

# Solar Hydrogen Project at Neunburg vorm Wald, Germany

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## **Improved handling of liquid hydrogen at filling stations: review of six years' experience**

Dr.-Ing. Franz-Josef Wetzel

### **Abstract**

Within the industrial-scale solar hydrogen demonstration facility operated by SWB at Neunburg vorm Wald in Germany, a liquid hydrogen (LH<sub>2</sub>) filling station has been installed for optimization of the LH<sub>2</sub> transfer process to various vehicle fuel tank systems.

New types of vehicle tanks and coupling systems for LH<sub>2</sub> filling lines were realized and tested. Designed for positive self-closing, these coupling systems can be disconnected while containing LH<sub>2</sub>.

With these coupling systems and vehicle tanks, time needed to refuel LH<sub>2</sub> vehicles is reduced from more than 1 h to less than 3 min, and hydrodynamic losses of liquefaction energy are reduced from approximately 50 % of the transferred LH<sub>2</sub> to 0 %.

An optimized concept for an advanced LH<sub>2</sub> filling station and a vehicle LH<sub>2</sub> tank are described. 1998 International Association for Hydrogen Energy

### **Nomenclature**

GH<sub>2</sub>      Gaseous hydrogen  
LH<sub>2</sub>      Liquefied hydrogen

## **1. Introduction**

As a secondary energy medium, hydrogen on the one hand is environmentally friendly to a high degree on account of its chemical properties and thus is desirable for use as a motor fuel, powering vehicles without producing noxious emissions. On the other hand, this medium places special demands on distribution due to its low volumetric energy density and safety

technologies due to its reactivity .

For use as a fuel, hydrogen can in principle be transported and handled in the gaseous form stored in pressure vessels, chemically combined in liquids or metal hydrides, or in liquefied form stored in vacuum-superinsulated vessels.

Investigations conducted at SWB include storage technologies for gaseous hydrogen (GH<sub>2</sub>) in pressure vessels and metal hydrides as well as liquid hydrogen (LH<sub>2</sub>), this latter being the focus of the present paper with regard to its handling properties when filling vehicle fuel tanks. In comparison with standard traffic licensed vehicle fuel tank systems for pressurized GH<sub>2</sub> (e.g. 200 bar) the LH<sub>2</sub> counterpart has 12 times the mass energy density and more than twice the volumetric energy density [1]. When using LH<sub>2</sub> as fuel for automobiles, this is of central importance to fuel weight and mileage range, which has led SWB shareholder BMW to concentrate research and development work in hydrogen power since the end of the 1970s on LH<sub>2</sub> [1 - 4]. During the first years, BMW cooperated closely with the Institute of Engineering Thermodynamics of the German Aerospace Research Establishment (DLR) in Stuttgart, where the first LH<sub>2</sub>-fuelled BMW car was realized.

Since about 30 % of hydrogen's energy content must be expended for liquefying the gas [5], attention must be directed above all to maintaining the liquid aggregate state during all phases of the distribution process (liquefier - storage tank - transport tanker - filling station - liquid hydrogen-fuelled vehicle).

Work on optimizing the fuelling of LH<sub>2</sub>-powered BMW cars has been proceeding at SWB since 1991 [6, 7]. For this purpose a LH<sub>2</sub> filling station was constructed (the principle of which is illustrated later in *Fig. 2*). The storage tank (1) holds a maximum LH<sub>2</sub> capacity of 3000 l. By means of a pressure control valve (15), the LH<sub>2</sub> is conditioned according to its vapor pressure curve during standby intervals. The desired pressure to feed the LH<sub>2</sub> is set on valve (15) immediately before commencing a new series of vehicle tank fillings. This is done by opening valves (2) and (13) and vaporizing LH<sub>2</sub> in the ambient air vaporizer (14) until the desired pressure is obtained in the storage tank (1), the LH<sub>2</sub> thereby being subcooled. Once the vehicle tank system (6) has been connected via flexible lines for LH<sub>2</sub> (3) and cold GH<sub>2</sub> return gas (10), the tank can be filled under program control.

In the trials undertaken for optimization of LH<sub>2</sub> vehicle tank filling, considerable reduction has been achieved both in the losses of LH<sub>2</sub> energy occurring and in the time required for filling. In actual terms there is a loss of liquefaction energy incurred due to phase transition of LH<sub>2</sub> to GH<sub>2</sub> caused by the sensible heat relative to the LH<sub>2</sub> temperature which is stored in the LH<sub>2</sub> transfer line between filling station and vehicle tank at the commencement of the filling operation. This sensible heat is transferred to the LH<sub>2</sub> flow by means of heat transport processes until the difference in temperature between LH<sub>2</sub> flow and filling line is cancelled and equilibrium is attained. Further vaporization of LH<sub>2</sub> takes place due to friction within the flow. In case of LH<sub>2</sub> vehicle tank systems like (6), the portion of LH<sub>2</sub> that is converted to gas cannot however be used by the driver of a LH<sub>2</sub> vehicle and - for lack of any means of storing it in the vehicle - this GH<sub>2</sub> together with the inherent residual cold should be returned to the filling station for energy utilization. There the gas can, for example, be filled into pressure cylinders and marketed or used as heating fuel. In principle this gas could also be reliquefied, for example at large filling stations. Because it is impossible for reasons of cost, space and weight to avoid input of ambient heat to the LH<sub>2</sub> transfer line between two vehicle tank fillings, the energy which must be expended to compensate this heat constitutes a loss in a LH<sub>2</sub> fuel system. In the present paper, the phenomenon as described is therefore summarily termed "losses of liquefaction energy".

Reduction of these losses has been achieved especially as a result of a better understanding of the processes of cryogenic flows and ensuing improvements of fluid flow management provided in part by the work of Refs. [7 - 10] > [10] by the use of novel couplings between the LH<sub>2</sub> filling station and vehicles and - since 1996 - single-flow vehicle tank systems with condensation device, as described in section 2 and 3.

Mechanical connection of the couplings necessary for filling is made manually, while fluid flow management varying with the type of vehicle tank system installed is performed by program control. The vehicle tanks are filled either by means of pressure head or with a special LH<sub>2</sub> pump.

Sensors are installed for safety monitoring of the LH<sub>2</sub> filling station [11].

Regarding concurrent minimization of time expenditure and losses of liquefaction energy, LH<sub>2</sub> vehicle tank filling operations are subject to a number of conflicting aims.

The currently used vehicle tanks are designed for a working pressure of 1.25 to 5 bar. The temperature of the contained LH<sub>2</sub> - assuming thermodynamic equilibrium - is therefore in the range from 21 to 27 K. Given an annual variation of ambient temperature between 250 and

310 K, the temperature difference between LH<sub>2</sub> and ambient air is about 220 to 290 K, which causes heat flow of approximately 1 W to the inner tank despite vacuum superinsulation. This means that, at the commencement of filling, a certain amount of heat relative to the temperature level of the LH<sub>2</sub> is stored in the transfer line and the vehicle tank system components that come into contact with LH<sub>2</sub>. This heat must be removed during the introductory phase of the filling process by heating the LH<sub>2</sub> initially entering the piping system to boiling, vaporizing it and partially heating the resulting GH<sub>2</sub>. When all the components concerned have been cooled down to LH<sub>2</sub> temperature, liquid hydrogen will enter the vehicle tank and filling commences.

The expenditure of liquefaction energy for cooldown can be reduced by:

- minimizing the heat capacity of all LH<sub>2</sub>-contacted components by minimizing their mass (length, wall thickness) and using materials of low specific heat capacity ;
- minimizing the solid-body heat conduction in valves and connecting components by using materials of high heat conduction resistance and optimized geometry of components ;
- minimizing the heat transport via Braun's molecular motion and radiation by means of vacuum-superinsulating all LH<sub>2</sub>-contacted components.

While filling the vehicle tank, additional losses of liquefaction energy occur in the LH<sub>2</sub> flow from the storage tank to the vehicle tank due to the following irreversible processes:

- residual heat gain through vacuum-superinsulation and by solid-body heat conduction in valves and connecting components ;
- input of frictional heat from pressure losses as a result of friction at pipe walls, sharp-edged transitions, in valves and corrugated tubing.

Losses of liquefaction energy caused by heat gains and the flow process itself can be minimized by an optimized design of the components containing the LH<sub>2</sub> flow. Items to be avoided are:

- unnecessarily large surface-to-volume ratios of all components ;
- unnecessarily long transfer line between filling station and vehicle tank ;
- highly turbulent flows due to excessively small pipe cross-sections, excessive surface roughness and bore-constricting components ;
- lowering of static pressure by acceleration of flow at bore constrictions or in piping bends .

The static pressure for every volume element of LH<sub>2</sub> flow should therefore at all times be higher than the vapor pressure obtained in the volume element. Fluid flow management must be matched to this by monitoring the flow with pressure sensors. Mathematical inferences as to the local values of thermodynamic variables of state can be drawn from the measurements. In this way it is possible, even under industrial conditions, to avoid a large part of the losses of liquefaction energy by retrograde determination of the setpoints. For the reversible amounts of LH<sub>2</sub> boil-off that still occur during filling, a device to condense them should be installed in the vehicle tank, as described in section 3.

## 2. Results

Starting conditions for all described vehicle tank filling operations were as follows in the interests of ensuring comparability and reproducibility:

- LH<sub>2</sub> in filling station storage tank subcooled at a temperature of approximately 22 K;

- previous filling operation 3 min ago;
- filling station components of positively self-closing clean-break LH<sub>2</sub> couplings at standby state in their supports;
- LH<sub>2</sub> in vehicle tank system (residual level 5 - 10 %) in thermodynamic state as adjusted by the fuel-mixing systems of the BMW LH<sub>2</sub> cars for driving;
- residual pressure inside the vacuum-superinsulation of LH<sub>2</sub>-contacted components less than 10<sup>-3</sup> mbar.

Fig. 1 summarizes the results of LH<sub>2</sub> vehicle filling processes from 1990 to 1996 under contracts of BMW and SWB.

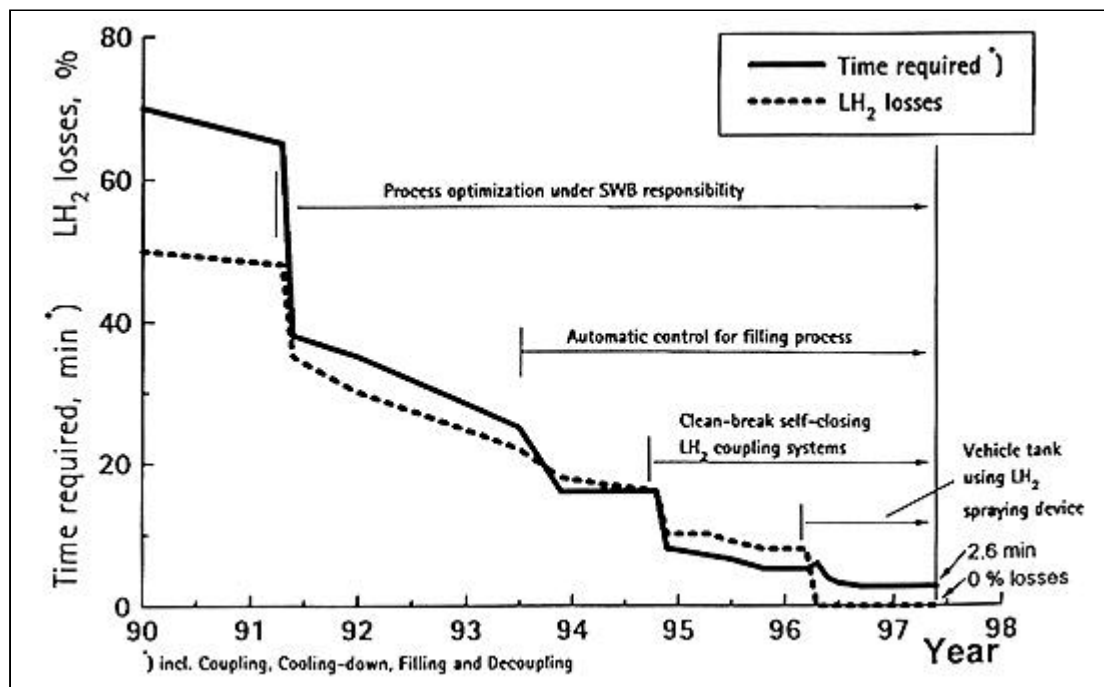


Fig. 1. LH<sub>2</sub> Vehicle Tank Filling Process  
(Under Contracts of BMW and SWB)

In comparison with the starting situation in 1990, the time for a complete vehicle tank filling cycle has been shortened gradually from over 60 min to less than 3 min in October 1996. In the same period of time the boil-off losses occurring during the refuelling procedure have been reduced from 50 % to 0 % of the liquid volume transferred, mainly by using clean-break coupling and a newly designed gas cushion recondensation system.

Using the newest technology of LH<sub>2</sub> coupling systems, successive vehicle tank filling procedures are possible within less than 1 min.

Vehicle tank filling takes place in three main phases; see Figs 2 - 8:

1. Connection of the piping (3, 10) and electrical/instrumentation leads between filling station and vehicle tank; piping system with valves and connecting devices are cooled to LH<sub>2</sub> temperature by flow of LH<sub>2</sub>.
2. Refuelling double-flow vehicle tank systems filling is started and stopped by opening and respectively closing the LH<sub>2</sub> inlet valve (5).
3. Pressure in the filling station piping system and vehicle tank system released, connecting lines (3 and 10) disconnected while filled with LH<sub>2</sub> and GH<sub>2</sub> respectively.

Figs 3 - 8 show measurements of the two main characteristics, boil-off rate and filling level, over time for a complete filling operation.

The following notes on refuelling LH<sub>2</sub> vehicles are grouped according to the respective manufacturer of the main components described.

Experience gained with the systems described under sections 2.1 - 2.3 has since been

incorporated into the software of the programmable logic controller. Except for connecting and disconnecting the couplings, LH<sub>2</sub> tank filling now proceeds automatically in optimized form.

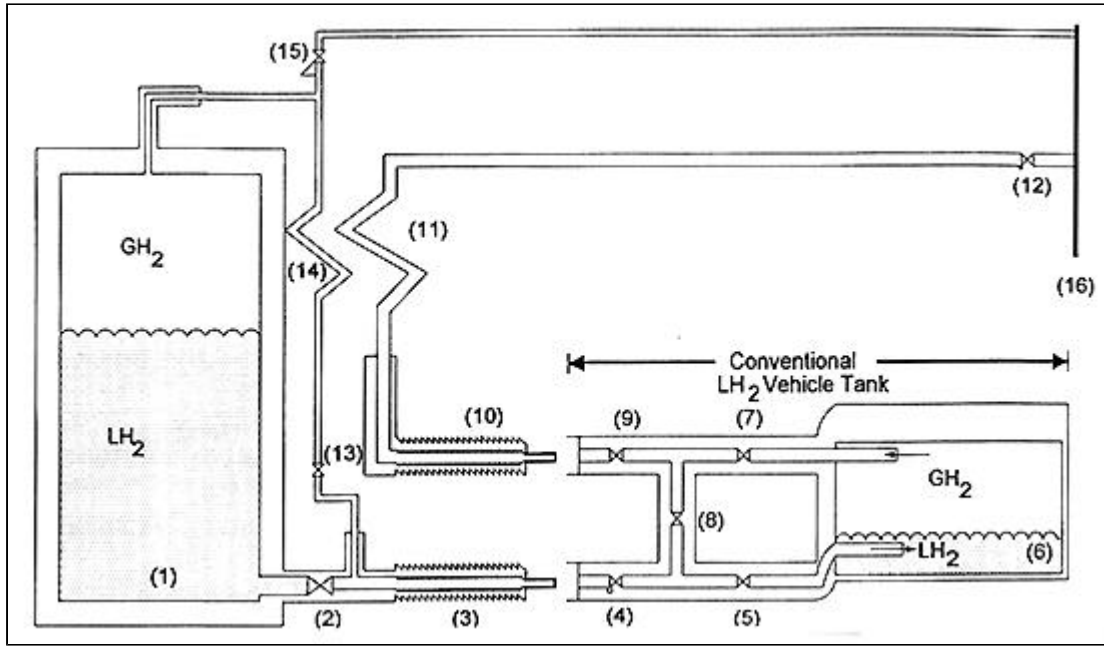


Fig. 2. Existing LH<sub>2</sub> Filling Station

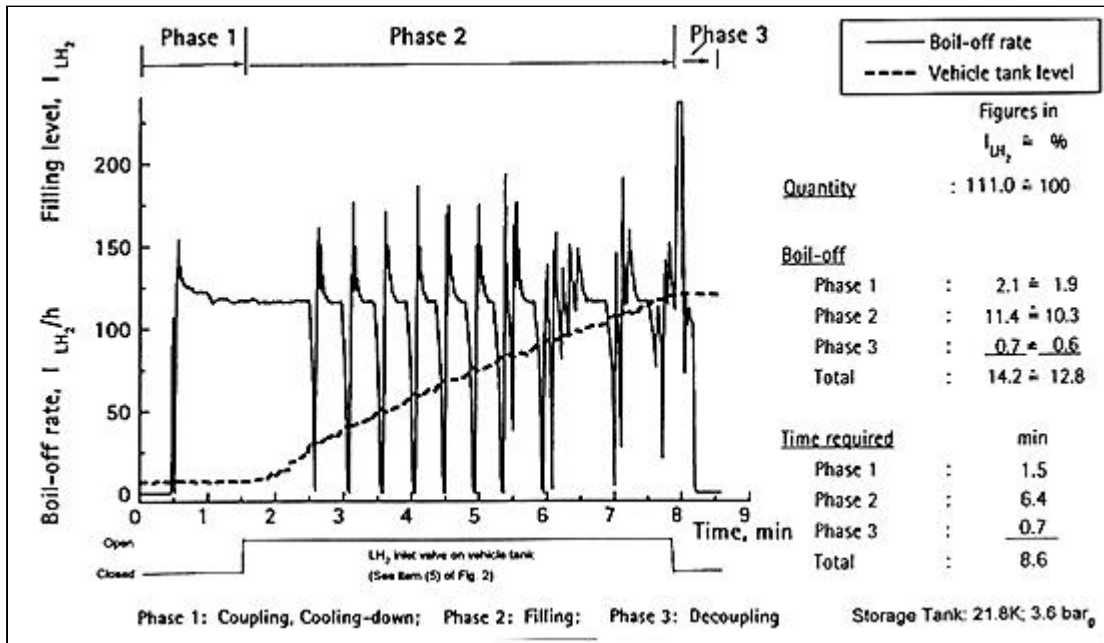


Fig. 3. Linde Double-Flow Tank System with Clean-break Coupling, Filling by Pressure Head

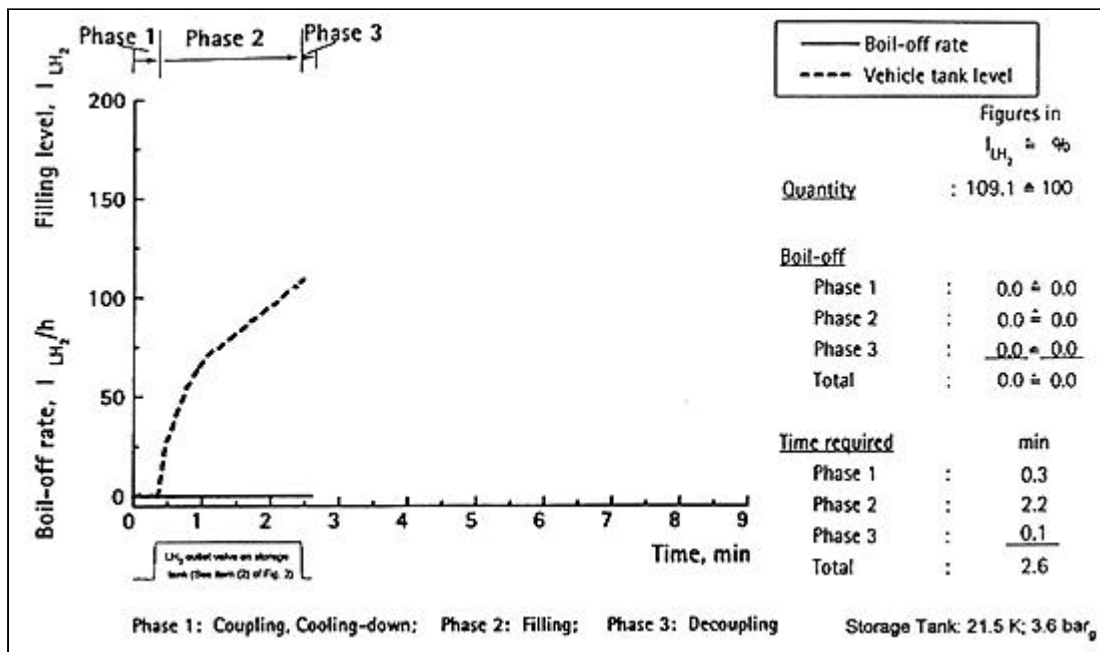


Fig. 4. Linde Single-Flow Condensation Tank System with Clean-break Coupling, Filling by Pressure Head

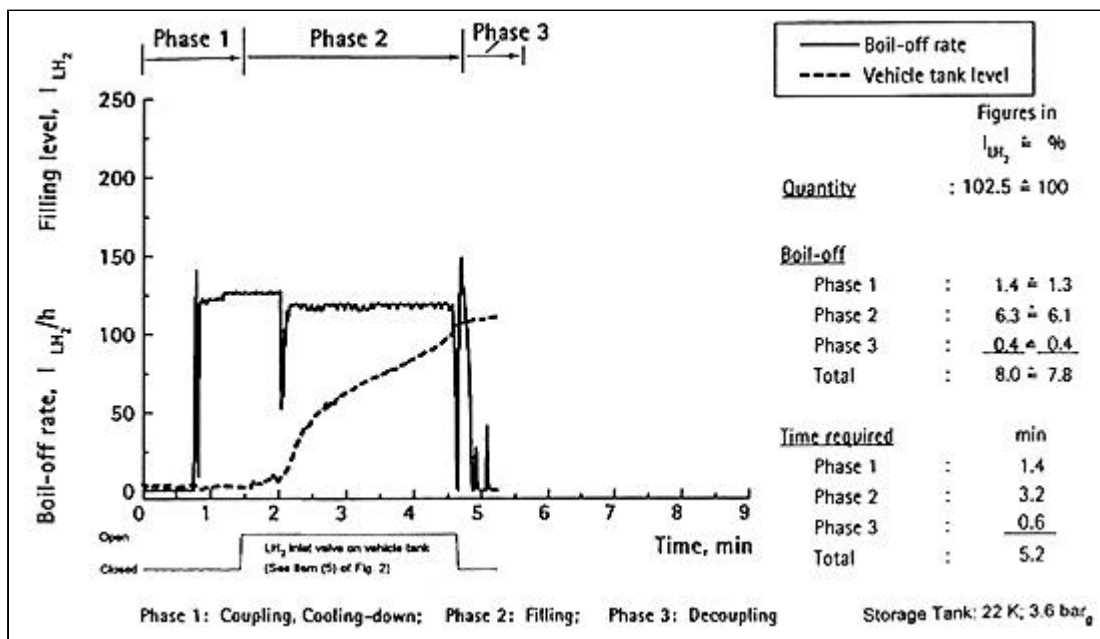


Fig. 5. Messer Griesheim Double-Flow Tank System with Clean-break Coupling, Filling by Pressure Head

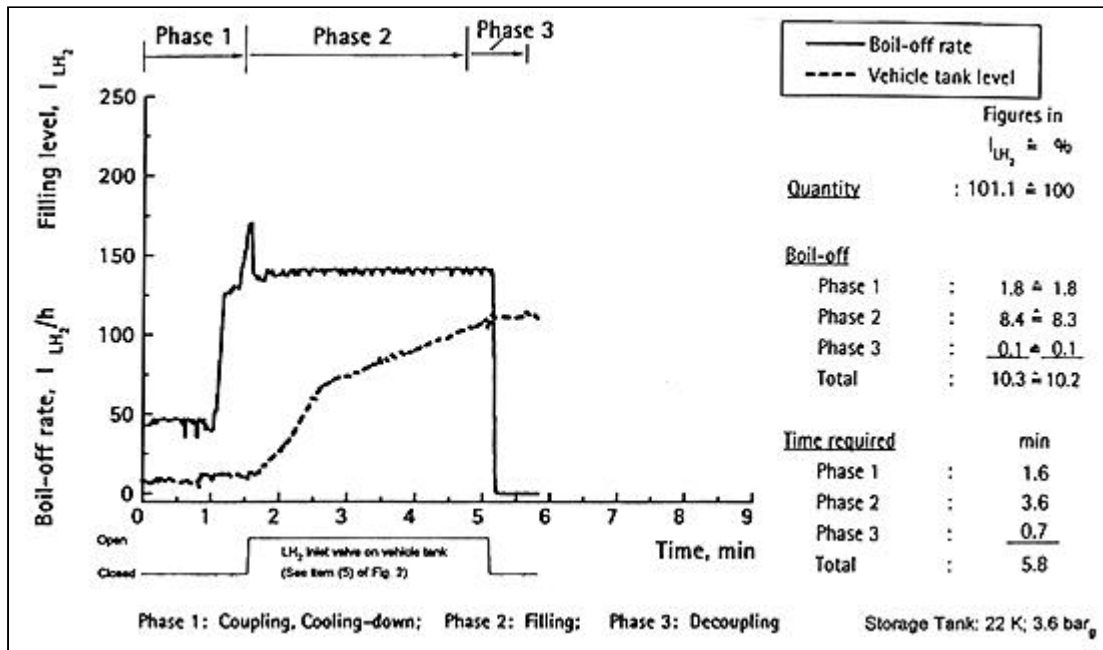


Fig. 6. Messer Griesheim Double-Flow Tank System with Clean-break Coupling, Filling by Linde LH<sub>2</sub> pump

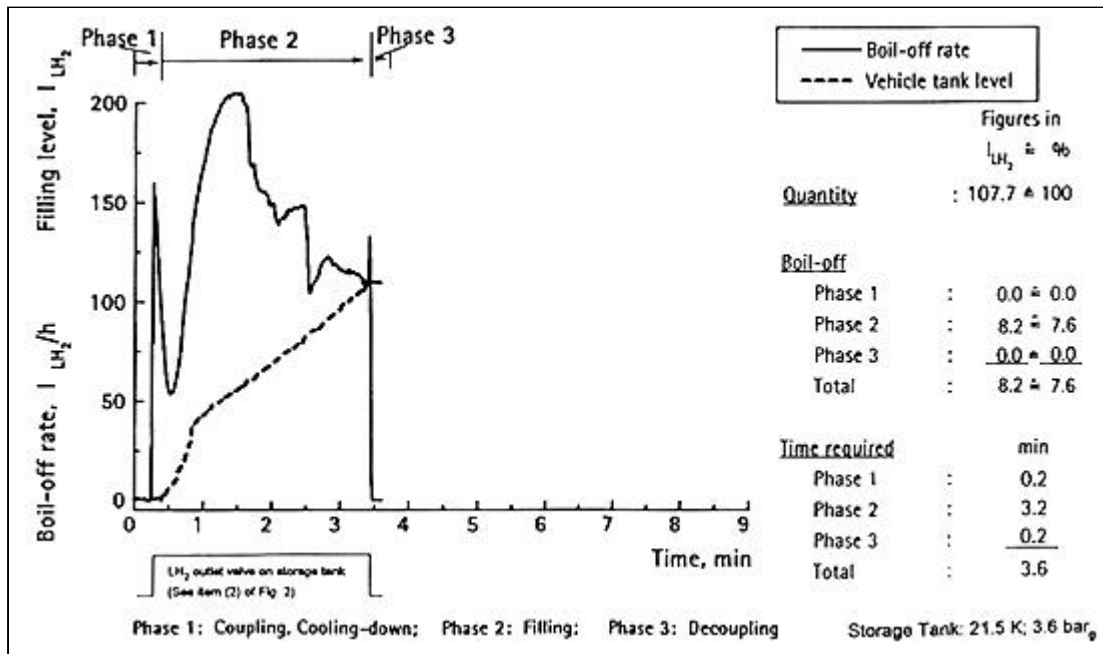


Fig. 7. Linde Single-Flow Condensation Tank System with Clean-break Coupling, Filling by Linde LH<sub>2</sub> pump

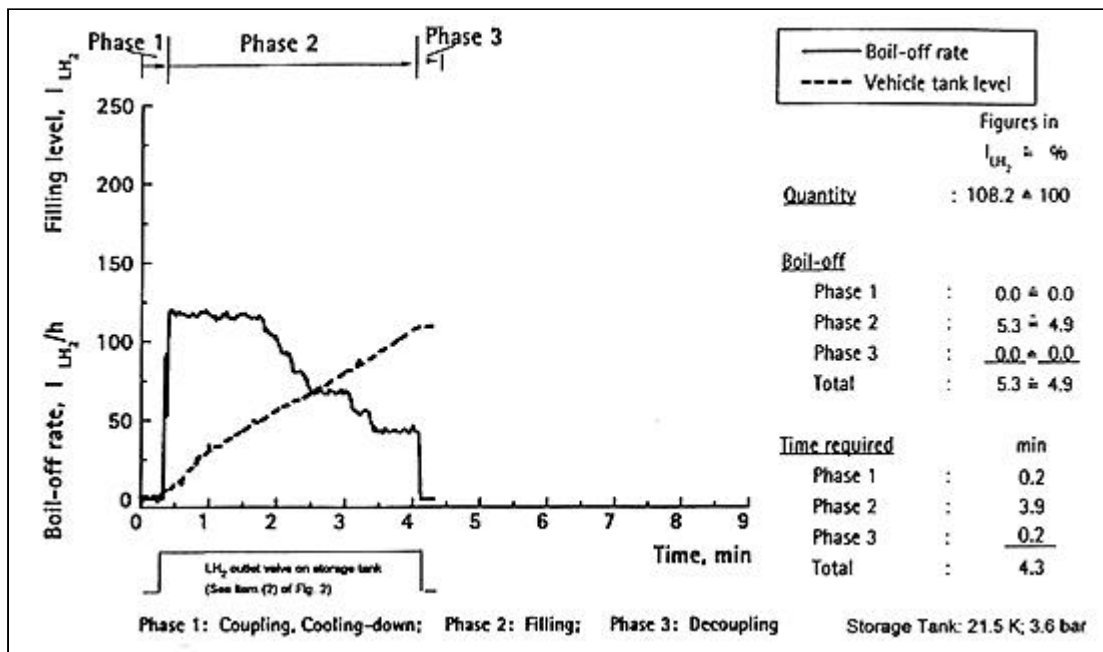


Fig. 8. Linde Single-Flow Condensation Tank System with Clean-break Coupling, Filling by Linde LH<sub>2</sub> pump

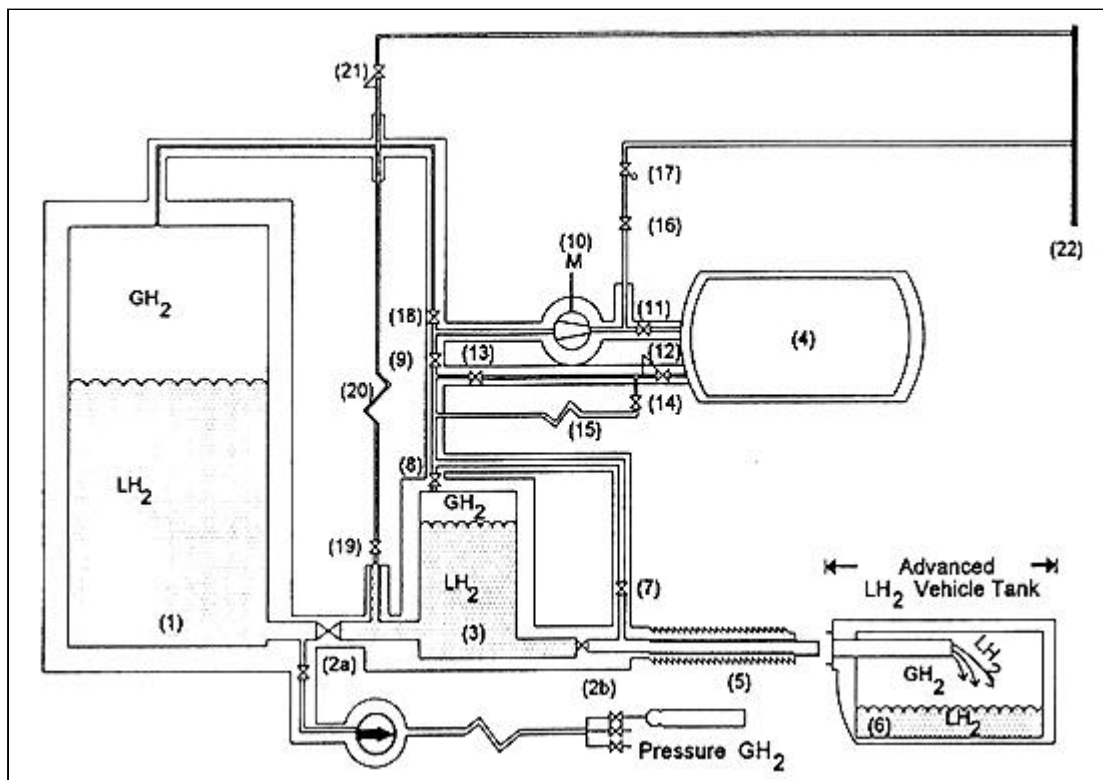


Fig. 9. Improved LH<sub>2</sub> Filling Station

## 2.1 Linde LH<sub>2</sub> vehicle tank systems

The Linde coupling system (Patent Nos. DE 41 04 711 A1 / C2 and DE 41 04 766 A1) varies from Fig. 2 in that it is of coaxial design. LH<sub>2</sub> is supplied to the vehicle tank through the inner tube while the cold boil-off GH<sub>2</sub> returns from the vehicle tank through the concentric outer tube. The bayonet coupling is connected within about 20 s. While connection is being made, a gearing arrangement opens two ball-valves, which close the piping system at the filling station and the vehicle half-coupling to the atmosphere. The LH<sub>2</sub> transfer line is pneumatically pushed from the filling station half of the coupling into the vehicle half and there forced against a seal ring to ensure separation of the LH<sub>2</sub> vs. return GH<sub>2</sub> flows.

At the commencement of filling, there will usually be a mixture of LH<sub>2</sub> and cold GH<sub>2</sub> remaining

inside the filling station LH<sub>2</sub> line from the previous filling operation. Referring to *Fig. 2*, in case of the conventional Linde LH<sub>2</sub> vehicle tank system this mixture is forced through a bypass line (8) inside a vehicle tank valve container at the commencement of LH<sub>2</sub> flow and is used to precool the vehicle LH<sub>2</sub> filling line which will have become warmed since the last filling, as described in the Introduction. As soon as stable LH<sub>2</sub> flow is obtained in the bypass line, the bypass valve (8) is closed and the LH<sub>2</sub> is directed into the inner vehicle tank of 125 l capacity (6), pressure in the tank being released by opening valve (7).

When the vehicle tank is full, its solenoid valves (5, 7, 9) have been closed and the filling station piping system has been depressurized, the coupling is disconnected, which takes just under 10 s. Filling the next vehicle tank can commence immediately. The Linde LH<sub>2</sub> coupling system is rightfully defined as a self-closing clean-break system.

*Fig. 3* plots the boil-off rate and filling level against time for filling a Linde LH<sub>2</sub> vehicle tank of the design used up to 1995. Including all coupling manipulations, filling with 111 l is completed in 8.6 min, which is more than 30 % off the time required with the Johnston-Cox cryotube screw couplings used earlier [7]. The serrated shape of the boil-off rate curve is a product of the optimized control of LH<sub>2</sub> and GH<sub>2</sub> fluid flows adapted to this vehicle tank system, which works with intermittent pressure release from the vehicle tank. In this test a volume of GH<sub>2</sub> equivalent to 14.2 l LH<sub>2</sub> had to be removed, about half of this being the LH<sub>2</sub> equivalent of the gas cushion displaced from the vehicle tank. Including compensation of sensible heat, the liquefaction energy of 14.2 l LH<sub>2</sub> is less than 13.5 kWh in industrial systems [6]. Experience and knowledge acquired with the double-flow Linde LH<sub>2</sub> vehicle tank system has resulted in the new Linde design described in the Conclusion (see also *Fig. 9*), with which the potential of the new Linde LH<sub>2</sub> coupling is brought out to still better effect.

During the second half-year of 1996, SWB has tested the new type of Linde LH<sub>2</sub> vehicle tank system. It recondenses the gas cushion by means of a LH<sub>2</sub> spraying device. This single-flow condensation tank system with clean-break coupling system has no cryovalves. The shut-off valves are realized by means of ball valves which are manipulated by the Linde clean-break coupling.

*Fig. 4* shows the results: The time required for a complete refuelling procedure is less than 3 min. Return gas flow is totally eliminated by means of recondensation of the vehicle tank gas cushion.

## 2.2 MG LH<sub>2</sub> vehicle tank systems

The LH<sub>2</sub> coupling system supplied by MG (Patent No. EP 0 657 674 A2) is of double-flow design with separate couplings for LH<sub>2</sub> and cold return H<sub>2</sub> gas. On the SWB version of the MG coupling, the filling station and vehicle half-couplings are joined by manually turning a union nut. As the coupling is joined, its internal parts are forced against one another to completely open the respective duct for LH<sub>2</sub> or GH<sub>2</sub>. Technical details are described in Refs. [12, 13].

With the double-flow version of the MG LH<sub>2</sub> vehicle tank system, filling time has been reduced to 5.2 min; see *Fig. 5*. Fluid flow management is performed in the same manner on the MG coupling as for the double-flow Linde type described above, however with continuous rather than intermittent pressure relief of the vehicle tank.

When filling a LH<sub>2</sub> volume of 102.5 l, the return gas flow was 7.8 %. From the amount of vapor removed during filling (phase 2), equivalent to 6.3 l LH<sub>2</sub>, it may be concluded that in sum about 10 % of the gas cushion present in the vehicle tank at the commencement of filling and all the boil-off occurring during filling condensed on the boiling surface of the subcooled LH<sub>2</sub> fed to the tank.

Meanwhile, some 500 filling tests have been undertaken with the MG coupling system, this corresponds to a distance of about 150,000 km travelled by the BMW LH<sub>2</sub> test vehicles. During this time the couplings proved to be durable. They similarly deserve the definition self-closing and cold-break.

In 1994 MG developed a single-flow LH<sub>2</sub> vehicle tank system with a recondensation device for the gas cushion. It has been integrated in a BMW LH<sub>2</sub> test car of newest type [3, 4]. SWB's experience showed that return gas no longer forms when controlled condensation of the gas cushion in the vehicle tank is accomplished during the filling operation Phase 2 of the LH<sub>2</sub> vehicle tank filling process for 132 l LH<sub>2</sub> is thus reduced to about 3.7 min. Owing to the LH<sub>2</sub> coupling between filling station and vehicle tank at the moment not being of the self-closing and clean-break type, the procedures described in Ref. [7] must be carried out properly prior and after the filling operation.

## 2.3 Linde LH<sub>2</sub> pump

A LH<sub>2</sub> pump has been developed by Linde for the SWB LH<sub>2</sub> filling station. This has been integrated in the LH<sub>2</sub> line between items (2 and 3), - see *Fig. 2*. The pump is of novel design and constructed of materials possessing minimized heat capacity and friction. To date it has been operated and tested mainly in combination with the MG vehicle tank system described above.

Boil-off rate and filling level for the vehicle tank are plotted against time in *Fig. 6* for a complete filling operation commencing about 3 min after the preceding tank filling. Time required was 5.8 min. Filling a quantity of roughly 101 l LH<sub>2</sub>, liquefaction energy of 10.3 l LH<sub>2</sub> corresponding to an energy amount of approximately 10 kWh was used to cool down the LH<sub>2</sub> transfer line between filling station storage tank and vehicle tank, maintaining it in cold state (including the pump components) and compensating internal pump frictional heat.

A noteworthy feature is the rise in liquid level in the vehicle tank by about 40 l in the time interval between 2 and 2.5 min. At this filling rate the time for filling (Phase 2) of 100 l LH<sub>2</sub> would be about 1.25 min. Given the present level of knowledge the LH<sub>2</sub> pump cannot develop its full potential with the double-flow vehicle tank systems including cryovalves, since their piping systems block flow at feed rates exceeding 50 l/min due to the effect of pressure loss multipliers [8]. It may be assumed that the potential of the LH<sub>2</sub> pump could be exploited with suitably dimensioned LH<sub>2</sub> vehicle tank systems, for instance those of buses, not least of all in view of the larger quantity of LH<sub>2</sub> to be filled. This could also hold true for filling the new types of LH<sub>2</sub> vehicle tanks for cars described in the following section on account of all cryovalves being deleted.

In the second half-year of 1996, the Linde LH<sub>2</sub> pump was tested in combination with the Linde single-flow condensation tank system including Linde clean-break coupling system.

The time needed for a complete refuelling process with more than 100 l LH<sub>2</sub> could be reduced to 3.6 min, see *Fig. 7*. In this test a volume of GH<sub>2</sub> equivalent to 8.2 l LH<sub>2</sub> had to be removed. In comparison with a double-flow tank system - *Fig. 6* - this is a reduction of about 20 %. It is a conflict of aims between time needed for filling and vaporization of LH<sub>2</sub>. In acceptance of 4.3 min refuelling time, the loss of LH<sub>2</sub> decreased to 5.3 l, see *Fig. 8*. Versus *Fig. 6* this corresponds to a reduction of approximately 50 %.

### 3. Conclusion

From the superposition of the advances recorded at SWB in collaboration with BMW, Linde and Messer Griesheim regarding the application of LH<sub>2</sub> as motor fuel, it may be stated that there are now no prohibitive restrictions on the handling of cryogenic fuels in the distribution process, including the filling of vehicle tanks.

A practically viable LH<sub>2</sub> filling station needs to be optimized in respect of filling time, operating energy expenditure entailed for both cooling down the LH<sub>2</sub> transfer line and overcoming flow resistances, and also production costs. Design as illustrated in *Fig. 9* is to be recommended from the experience gained at SWB. At the start, all valves are closed. The filling station storage tank (1) contains LH<sub>2</sub> conditioned by means of pressure control valve (21) in equilibrium with the gas cushion. A quantity of LH<sub>2</sub> as requested by the vehicle driver is filled into a filling station working tank (3) by creating negative pressure in working tank (3) relative to supply tank (1) using compressor (10) with valves (8, 9 and 11) open. When valves (8, 9 and 11) are closed and valve (2a) is opened, the requested quantity of LH<sub>2</sub> passes into the working tank (3). After closing valve (2a), valves (8, 12 and 13) are opened. The required feed pressure builds up in working tank (3) by adjusting pressure control valve (12). In the meantime the vehicle tank system (6) has been connected to the filling station by a robot-actuated self-closing clean-break coupling (5). On opening valve (2b), the LH<sub>2</sub> is filled into the vehicle tank (6) of novel design as described below.

The inflow of subcooled LH<sub>2</sub> trickles down through the gas space of the vehicle tank, causing most of the gas cushion to condense. Since this preserves a pressure differential between tanks (3 and 6) as the driving force for LH<sub>2</sub> feed, no second pipe connection to return LH<sub>2</sub> feed boil-off is required.

Should starting pressure in the vehicle tank (6) be too high for successful application of the trickle-feed filling method, it can be reduced in advance of opening valve (2b) by opening valve (7) to pass out GH<sub>2</sub> through valves (9, 10 and 11) for it to be collected in buffer tank (4). When maximum working pressure is attained in buffer tank (4), valve (11) is closed and valve (16) opened for the GH<sub>2</sub> to pass into the GH<sub>2</sub> line (22) for further use.

All other components shown in *Fig. 9* are required for fluid flow management during maintenance and repair jobs and for special LH<sub>2</sub> conditioning operations.

While the filling station is on standby, the flow of cold GH<sub>2</sub> resulting from conditioning the LH<sub>2</sub> in supply tank (1) must be conducted so that it can be used to maintain the LH<sub>2</sub>-contacted

filling station components in cold state.

With this LH<sub>2</sub> filling station configuration, pressure relief of the storage tank (1) otherwise required for conditioning the supply of LH<sub>2</sub> can be omitted. The energy expenditure entailed for this pressure relief and rebuilding feed pressure is thus saved. A LH<sub>2</sub> pump, which has moving parts that generate frictional heat and are subject to wear, is no longer required. Previous concepts of LH<sub>2</sub> vehicle tanks required solenoid cryovalves to control the fluid flows while filling and running the vehicle. These can be deleted entirely with the novel tank design illustrated as item (6) in *Fig. 9*, thereby eliminating their susceptibility to trouble regarding serviceability and tightness. Moreover, the absence of expensive solenoid cryovalves together with the associated controls and cryo-suitable wiring altogether greatly diminishes production cost of the vehicle tanks. Given the same previous vacuum-superinsulation, omission of the GH<sub>2</sub> line and power cables for solenoid cryovalves reduces residual heat leak into the inner vehicle tank by about 20 %. Tank filling itself is optimized by the absence of interference with LH<sub>2</sub> flow on sharp edges in valves and heat gain from solenoids.

Closing to the atmosphere is ensured by the vehicle section of the clean-break coupling system. Excepting the instrumentation and control devices for filling level, pressure and possibly temperature, all electrical components of previous vehicle tank systems are thus avoided. Fluid flow management is accomplished by a solenoid valve located in the ambient-temperature section of the fuel mixing system on vehicles with external fuel mixing. Energy to feed the fuel to the engine is taken from the engine cooling water circuit and supplied to the vehicle tank by heat exchanger via a flow of GH<sub>2</sub>.

SWB had placed an order with Linde for a LH<sub>2</sub> tank system (6) built to this concept. Results of our tests from June to December 96 at the solar hydrogen test facility at Neunburg vorm Wald have been described in section 2.1.

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