EUROPEAN INTEGRATED HYDROGEN PROJECT – Phase II
(E I H P 2)

Hydrogen vehicles and infrastructure in view of European licensing

- P U B L I S H A B L E -

36 Month Technical Report

Reporting Period: From 01 February 2001 to 31 January 2004

Work Packages:
- **WP 3.3: Liquid Hydrogen Interface**
- **WP 4.4: LH2 Regulations and LH2 On-Board System**

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2. Executive publishable summary

see coordinator report / joint final publishable report

3. Objectives and strategic aspects

A) The main objectives of **WP3.3** may be summarized as follows:

1. Development of LH_2 refuelling procedures
   - requirements
   - fuelling concepts
   - tests with one nozzle
   - operating parameters
2. German approval for a LH2 connector
   - integration in test facility
   - acquisition of authorities statement
3. Development of recommendations for requirements of LH2 interface to standardisation committees (e.g. ISO TC197)

The LH2 interface is seen as a core system of the future liquid hydrogen logistic as it influences both, the vehicle storage tank and the refuelling station

B) Main objectives of **WP4.4**:

During the EIHP1 project (1998 – 2000) a first proposal for a new draft regulation had been developed:

UNIFORM PROVISIONS CONCERNING THE APPROVAL OF:
I. SPECIFIC COMPONENTS OF MOTOR VEHICLES USING LIQUID HYDROGEN;
II. VEHICLES WITH REGARD TO THE INSTALLATION OF SPECIFIC
COMPONENTS FOR THE USE OF LIQUID HYDROGEN

The Objectives of EIHP2 were the validation and development of the existing draft regulations for LH_2 fuelled road vehicles by constructing and gaining licensing approval for vehicles in accordance with the draft regulations. The following work had to be done by Messer within work package 4.4:

- Realization of a LH2 on board systems.
- Follow test and approval procedures for components and vehicles according to the requirements of the draft of EIHP 1 by Technical Services (Germany). Application for national Approval in this country.
- Minor modifications of the components on demand of technical services.
- Identification of necessary major hardware changes.
- Identification of necessary changes of EIHP 1 draft.

4. Scientific and technical performance

4.1 Summary

A) WP3.3:

The requirements for refuelling procedures for LH2 vehicles from the point of view of vehicle manufacturers have been defined. The requirements have been discussed and updated with BMW, Opel, LAL, and Messer.
Possible refuelling concepts were identified together with the partners.
Test procedures for LH2 couplings have been discussed. A new coupling for liquid hydrogen has been manufactured and first cryotests with liquid nitrogen were carried out before starting tests with liquid hydrogen.
A test stand for refuelling tests with liquid hydrogen has been designed and constructed and first tests with liquid hydrogen were performed.
With the CBC (Clean-Break-Coupling) equipped with additional high level temperature and pressure sensors very good measuring data could be obtained.
The test stand has further been improved for subcooled fuelling similar to fuelling with a pump system.
With the improved test stand and measuring system many fuelling procedure tests for different interface concepts and under various pre-conditions have been performed.

From these results recommendations for the fuelling process could be derived.

B) WP4.4:

The first "European Liquid Hydrogen Vehicle Storage Tank" has been constructed by Messer according to the EIHP draft version 10...12. For the approval procedure with two TÜV organisations 103 new items had to be clarified. The approval successfully could be obtained.
As the liquid hydrogen system is planned to be installed into a new BMW 7 series vehicle the additional specifications from BMW could be fulfilled to a great extent.
The whole tank system was tested at the Messer liquid hydrogen test stand. It shows excellent data e.g. referring to the overall insulation quality, the autonomy time and the supply flow of more than 20 kg/h.
While working on the tank system the EIHP draft has further been developed together with BMW towards version 14 to be delivered to GRPE by BMW.

4.2 Technical progress and main results

A) WP3.3 - Liquid Hydrogen Interface

A1) Definition of refuelling procedures

In principle two different kinds of refuelling can be distinguished which can be further subdivided:

1. Differential pressure systems
   - 1.1 Two flow system
   - 1.2 One flow system

2. Pressure raising systems
   - 2.1 Pump system
   - 2.2 Subcooled liquid

For these different principles the refuelling process leads to different courses of pressure and fuelled mass vs. time in the vehicle tank which have been calculated for given boundary conditions.
For differential pressure systems two examples of calculations for a two flow and a one flow procedure are shown in figure 1 and figure 2.

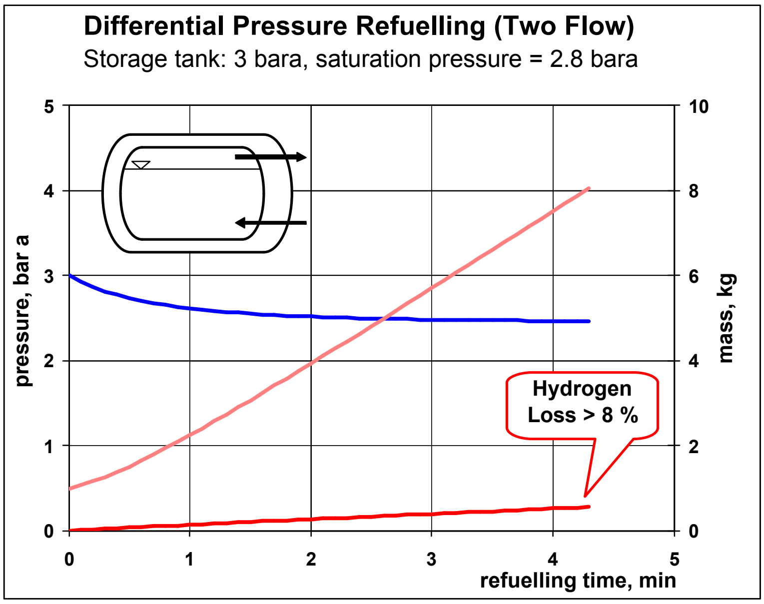


Fig. 1: Differential pressure refuelling / 2-flow

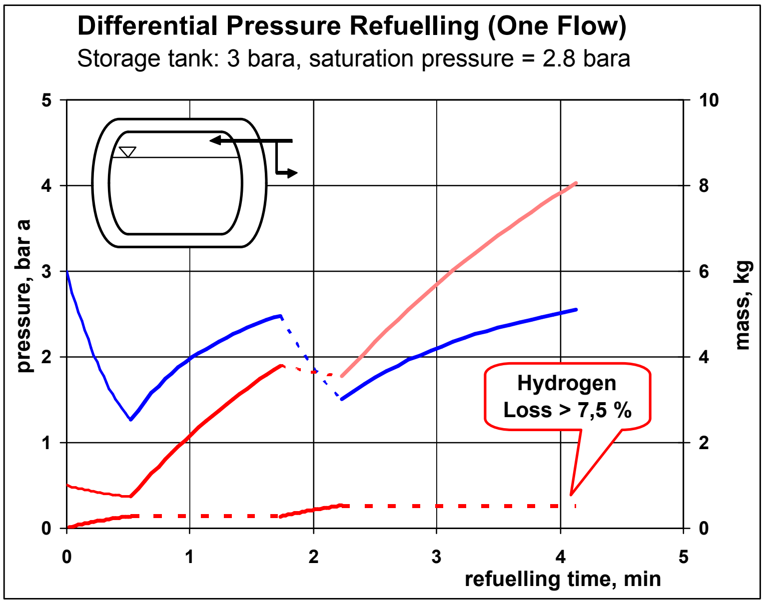


Fig. 2: Differential pressure refuelling / 1-flow (Interval procedure)

For differential pressure systems losses in terms of gas evaporation are in the range of at least 8% referring to the refuelled mass. With a pump system these losses can be reduced down to zero, as shown in the following figure 3.

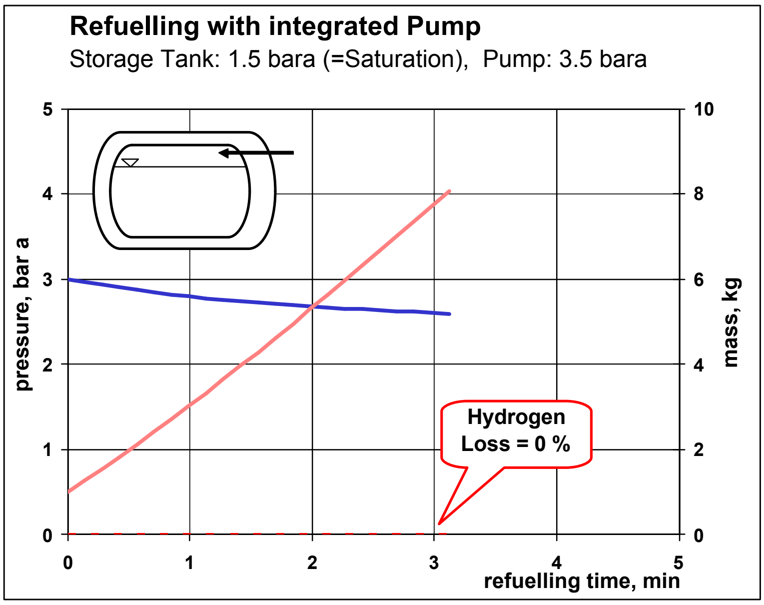


Fig. 3: Pump refuelling / 1 flow

The calculations were done with a software program from Messer Griesheim using the specific thermodynamic gas data at every point of iteration.

For the validation of the calculations the fuelling of a liquid hydrogen vehicle storage tank was tested according to the mentioned refuelling concepts. A scheme of the test system is shown in the following figure 4.

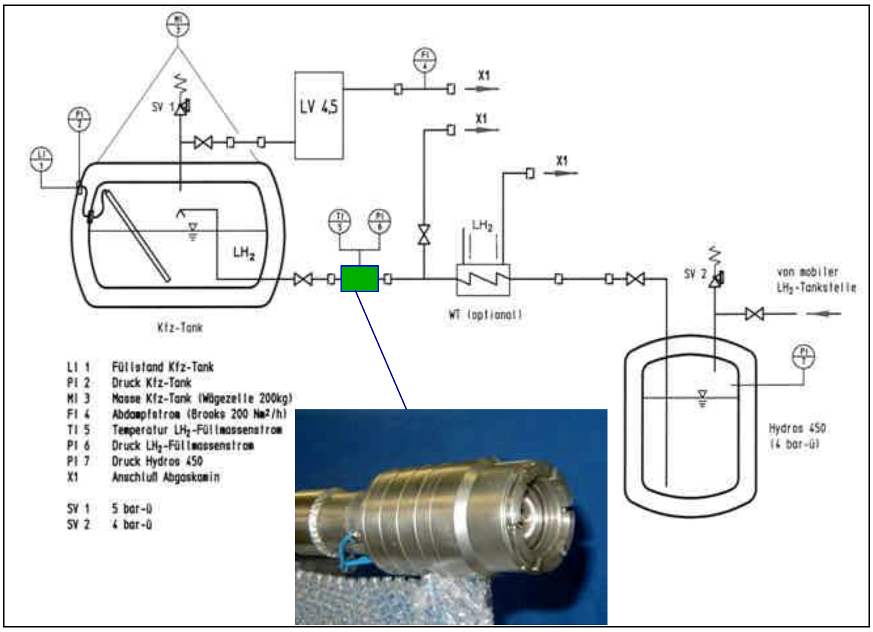


Fig. 4: Test of Clean Break Coupling with Liquid Hydrogen

With the equipment available at the Messer liquid hydrogen test stand [figure 5] the different fuelling concepts could be realized.

Fig. 5: Equipment for Test Fuelling of LH2 Storage Tank

For the correct valuation of the possible fuelling processes, e.g. the losses of liquid phase by evaporation while refuelling, an excellent measuring system is required. For this task a new measuring unit has been constructed [figure 6].

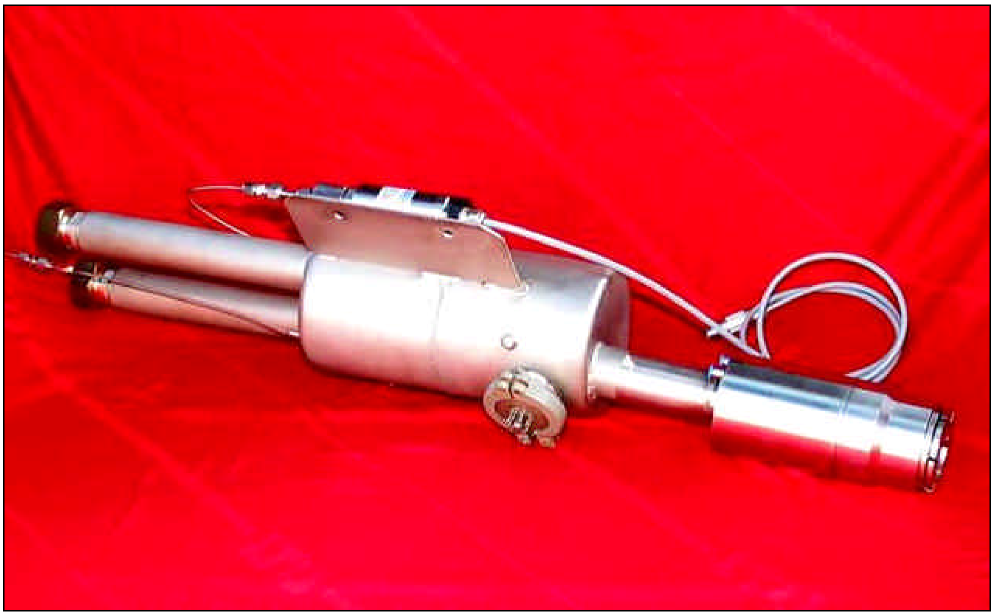
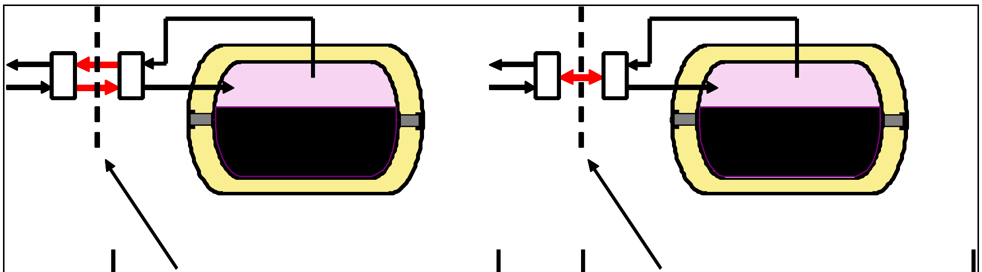


Fig. 6: Clean Break Coupling with Vacuuminsulated Measuring Unit

The measuring unit is a vacuum insulated part equipped with the new WEH clean break coupling and with LH2- and GH2-connections at the other end. It is also equipped with high grade sensors for the measuring of temperatures and pressures directly before the inlet of the clean break coupling.

All tests were done with the same equipment for the reason of achieving comparable test results. For the tests 4 different principle fuelling concepts were distinguished as shown in the following diagram [figure 7]:



	2-Flow Interface		**1-Flow Interface**
1	**Standard**	**2**	**Intervals**
3	**Subcooled:** **standard pressurization with „warm“ gas**	**4**	**Subcooled** **pressurization with cold gas (= best pump simulation)**

Fig. 7: Principle Fuelling Concepts: 4 Test Groups

The tests for a 2-flow filling have been done in the standard way by continuously filling liquid hydrogen into the tank and withdrawing the evaporating gas at the same time till the desired filling level was reached. During this procedure the vehicle tank was kept at a constant pressure by a pressure regulating device in a practice-oriented way.

The tests for a 1-flow filling have been done by filling liquid hydrogen into the tank till a certain limiting pressure had been reached followed by a depressurization by with-drawal of the evaporated gas afterwards. These filling and withdrawal phases have been continued in fast succession till the desired filling level was reached while meas-uring the amount of escaping gas at the outlet in the same way as for the 2-flow filling.

For the tests with subcooled liquid the storage tank has been externally pressurized with gaseous hydrogen. In a first step warm gas was used for the pressurization but in this way evaporation losses during fuelling could not completely be avoided. Moreover after some fuelling procedures the storage tank had to be depressurized as the liquid had warmed up such producing high additional evaporation losses.

For this reason further tests with subcooled liquid have been performed by pressurization with cold gaseous hydrogen. In this way evaporation losses in the vehicle tank could be avoided completely and it was not necessary to depressurize the storage tank as the liquid remained cold.

For each test group several tests have been performed. The characteristic results of the 4 test groups are summarized in the following diagram [figure 8]:

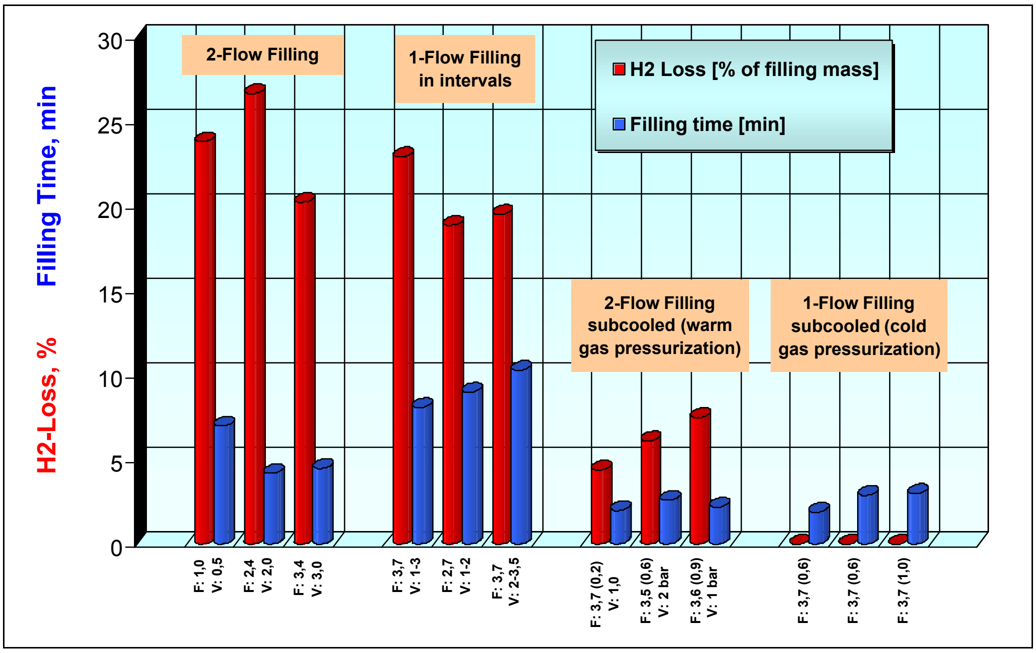


Fig. 8: Results of Fuelling Tests

In the diagram "F" stands for the pressure in the Filling Station (in brakes: saturation pressure) and "V" for the pressure in the Vehicle Tank during filling.

One can clearly see that the different approaches for refuelling are extremely influencing the hydrogen losses (evaporation of liquid) and the duration of the filling process. Differential pressure filling tests produced evaporation losses in the range of 20%, both for 2-flow and 1-flow filling.
The filling time which of course also depends on the length and diameter of the filling hose was around 5 minutes for the 2-flow filling and 7 – 8minutes in average for the 1-flow interval filling. Both can significantly be reduced by fuelling with a pressure raising system.

For the fuelling with subcooled liquid hydrogen, where in the first step pressurization took place by warm gaseous hydrogen and which showed to be not optimal for the existing equipment, evaporation losses could be reduced down to about 5% of the fuelled mass and fuelling time down to about 3 minutes.
With the cold gas pressurization, which for the existing equipment is the best procedure for simulation of an integrated pump, zero evaporation losses were within easy reach and the fuelling duration was very short (2 – 3 minutes).

The results clearly show that fuelling with subcooled liquid hydrogen has many advantages. However, when subcooling is done by external warm gas pressurization the liquid in the storage tank heats up in the course of the time requiring depressurization of the storage tank after some refuelling procedures such producing high additional gas losses. In figure 9 an example for depressurization gas losses is shown for a 3000 liter liquid hydrogen storage tank. After depressurization for cooling-down of the liquid a repressurization of course is required.

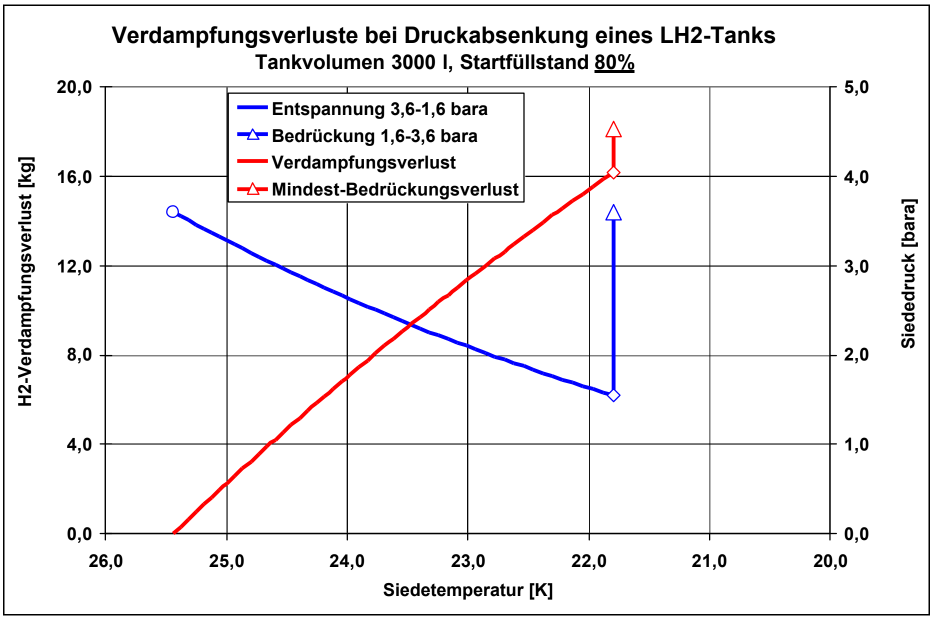


Fig. 9: Gas losses by depressurization of a LH_2 storage tank

For the assumed conditions the evaporation losses are at least 18 kg which is about 2 times the refuelling amount of a BMW LH2 vehicle storage tank.

For this reason a fuelling system with an **integrated liquid hydrogen pump** in the fuelling station tank is recommended. A system with a LH_2 pump produces the least evaporation losses for the complete fuelling chain and only with a LH_2 pump a real “zero-loss” filling is possible.

On the other hand, if the fuelling station is equipped with an integrated LH_2 pump **a 1-flow system is sufficient** for the interface. Besides, such an interface is less complicated and has a less expensive receptacle compared to a 2-flow system.

For the case that a conventional storage tank without pump is used in the fuelling station a differential pressure filling is required. Then a 2-flow system is more reasonable. This leads to a more time saving procedure compared to a 1-flow interval filling and is advantageous especially at non-optimal conditions (long filling line, non-continuous operation, …).

A2) Approved LH2 connector

A new fuelling coupling, which was originally developed by Messer and further constructed and manufactured by company WEH, has been tested by the German TÜV according to a specific test program.
The successful passing of pressure tests, leakage tests and functional tests is certified by a test report of the TÜV.
The test program has been set up by the TÜV-Süd.

A3) Recommendation of requirements for LH2 interface

The fuelling interface is a core component for LH_2-driven vehicles. A LH_2 fuelling system consists of the following main parts [figure 10]:

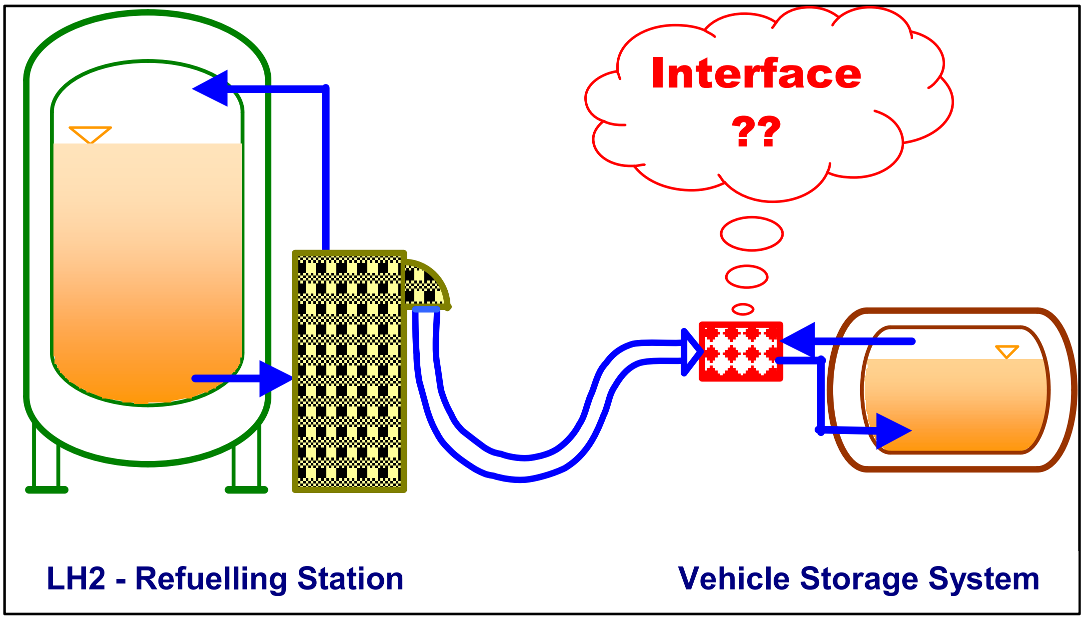


Fig. 10: Liquid Hydrogen Fuelling System

It was found that requirements for the fuelling of liquid hydrogen can be devided into three different types of requirements:

i) General requirements for the fuelling system
ii) Specific requirements for the coupling interface
iii) Requirements for the fuelling process

Concerning the **general requirements** for the Fuelling System the following points have to be taken into consideration:

1. according to EIHP1 draft (and national?) regulations
2. in compliance with ISO 13984 (LH2 - Land vehicle refuelling system interface)
3. suitable for public use
   3.1 operation by laymen (optional: robot operation)
      3.1.1 no special service personnel required
      3.1.2 safe against misoperation (within reasonable limits)
   3.2 ergonomic manual handling
   3.3 without need of protection wear e.g. helmets, gloves, goggles, ...
      3.3.1 no serious cool-down at surface of coupling
4. operation under common ambient weather conditions
5. one coupling unit for all required connections:
   5.1 filling connection for liquid hydrogen
   5.2 gas return / depressurization connection for gaseous hydrogen, if necessary
   5.3 vehicle grounding
   5.4 electrical interface ?
6. receptacle suitable for vehicle integration (compact design)

Beyond these points it is important to regard the crucial differences compared to common fuelling interfaces that derive from the influence of the low temperature of liquid hydrogen (-253°C). Every kind of non-insulated coupling such as usual ones for high pressure would produce serious problems, e.g.:

- skin freezing on cold surface
- O2-liquifaction / increased flammability
- ice production on interface
- leakage / damage
- heat transfer to LH2 / increased evaporation losses

For these reasons only solutions with high-grade insulation are applicable! This of course leads to a more complex design as for warm gas solutions.

For the **specific LH2 interface requirements** it was found that 3 main positions must be fulfilled:

1. Reliable functions
2. Inexpensive receptacle
3. Safe

The requirements which directly refer to the coupling hardware may be sub-devided as follows:

1. Fundamental safety requirements
2. Operational needs
3. Ergonomical demands
4. Economical recommendations

The fundamental safety requirements represent a minimum, which, at least, shall be met by the concerned equipment.

1.1 fuelling station, nozzle in parking position:
-no release of H2
1.2 nozzle and receptacle connected:
-no loss of product to the surrounding
1.3 refuelling process:
-no transport of trapped air or oxygen into the LH2–system
1.4 separation of coupling devices:
-neither leakage from the nozzle nor from of the receptacle

The operational requirements for the LH2- coupling device depend heavily on the refuelling procedure chosen. For all procedures precautions must be taken concerning:

- dead volume / trapped air

- various vehicles / connecting procedures / closure devices

As an important additional point the question concerning “Refuelling Signals” was raised at the 24 month meeting. In answer to that requirements for refuelling signals have been investigated under the chairmenship of Linde. The results have been summarized and an intermediate recommendation has been worked out for a bi-directional signal transfer.

The ergonomical requirements demand that an operation by laymen must be without problems, that means:

- no tools
- no protection equipment
- no special training
- suitable operational comfort

Concerning the economical requirements the following points should be considered:

- If LH2 vehicles go into mass-production, the number of on-board storage systems will be much higher than the quantity of filling stations.
- Check and maintenance procedures especially during the introduction phase of the new technology are less difficult to be performed at the non-mobile side (refuelling station).

The **requirements for the fuelling process** may be explained by the following schemes [figure 11 and 12]:

A: Differential pressure system

- the flow is produced by the lower vehicle system pressure
- gaseous hydrogen develops by evaporation (> 10% lost)
- return of GH2 requires a two-flow system or interval filling

→ more complex interface
→ more expensive at vehicle side

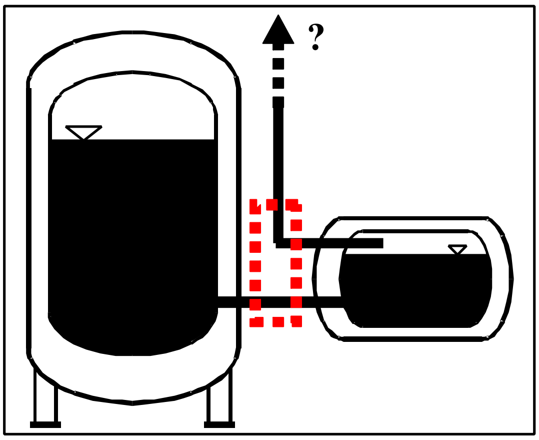


Fig. 11: Differential Pressure System

B: Pressure raising system

- the flow is produced by a pump system
- subcooled liquid causes condensation / pressure decrease
- no gas losses
- one-flow system is sufficient

→ more complex fuelling station
→ less expensive at vehicle side

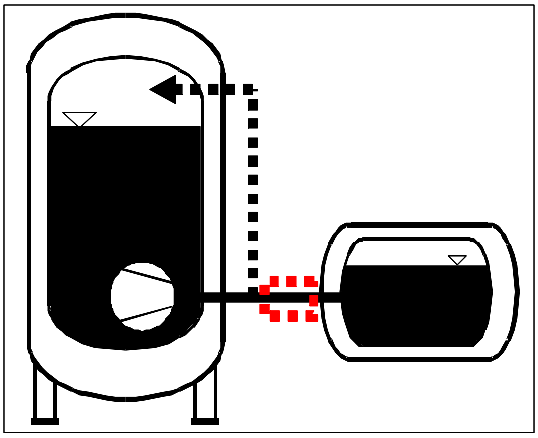


Fig. 12: Pressure Raising System

The quality of these important influences has been discussed and proved by test results in chapter “A1) Definition of refuelling procedures”. As result of the examinations the following must be clearly stated:

- The LH2 interface essentially depends on the fuelling principle
- There is a need for further development on fuelling stations
- It is to early for a final standardisation of hardware / receptacle
- Recommendations for standardisation at the present should concentrate on general requirements / fuelling procedures

B) WP4.4:

During the design process of the liquid hydrogen vehicle storage system the original EIHP1 draft “SPECIFIC COMPONENTS OF MOTOR VEHICLES USING LIQUID HYDROGEN” could be further discussed and developed with the partners and the TÜV as far as version 10. During construction of the tank system the draft has been further developed towards version 12.

In figure 13 the first “European Liquid Hydrogen Vehicle Storage Tank” manufactured by Messer is shown with its main performance data.

First „European“ Liquid Hydrogen Vehicle Storage Tank *

- **New design and insulation concept**
- **12 kg LH2 storage capacity**
- **> 20 kg/h hydrogen supply**
- **> 3 days authonomy without evaporation**
- **< 3%/d evaporation rate**
- **Demonstration planned in a new BMW-7 vehicle**

*) Design and approval according to the new European draft standard (EIHP Rev.10 …12)

Fig. 13: Messer LH2 vehicle storage system

The approval of the prototype took place in several steps and needed more time than expected (figure 14). The amount of 103 new items was found to be clearified with the two participating TÜV organisations.

Approval of the Messer LH_2 Storage System EIHP – WP 4.4

According to EIHP1 Draft Rev.10 for LH2 Vehicles

Nr.	Komponente	Prüfung	EIHP Kapitel	Auslegungsmerkmale	wer	Bemerkungen	durch-geführt am:
1	Behälter	Kennzeichnung	Part I, 4.	Kennzeichnung über-prüfen	innen: TÜV RH außen: TÜV Süd	Grundlage EIHP Rev. 12 Fabrikschildentwurf vorab als Zeichnung an TÜV Süd senden	
2		Kompatibilität gegenüber H_2	Part I, 6.	Prüfung nach ISO 11114, Teil IV		Norm existiert noch nicht Nachweis über Datenblätter, 3.1B-Zeugnisse, analog DruckbehV	
3	Behälter-auslegung	Vorprüfung Auslegung	Annex 7A 2.2.1.2 2.2.1.3	Innenbehälter p_{test} = 1,3 ($p_{max\ working}$ +0,1)Mpa 0,1 MPa Vakuum Auslegungstemperatur 20 °C (7A 2.3.1) $s = \frac{Rm}{3{,}25}$; $s = \frac{Rp}{1{,}5}$	Vorprüfung TÜV Süd	EN 1251-2: K bei 20°C: 1% Dehngrenze für austen. Stahl AD: K bei 20°C Beanspruchungsfall II ≙ 75 % oder I je nach Werkstoff durch VP erledigt	
4	Behälter-auslegung	Vorprüfung auf zul. Spannungen	7A, 3.4.3	max. zul. Spannung darf nicht überschreiten	klären?! AD-Merkblatt	entfällt	

TÜV confirmations in original paper

103 items clearified with TÜV-Süd and TÜV-Rhld. Approval

Fig. 14: Approval list (example)

The approval successfully could be obtained.

Concerning the planned installation of the prototype tank system into a new BMW 7 series vehicle, additional specifications from BMW had to be fulfilled. An overview of the mandatory requirements given by BMW (P1-specifications) and the quality of their fulfillment by the Messer LH2 system is listed in figure 15.

Features of the Messer LH_2 Storage System EIHP – WP 4.4

compared to BMW „P1“-Specifications (Mandatory)

1 EIHP, Draft for Regulation	☺	13 instruction manual	under work
2 tank evacuatable	☺	14 no liquid fuel run out	☺
3 refuelling no longer than 5 minutes	☺	15 gas tight housing vented to the fuel filler cap	☺
4 - possible at 5°	☺	16 2 separate vent lines pressure relief	☺
5 - stop automatically	☺	17 Accurate cleaning	☺ no doc.
6 hold time (P1) > 3 days	☺	18 refuelling connection on the right side	☺
7 supply temp. -40 °C to +80 °C	☺	19 basic shape cylindrical	☺
8 mass flow rate 0 to 20 kg per hour	☺	20 service intervals = vehicles service intervals	s. EIHP
9 min. to max. flow within 1 second	☺	21 electrical signals shall be accessible	☺
10 total leakage < 5 g/H_2 per day	☺	22 empty tank without power supply	☺
11 no electromagnetic interferences	☺ ?	23 Safety Relief Valves: design temp. 30 K .. 363 K	☺
12 electrical grounding	☺	24 Boil-off Valves: design temp. 218 K .. 363 K	☺

Fig. 15: Fulfillment of BMW specifications by the Messer LH2 storage system

The whole tank system was tested at the Messer liquid hydrogen test stand according to a specific test program (figure 16).

1. Sichtprüfung des Systems
2. Herstellen der Füll-, Entspannungs- und Messanschlüsse
3. Funktionstests drucklos
4. Inertisieren
5. Dichtheit / Funktion warm
6. LH2 - Befüllen, Abdampfrate
7. Füllgrad 50-55 % herstellen / stationären Zustand abwarten
8. Druckverlauf und Druckaufbauzeit von 1 nach 4,5 barü messen
9. Dichtheit / Funktion kalt
10. Entnahmemessung
11. Neubefüllung / Wiederholung Messungen
12. System entleeren und inertisieren.

Fig. 16: Summary of test program

For the filling of the tank a special adapter had to be designed and manufactured (figure 17).

Fig. 17: Filling adapter for 2-flow interface

The evaporation rate at ambient temperature and pressure is one of the essential quality data of such a system.
2.8 %/day could be reached, such proving an extremely high value of the overall insulation system quality.

A further essential quality requirement is a high system autonomy, which means a long resting time without any product loss. This is proved by the pressure increase (figure 18) during “parking” when no product is withdrawn from the tank. For the Messer tank the autonomy was more than 3 days which is also a really good value. The measured data were very close to the calculated data and no irregularities could be observed during the pressure increase.

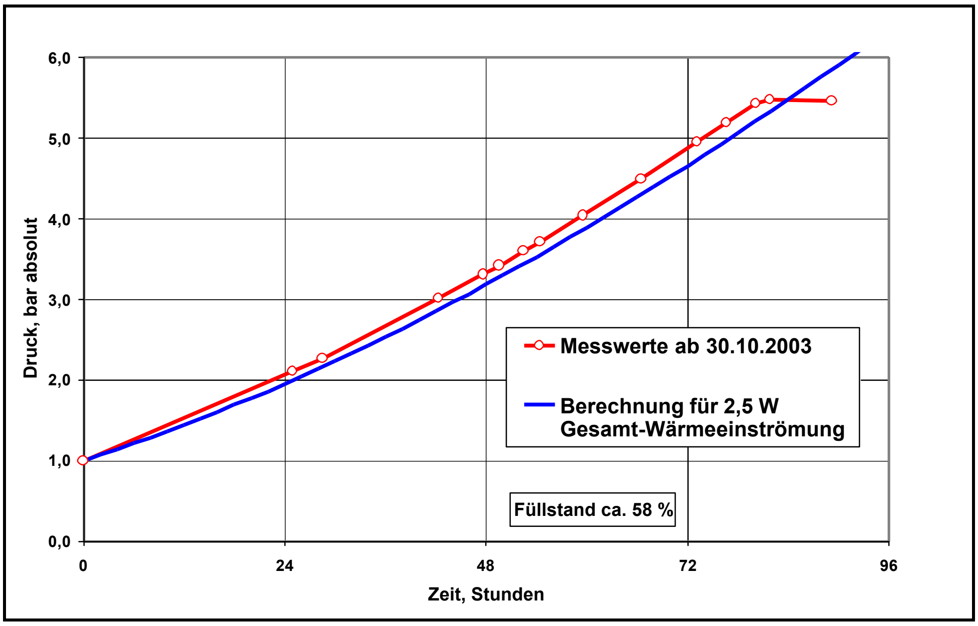


Fig. 18: Pressure increase graph (system autonomy)

For the operator of an internal combustion engine the fuel supply flow is of high importance particularly at fast accelerations. This point was specially stressed for the EIHP tank system and could be very good fulfilled by the Messer pressurization system. An example with high hydrogen flows and fast flow changes is shown in figure 19. It is characteristic for the Messer solution that even at demanding supply flow changes the tank pressure is scarcely influenced.

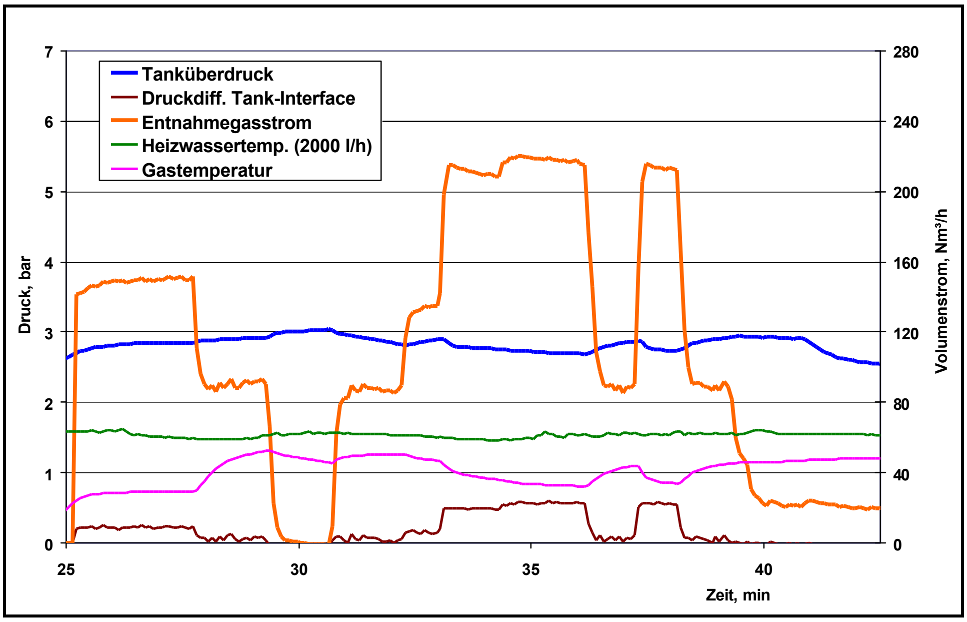


Fig. 19: Withdrawal tests with fast supply changes

A supply flow from out of the liquid phase of more than 20 kg/h could be realized without problems and even from the gas phase a satisfying flow could be reached.

After delivery of the LH2 vehicle storage system to BMW additional tests have been performed at the test stand of ET. The ET test results confirmed the high quality of the Messer LH2 system and we are proud to hear from ET that this LH2 vehicle storage system was the best one they ever had on their test bench.

8. Glossary

LH2	liquid hydrogen
GH2	gaseous hydrogen
CBC	Clean-Break-Coupling
GRPE	Working Party of the UNECE on Pollution and Energy
ET	Company “Energie Technologie” in Munic