# Liquid-Hydrogen Technology for Vehicles

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**Abstract**

This survey focuses on the use of liquid hydrogen as an automotive fuel in comparison with the use of compressed gaseous hydrogen. The energy penalties associated with liquefaction versus gas compression are compared, followed by an examination of the weight of hydrogen relative to carrier weight for the two alternative approaches. The optimum form and design of $LH_2$ tanks are discussed, followed by the important topic of how to achieve quick and easy transfer of $LH_2$ from a storage tank to a vehicle.

***Keywords:*** *compressed gaseous hydrogen, hydrogen storage, liquid hydrogen, liquid-hydrogen transfer, hydrogen transport.*

## Introduction

More than 100 years ago, James Dewar succeeded in the first liquefaction of hydrogen. Liquid hydrogen ($LH_2$), with a cryogenic temperature of 20 K (−253°C), has been produced and distributed in a safe and reliable manner by the gas industry for all kinds of industrial needs for more than 70 years. Twenty years ago, car manufacturers began the implementation of $LH_2$ applications in prototype cars. The expected public use of cryogenic fuels like $LH_2$ will require suitable, safe, and reliable storage and filling facilities, in particular, safe and easy-to-use filling equipment comparable to conventional gas stations. This article outlines the advantages of $LH_2$ in comparison with compressed gaseous hydrogen ($CGH_2$). The necessity of purpose-designed tank systems to fit the restricted available space within vehicles will be highlighted. A hermetic, clean, and leak-free break coupling for the filling and refilling of cryogenic fuel systems will also be discussed; this coupling enables the safe and easy handling of $LH_2$, short filling and coupling times, and a high filling rate (number of vehicles filled per unit of time).

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## Liquid Hydrogen and Compressed Gaseous Hydrogen: A Comparison

As a rough overview of the comparison between $LH_2$ and $CGH_2$, three major aspects have to be considered:

- What is the energy content of the state of aggregation?
- What is the effort required to prepare a certain state of aggregation?
- What is the total volume and weight of the relevant tank system?

The energy content of the different states of aggregation of $LH_2$ and $CGH_2$ at different pressures is illustrated in Figure 1. For a $LH_2$ tank system, the typical nominal operational pressure is in the range from 0.1 MPa up to 0.35 MPa. Grading for $CGH_2$ considers 24 MPa a common pressure today and 35 MPa common in the near future. Pressures of up to 70 MPa reflect an envisaged technical goal. As can be seen in the figure, the specific energy content of $LH_2$ is higher than that of $CGH_2$, within not only the common pressure range for both fuels, but also as compared with the envisaged $CGH_2$ pressure of 70 MPa or more.

As illustrated in Figure 2, the extra work for liquefaction based on a mid-sized liquefier is of the order of 30% of the specific energy content. The entire work for a gaseous compression unit, in comparison, is up to 18% of the specific energy content. Nevertheless, the use of $LH_2$ for vehicle applications offers many advantages that clearly stand out and compensate the greater work required to prepare the liquid state of aggregation. As can be seen in Figure 2, the comparison of storage volume and storage weight highlights the advantages of $LH_2$, especially concerning its use as a vehicle fuel.

To round out the comparison of the states of aggregation of hydrogen, it is useful to look at the current methods of commercial transport for $LH_2$ and $CGH_2$. Figure 3 shows a trailer for $LH_2$ (total weight, 40 tons; hydrogen load, 3370 kg). Compare this with the trailer for $CGH_2$ shown in Figure 1 of the article by Irani in this issue (total weight 40 tons; hydrogen load, 530 kg at 20 MPa). The $LH_2$ trailer is able to transport more than six times the hydrogen load of the $CGH_2$ trailer.

## Liquid-Hydrogen Storage

The storage of cryogenic liquids like $LH_2$ requires special equipment. These so-called cryostats are metallic double-walled vessels with insulation sandwiched between the walls. To avoid or minimize thermal losses, three basic mechanisms of heat input have to be considered: thermal radiation, thermal convection, and thermal conduction.

To minimize the heat input via thermal radiation, the inner vessel that contains the cryogenic hydrogen is insulated with so-called multilayer insulation, consisting of a number of layers of a metallic foil with spacer material (a thin layer of glass wool) between each foil layer to provide a thermal barrier. The insulated inner vessel is mounted within the outer vessel by means of specially designed internal fix-

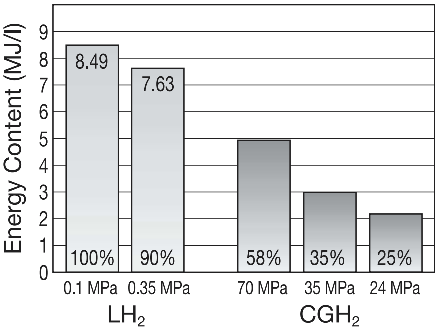

*Figure 1. Energy content of the different states of aggregation of liquid hydrogen ($LH_2$) and compressed gaseous hydrogen ($CGH_2$) at different pressures.*

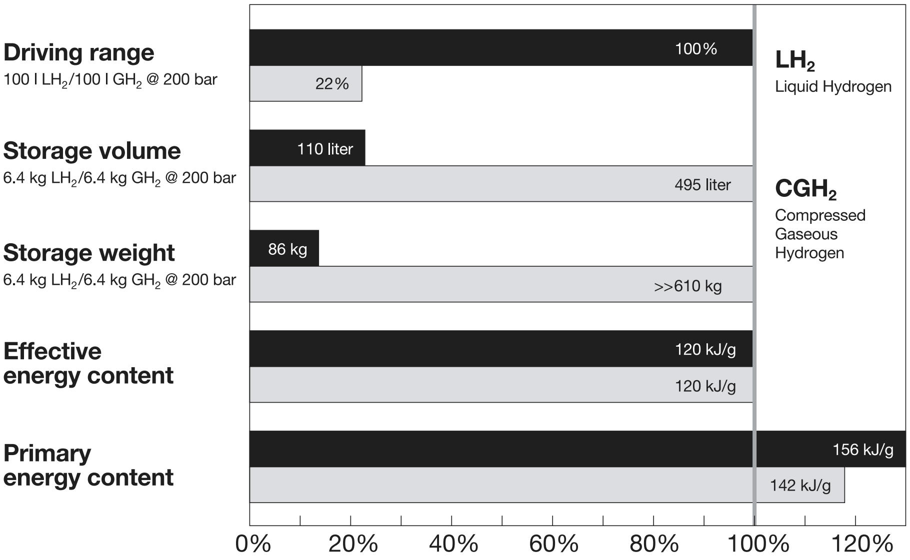

*Figure 2. Comparison of $LH_2$ and $CGH_2$ on a basis of 6.4 kg hydrogen: $LH_2$ at 0.1 MPa in a vacuum-insulated cryostat; $CGH_2$ at 20 MPa in a conventional steel bottle. The primary energy content is the energy necessary to compress or liquefy the hydrogen. Approximately 15% of the specific value will be necessary to compress hydrogen up to 200 bar, and approximately 28% will be necessary for liquefaction.*

*Figure 3. Trailer for $LH_2$ transport (total weight, 40 tons; hydrogen load, 3370 kg). Compare this with the trailer for $CGH_2$ shown in Figure 1 of the article by Irani in this issue (total weight 40 tons; hydrogen load, 530 kg at 20 MPa). The $LH_2$ trailer is able to transport more than six times the hydrogen load of the $CGH_2$ trailer.*

tures. The resulting volume between the two vessels is evacuated to avoid heat leaks caused by thermal convection. Vacuum superinsulation is another common name for this kind of insulation. To minimize heat leaks caused by thermal conduction, a specialized knowledge of cryogenics is required for the proper design and materials selection of the internal fixtures of the vessel and the tube system for injecting and extracting the hydrogen.

## Vehicle Applications

### *Purpose-Designed Tank Systems*

A schematic illustration of a typical $LH_2$ tank system for vehicles is shown in Figure 4. The final layout, design, and dimensions of such a system ultimately depend on its destination, whether in a bus, a truck, or a passenger car.

The shape of the cryogenic storage system (i.e., of the cryostat itself) has to be fitted to the restricted available space. Basing the shape of the tank system on the available mounting space within the vehicle naturally results in different useful volumes. For example, the useful volume can be increased from approximately 50% of the available space when a conventional (cylindrical) tank system is installed to nearly 100% if the design of the tank system is fitted to the available space.

### *Minimizing Boil-Off*

In addition to the shape of the tank system, special measures are required for the storage of $LH_2$ in vehicles. Based on the principle of a thermal flask that keeps cold drinks cold, an insulated $LH_2$ tank provides the liquid hydrogen with a high degree of protection from unwanted heat ingress. Nevertheless, it is a physical law that cryogenic liquids will evaporate (also known as boil-off) due to the impact of heat on the tank system. This heat impact can be minimized but not avoided. In the course of time, the pressure in the tank rises because of the effects of heat ingress. As a result, if the vehicle is not used for a relatively short time (about three days), a critical pressure value is reached that results in unacceptable hydrogen evaporation losses.

However, that is now no longer the case. An innovation for which a patent has been applied makes possible a significant extension of the time (>12 days) before evaporation losses occur. When the vehicle is in operation, this time can be extended further, even indefinitely. The solution is an efficient re-cooling system that minimizes evaporation losses. Linde AG has developed such a re-cooling system, called Coo$LH_2$ (Figure 5). The surrounding air is drawn in, dried, and then liquefied by the energy released as the hydrogen increases in temperature. The cryogenically liquefied air (−191°C) flows through a water cooling jacket surrounding the inner tank and thus acts like a refrigerator. This leads to a significant delay in the temperature increase of the $LH_2$ and a sensible use for the energy stored in the

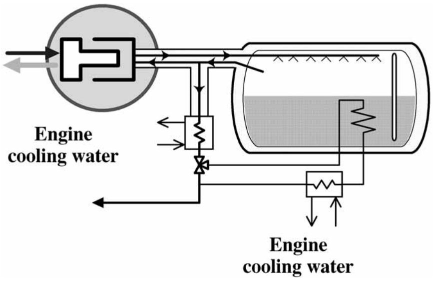

Figure 4. Schematic illustration of a typical $LH_2$ tank system.

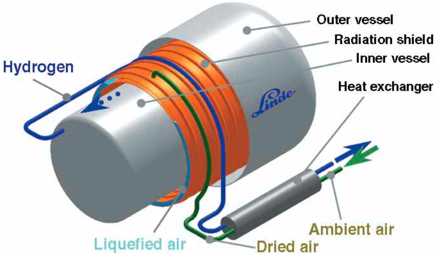

Figure 5. Principal design of a novel recooling system to minimize evaporation losses in a $LH_2$ storage tank.

liquid hydrogen. Since the cooling system can be accommodated in the existing insulating layer of the tank, it does not affect the size of the tank.

In its liquid form (−253°C), hydrogen has a considerably higher energy density than in its gaseous form. $LH_2$ thus enables vehicles to cover almost the same driving range that can be covered using normal fuel systems. The energy stored by the liquefaction of hydrogen was, however, not put to good use previously, but was actually removed in a cooling water heat exchanger because the operation of a fuel cell or an internal-combustion engine requires hydrogen at room temperature.

## Cryogenic Filling Equipment

The transfer of cryogenic liquids like $LH_2$ requires special transfer lines. To avoid unacceptable heat ingress during the filling/refilling sequence, the transfer lines have to be adequately insulated, applying insulation methods similar to those used in the cryogenic storage system. For ease of handling, the transfer lines have to be somewhat flexible, and they have to be mountable and dismountable.

The weak link in a cryogenic transfer chain is the dismountable part, the "cryogenic coupling." The surface of the connection region of two cryogenic transfer lines has to be designed to provide adequate thermal insulation; this tends to be a costly, delicate, and not completely fail-safe process. Conventional cryogenic couplings require skilled, specialized operators wearing protective gloves and goggles. Thermal leaks may freeze the two lines together; dismantling them requires heating and takes time. The components also need to be cleaned after each use.

To avoid these problems, a novel cryogenic coupling was developed by Linde nine years ago. This coupling fulfills all of the basic requirements for public use and has been continually improved since its introduction.

The principal design is illustrated in Figure 6. Each counterpart, one on the vehicle side, the other on the fuel station side, consists primarily of a ball valve that is closed in its normal state. Only when the counterparts are connected can the ball valves be opened together. After the ball valves have been opened, a common tubular volume is created that is hermetically protected against the outside environment. Within this tubular volume, the "cold finger" on the fuel station side will be extended deep into its counterpart on the vehicle side. Thus, a coaxial, well-insulated, and hermetically closed connection between both parts of the coupling is established.

The innermost line of this connection, which is separately insulated, performs the transfer of the cryogenic $LH_2$ from the fuel station to the vehicle tank system. An outer coaxial line, which is also insulated, guides the vent gas back to the fuel station. Once the tank is filled, the cold finger is retracted to a safe and covered position within the fuel station side of the coupling. The internal counterpart in the vehicle side of the coupling remains in its safe and covered position. Only when the cold finger has been retracted can the ball valves be closed and the coupling disengaged.

Decoupling can be accomplished without any warming up, flushing, or cleaning of the coupling. The next filling/refilling sequence can be started immediately—there is no waiting time between filling/refilling sequences.

For a $LH_2$ vehicle tank system with a fuel content of about 100 l, this filling sequence takes less than 2 min. Compared with the conventional $LH_2$ filling procedure, the operation is much shorter, safer, and simpler. The return gas produced during cooldown of the tank system is passed back to the fuel station via the coaxial $LH_2$ clean break coupling.

In summary, the main features of the hermetic clean break coupling are

- easy and safe handling,
- minimization of $LH_2$ losses,
- avoidance of cold valves to minimize condensation and contamination,
- short filling/refilling times,
- short coupling/decoupling times,
- high filling rate (number of vehicles filled per unit of time), and
- high potential for further optimization.

## Liquid-Hydrogen Fuel Stations

To supply vehicles with $LH_2$, a suitable fuel station is necessary. This station needs to be connected to an adequate $LH_2$ storage tank and must have the necessary equipment to manage the cryogenic transfer from the storage tank to the vehicle tank. A typical filling/refilling sequence by means of a manually operated $LH_2$ fuel station using existing $LH_2$ technology in-

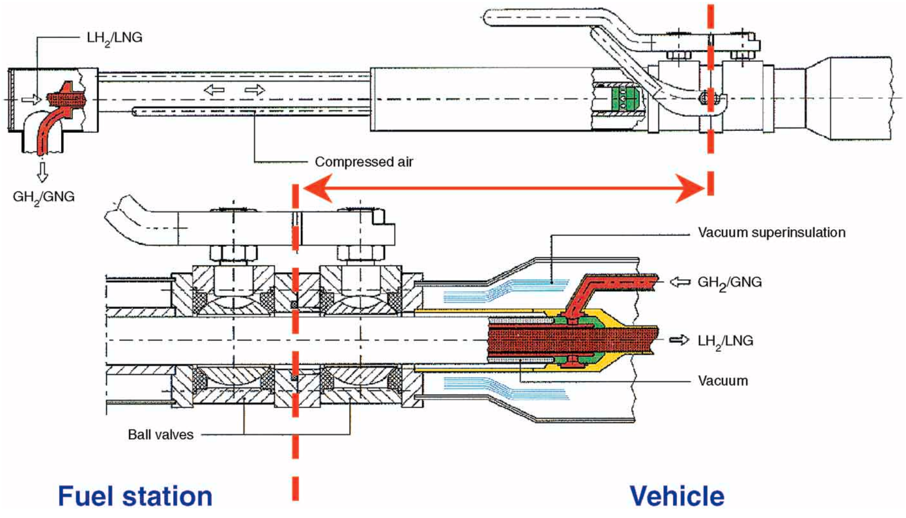

Figure 6. Principal design of the cryogenic coaxial clean break coupling developed by Linde AG.

volves the following steps: The coupling is done manually. By means of a push-button control on the fuel station, the coupling is flushed with gaseous helium to clean the small volume enclosed by the connected counterparts. A hand-operated locking mechanism provides a gas-tight connection between the vehicle tank and the fuel station. By using a second lever, the ball valves on the vehicle side and on the fuel station side are simultaneously opened. The cold finger inside the fuel station side of the coupling is driven pneumatically into the vehicle side of the coupling and ensures a proper cryogenic connection. When the vehicle tank is full, a "tank full" signal from the vehicle automatically stops the filling procedure. The cold finger is retracted, the ball valves are closed, and the locking mechanism is released. Finally, the coupling is manually returned to its holder.

A public $LH_2$ filling station of this type is currently in operation at Munich Airport, using the hermetic clean break coupling described here. □

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