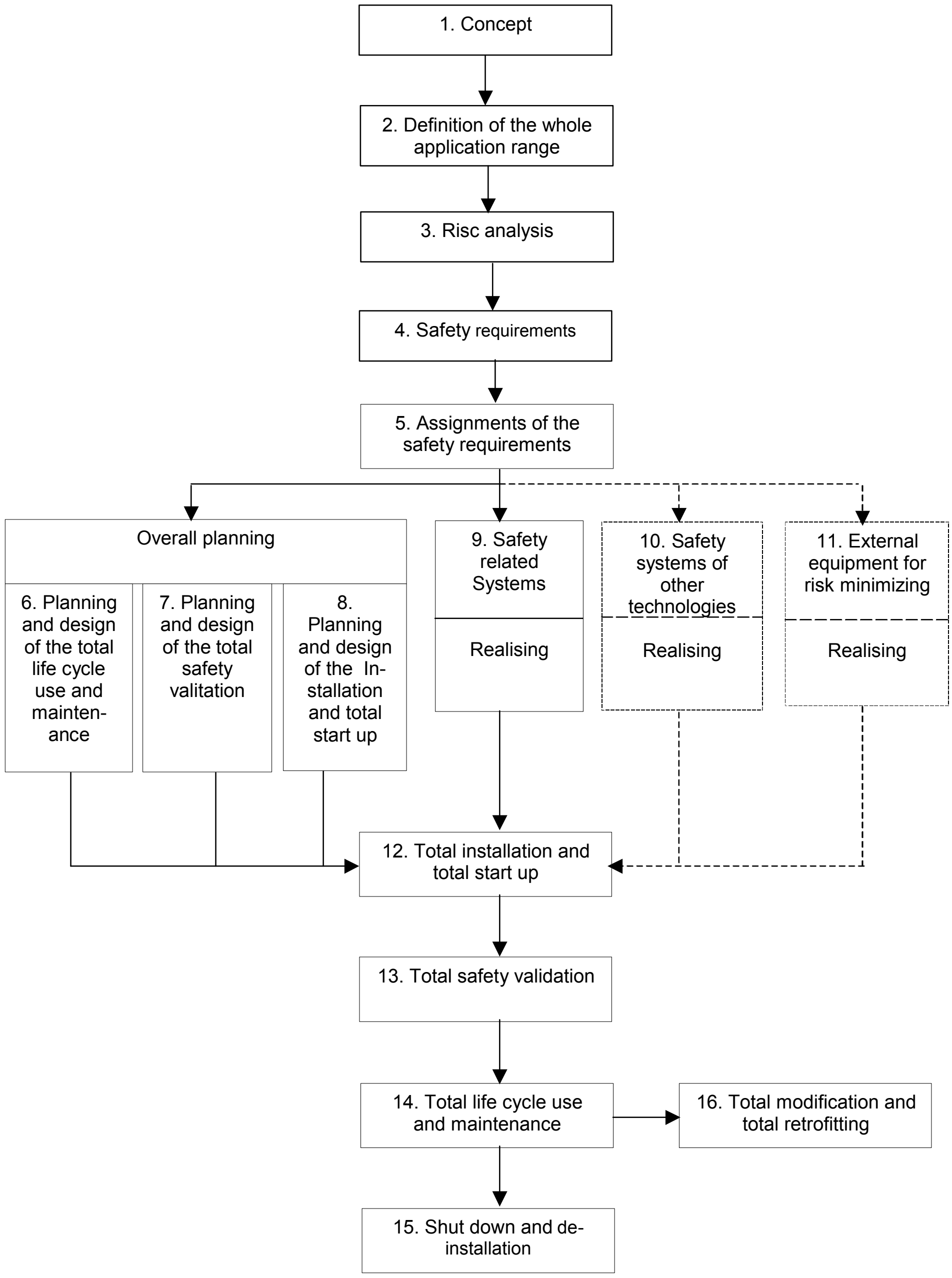


Figure 2: Safety life cycle

2.1 Intrinsic safety concept

The auxiliary system box of the liquid hydrogen fuel tank, as shown in Figure 3, contains heat exchanger, valves and sensors located in a housing, sealed to the surroundings. It cannot be avoided that small amount of hydrogen penetrates through components into the air-filled housing. The mixture of hydrogen and air has a very low ignition energy over a wide range. Therefore, the design of intrinsically safe supply of electric components inside the housing require power supplies which limit the distributed energy to the components below the ignition energy of H2/air mixtures. A concentration of hydrogen inside the auxiliary system box will be detected by a hydrogen gas detector.

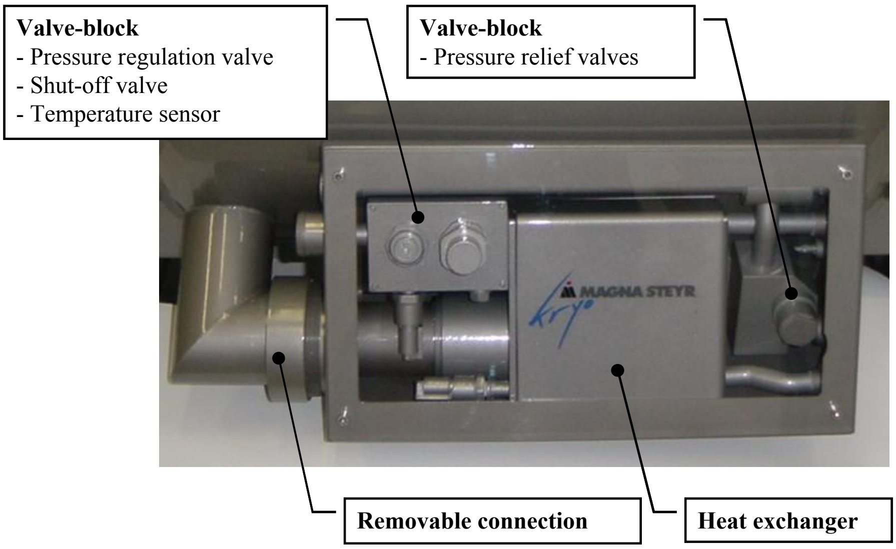


Figure 3: Auxiliary system box of a liquid hydrogen fuel tank

O-ring sealing materials (e.g. PCTFE, EPDM), conventionally used in the automotive industry, show a leak-rate of about 10^{-6} mbar l/s at ambient conditions and can exceed 10^{-2} mbar l/s at a temperature of 233 K. Therefore sensors and valves of the presented liquid hydrogen fuel tank are sealed with metallic HELICOFLEX® sealings. The leak-rate of this sealing is below 10^{-9} mbar l/s over a wide temperature range.

2.2 Thermal insulation

According to the Draft UN ECE Regulation, all components used for thermal insulation and the container shall be compatible with an atmosphere enriched with oxygen according to the European standard EN1797:2001 [4]. The certification requires an impact test for metallic and non-metallic materials. For liquid hydrogen fuel tanks these tests shall be performed at ambient pressure in a mixture of liquid nitrogen and liquid oxygen with minimum 50% liquid oxygen. An impact energy of 79 J/cm² has to be applied on each sample, as shown in Figure 4. The material passes the test if no reaction occurs on 20 samples. If a reaction occurs, the material can be used after performing a positive hazard analysis. On the other hand, experience based on the proof of a satisfactory long-term use qualifies the material, too.

Figure 4: Multi layer insulation ignition test with pure oxygen atmosphere

It shall be noted that the impact test is much stricter than flammability requirements for construction materials (e.g. for buildings). Even materials that are correctly classified as non-flammable (Class A1) in standard data sheets, e.g. due to their very low calorific values or because they are not flammable at ambient conditions, may fail the impact test. The impact test does not give any indication about the calorific value of the material or if it is self extinguishing or will support sustained burning. For glass fibre materials this means that even a very small portion of dressing or binder can cause a reaction in this test.

As impact test results are available only on few materials and new tests are time consuming and costly, the oxygen index has been used for a pre-selection of candidate materials. The oxygen index is defined as the minimum concentration of oxygen, expressed as a volume percent in a mixture of oxygen and nitrogen, that will support candle-like flaming combustion of a material (according to EN 4589 [5]). Moreover, it states that the burning behaviour of a material is largely dependent on size, shape and orientation of the probe. The test is useful for quality control (e.g. of flame retardation), for comparison of materials or for pre-selection in research and development. For foils the results are different depending on whether the edges are protected or not. The oxygen index shall not be used as the sole method to characterize the burning behaviour of a material. This test can never replace the impact test but it is still useful for a first pre-selection. As the critical impact test does not consider the further development of a fire but only reports if a probe has ignited (i.e. starts to react), flame retardants will probably not improve the oxygen compatibility.

3 MATERIALS

The outer jacket as well as the inner tank are made of stainless steel. It is widely used in cryogenic facilities and therefore its parameters at cryogenic conditions are well known. Furthermore, stainless steel has a cubic face-centred lattice and is resistant against hydrogen embrittlement. Stainless steel is excellently weldable and very well machinable. The outer jacket of the liquid hydrogen fuel tank is mainly in contact with the surroundings and shall be resistant against corrosion. The ambient temperature ranges from 233 K to 358 K. According to Table 2, a stainless steel with the material number 1.4404 has been chosen. The inner tank is not in contact with the surroundings but with liquid hydrogen at a temperature of 20 K. The inner tank and the pipe work is made of stainless steel of type 1.4306 because of its certification down to 4.2 K.

Table 2: Composition of stainless steel

Material Number	Composition	Certified lowest temperature [K]	Description
1.4306	X2 CrNi 19 11	4.2	Inner tank, pipes
1.4404	X2 CrNiMo 17 13 2	77	Outer jacket, housing

The thermal insulation is commonly composed of alternating layers of aluminium foils as radiation shields and glass fibre fleece as spacer material. With regard to hazard, the glass fibre fleece is the most critical component. The main advantages of glass are based on the following properties:

- Glass is mainly composed of oxides, is inert and therefore compatible with oxygen.
- The bulk material shows very low out-gassing behaviour. Off-gassing products such as water vapour are adsorbed to the surface and can be removed in the initial pumping sequence. The resulting vacuum is very stable.
- Glass has a low thermal conductance, especially at cryogenic temperatures.

The following properties are to be considered as disadvantages and require special attention:

- Glass fibres are respirable below a certain ratio of length to diameter and represent a potential hazard to humans.

- Thin glass fibre products need a polymeric binder to provide sufficient strength for a multi-layer super insulation production on industrial scale. Unfortunately, most binders are not oxygen compatible.

The glass fibre fleece is produced from staple fibres on a machine similar to a paper making machine, where the fibres are impregnated with binder, placed on a conveyor and run through an oven, in which the binder is cured. This overcoat can cause the glass fibre product to be flammable. In a baking process at 670 to 770 K, such a binder can be removed. This influences certain mechanical and handling properties of the product. Due to the industrial scale of production, use of non-standard binders (e.g. loaded with flame retardants) can only be justified when the demand is huge. The glass fibre fleece used in the liquid hydrogen fuel tank contains an acrylic binder. The insulation properties of this material are well documented, the material strength and handling is good, but the material is not oxygen compatible.

The glass fibre fleece with the acrylic binder material can be used due to a positive hazard analysis, which is based on the following aspects:

- Organic insulation material is used successfully within the vacuum space of cryogenic vessels for many years.
- The ignited glass fibre fleece within the multi-layer insulation is self-extinguishing, supported by the very high heat dissipation of aluminium foils.
- Convection is almost impossible between aluminium sheets.
- In case of a reaction the carbon dioxide displaces the oxygen.
- The potential energy density due to burning the spacer components between the aluminium sheets is small and will not cause the aluminium to melt.

4 METHODS TO MINIMIZE RISKS OF DESIGN FAILURES IN AN EARLY DESIGN PHASE

4.1 Failure mode and effect analysis (FMEA)

In the automotive industry methods for detecting potential risks are standardized.

There are many possibilities to detect potential risks in an early design phase but the most popular is the failure mode and effect analysis (FMEA). It is a tool to minimize the technical risk at an early stage of a project. Therefore a competent team discusses the potential failures, the possible causes and the consequences for the whole system. Then all the failures are evaluated concerning their severity, occurrence and detection.

In an innovative project like the development of a storage system for liquid hydrogen, it is essential to start with a system FMEA to define the safety concept. The results are a useful input for the development of the safety system. The system FMEA is the basis for the design FMEA, which starts in the concept phase and supports the design engineer to avoid failure in this early phase.

The costs for realising a FMEA are very high since it is very time consuming and requires highly skilled personnel. So in a conventional vehicle development project it is recommended to start with a risk identification system to identify the high risk parts in order to focus the FMEA on them. Developing a storage system for liquid hydrogen, there were too many completely new parts and, on the other hand, the experience was too limited to shorten this analysis. So a FMEA was performed for every single part of the whole liquid hydrogen fuel tank.

4.2 Lifetime estimation by use of finite elements method simulations

In the development process of a liquid hydrogen fuel tank, lasting from the concept phase to the final development phase, an essential contribution has to be done by analysis on structural durability. Most components in the fuel tank are subjected to loads generated by

- pressure due to vaporizing hydrogen,
- expansion of materials during thermal cycling, and
- external loads due to mechanical vibrations.

The finite element method (FEM), is used as a design tool for analysing different loads subjected to the components. It calculates deformations and structural stresses. Evaluation of the stress-time-histories, which are mainly multi-axial, with regards to material fatigue is carried out in consideration of material behaviour and production technique.

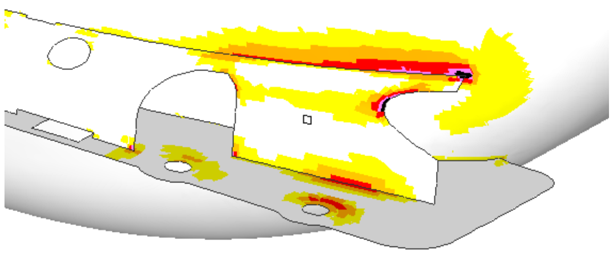


Figure 5: Stress plot of the support structure

The estimation of lifetime of a developed component has to include both physical tests and simulations. In case of simulations, e.g. with the software package FEMSITE, rate independent and range oriented counting methods are a good approach to fatigue oriented analysis of stress-time histories. The stress amplitudes and mean values of the stress-time-histories for each cutting plane are analysed by means of the Rainflow matrix.

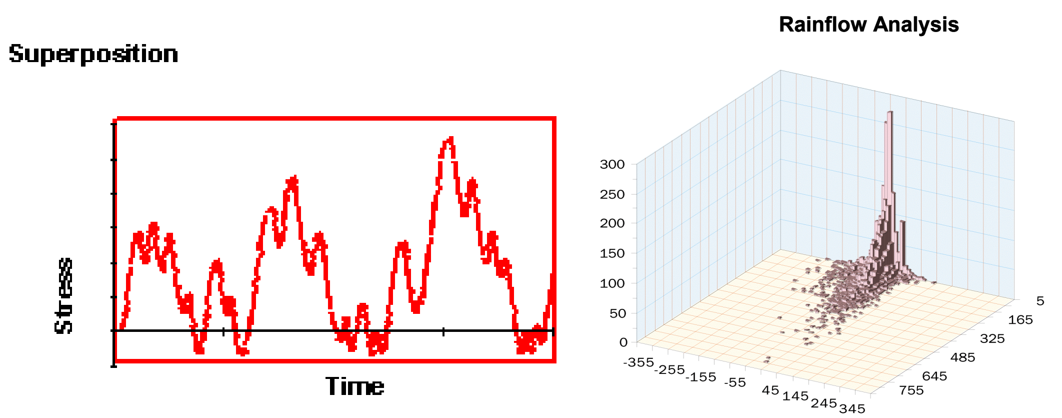


Figure 6: Stress-time history with corresponding Rainflow matrix

Post processing ranges from illustrative animations of the deformation behaviour and its resulting stresses in time range, damage distribution in the FEM model, structure fatigue capacity diagrams, detailed analysis of stress-time series, Rainflow matrices, damage matrices, to the damage distribution of the cutting plane [6].

5 NON-DESTRUCTIVE AND DESTRUCTIVE TESTS

As is common for an upcoming technology, like liquid hydrogen fuel tank systems, the experience about the lifetime of system components as well as their behaviour in extreme situations is rather limited. Compared to the component development for conventional vehicles, proper test procedures for hydrogen related components are available as preliminary drafts.

Therefore a design and validation plan has been defined. It lists all relevant tests on component and system level required for the release and certification of a liquid hydrogen fuel tank system:

- Functional tests to validate the targets during operational conditions,
- leakage and hydrogen permeation tests,
- temperature and pressure cycling tests,
- mechanical vibration tests to verify the system durability,
- vacuum loss tests and bonfire tests to verify the design requirements of safety relief devices,
- skid tests and real crash tests, and
- durability tests over lifetime in a vehicle.

5.1 Functional test

All liquid hydrogen fuel tanks perform a non-destructive functional test on a liquid hydrogen test bench in order to validate the quality of the storage system (see Figure 7).

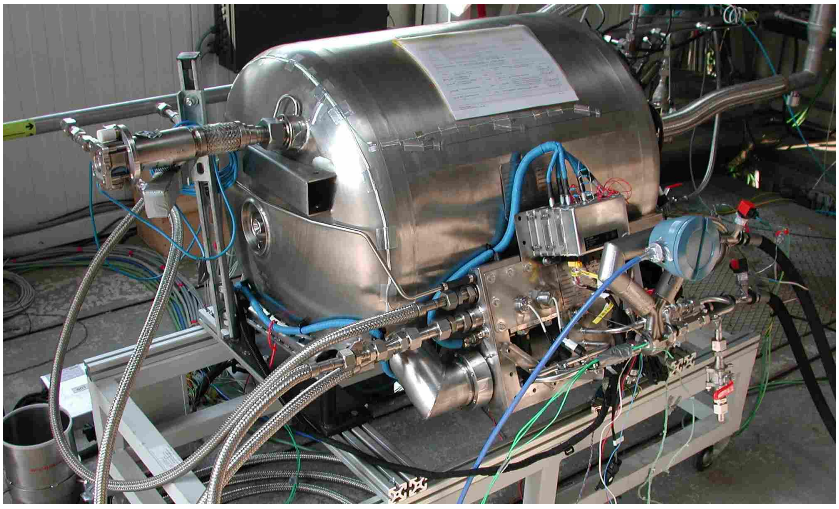


Figure 7: Functional test on the liquid hydrogen test bench (Source: ET GmbH.)

The basic test program includes:

- verification of valves, temperature sensors and pressure transducers at their operating temperatures,
- leak rate measurement on sealed components,

- verification of the time for refuelling (cold inner tank) and for the first filling (warm inner tank),
- validation of the liquid level indication overfilling detection,
- quality of the thermal isolation by determining the boil-off rate, and
- minimum and maximum extraction quantities.

An additional tank, equipped with sensors on pipes and support structure, has been built to be able to verify the thermal behaviour during different operating modes. The results will be used as the basis for optimising the design.

5.2 Dynamic vibration test

A certain amount of liquid hydrogen fuel tanks are submitted to a hydraulic pulse test bench according to Figure 8, to obtain statistic values for estimating the lifetime behaviour. Some test runs are performed with tanks at ambient temperature in the inner tank, while other tanks are partially filled with liquid hydrogen in order to get values as realistic as possible. Strain gauges are mounted on critical locations to detect weak points during durability tests.

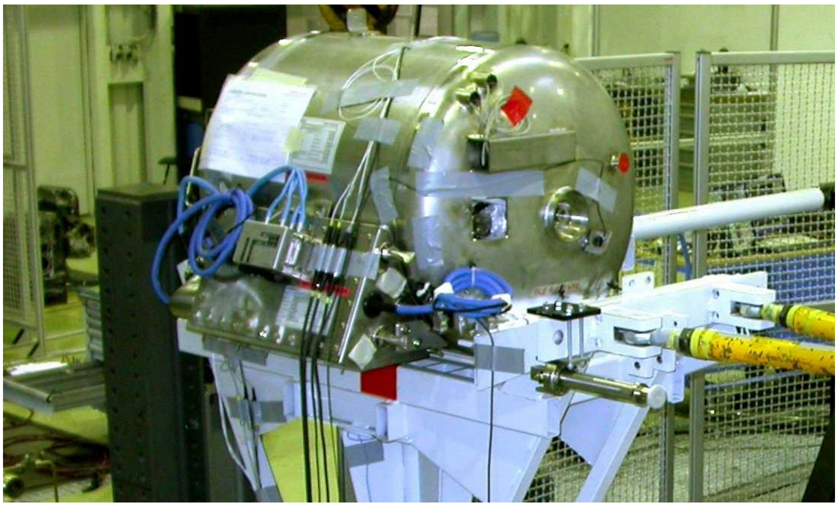


Figure 8: Dynamic vibration test of a liquid hydrogen fuel tank (Source: Magna Steyr)

The eigenfrequency of specific components in the system, e.g. inner tank and pipes, is investigated by a modal analysis on a fully equipped liquid hydrogen fuel tank.

5.3 Crash and skid test

Automotive standards require the performance of crash tests and skid tests in order to examine the connection between body and liquid hydrogen fuel tank as well as the suspension of the inner tank at high external loads. After the test the fuel tank system will be checked for leakage. Damages, like cracks and deformations, which can cause the hydrogen tank system to leak, must not occur during the skid test. For safety reasons, the liquid hydrogen fuel tank is filled with a mixture of liquid nitrogen and helium gas during the test (see Figure 9).

Figure 9: Skid test on the sliding test bench (Source: BMW Group)

5.4 Vacuum loss test

The vacuum loss test proves the design of the pressure relief devices in case of a degraded thermal insulation. For this test the liquid hydrogen fuel tank is filled with liquid hydrogen. By opening the evacuation valve, the insulation vacuum between the inner tank and the outer jacket get lost and thermal convection occurs. Moreover, the behaviour of the fuel tank is observed concerning the following aspects: tank pressure, temperatures, hydrogen blow-off behaviour, and hydrogen blow-off time.

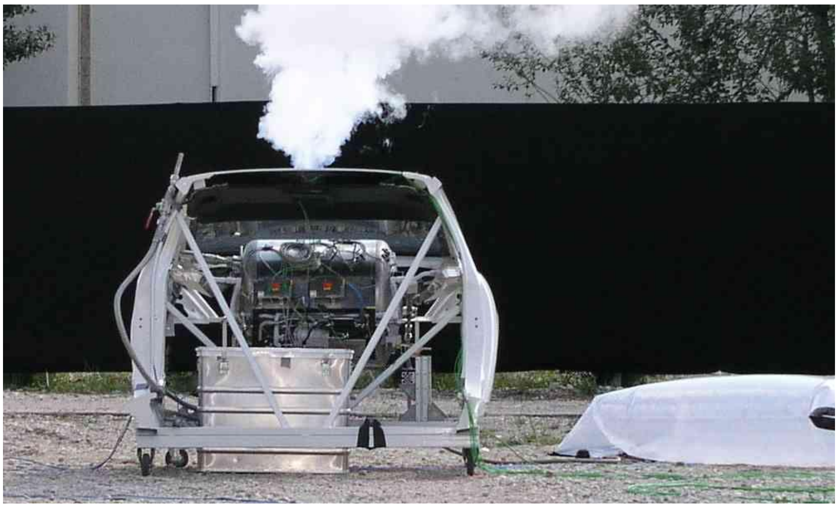


Figure 10: Investigation of pressure relief devices in case of vacuum loss (Source: ET GmbH.)

5.5 Bonfire test

The goal of the bonfire test is to prove the thermal operating strength of the liquid hydrogen fuel tank in order to verify the design of the pressure relief devices. When exposed to fire, as shown in Figure 11, the thermal autonomy of the liquid hydrogen fuel tank, equipped with its vacuum insulation, shall be at least 5 minutes. The average temperature of space 10 mm below the fuel tank shall be at least 863 K for the duration of the test. The lapse of time from reaching the average temperature until the opening of the primary pressure relief valve is measured. Once the pressure relief valve opens, the test is continued until the blow off of the pressure relief valve is finished. The tank shall not burst and the pressure inside the inner tank shall not exceed the permissible fault range of the inner tank. These criteria are verified by monitoring the internal pressure of the tank and by audiovisual observation of the system.

Figure 11: Bonfire test of a liquid hydrogen fuel tank (Source: BAM)

6 OUTLOOK

In the past, hydrogen had a bad unwarranted publicity due to the Hindenburg disaster. Today, we are able to demonstrate that hydrogen is not more dangerous than any other fuel. Currently the efforts for developing a liquid hydrogen fuel tank are huge, because appropriate regulations are only available as drafts. There is no public experience with alternative vehicles powered by hydrogen.

In the next decade it is up to us to inspire public confidence in this new technology. Apart from functional demands, safety demands will affect the development of new hydrogen storage system. Such systems are very complex and increases the cost. For the future liquid hydrogen fuel tank development, a gap analysis shall be undertaken at the conceptual and detailed design stages to ensure that the system being developed complies with the draft or published legal requirements or standards. That will decrease the costs for hydrogen tanks and makes them more competitive to conventional and other alternative fuel storage systems.

7 ACKNOWLEDGEMENTS

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