HYDROGEN PROJECT AT MUNICH AIRPORT

1. PROJECT GOALS

Traffic is currently one of the main sources of several air pollutants. Up to 50% of emissions at airports are caused by ground vehicles. Fourteen companies - partly funded by the state of Bavaria - launched the Munich Airport Hydrogen Project in 1997 in order to pave the way for the use of hydrogen to improve the local environmental balance. At the same time the technology is being tested in a realistic pilot trial.

In addition to a large number of methods to reduce pollution, all of which have advantages or disadvantages in terms of availability, storage density, local and global emissions, production costs, etc., hydrogen is especially suitable as a secondary fuel for reducing local emissions of CO, HC and – with lean operation of combustion engines – NO_x to near-zero levels. In addition, the use of hydrogen engines completely avoids soot emissions, the use of carcinogenic additives such as benzene, and – provided they are lean burners – the use of catalytic converters.

The hydrogen-generation methods used so far on an industrial scale doubtlessly represent the most cost-effective solutions at present. Their drawback, however, is that they use fossil fuel and appear unsuitable for decentralized production. For these reasons, technologies will primarily be used for the airport project that utilize power from the Bavarian grid or waste hydrogen from petroleum refineries. In the long term regenerative primary energy production will form a closed cycle, permitting cost-effective management.

For the use of hydrogen in the traffic sector, vehicle fleets with a limited range, which can be refueled at a central depot, are particularly suitable for the introductory phase.

Based on these general considerations, the main aims of the project are the

- Application of hydrogen, and
- Investigation of the cost-effectiveness of hydrogen.

The new international airport of Munich, opened in May 1992, provides an ideal proving ground for the following reasons:

- An independent GH2-powered bus fleet can be operated in a contained area. In addition, LH2-powered vehicles can be operated within the airport area as well as for transport between the city and airport.
- As a state-of-the-art airport, Munich Airport serves as an excellent showcase for the successful use of hydrogen.
- Reduced emissions are being introduced.
- The peripheral conditions for the economic use of hydrogen can be determined.
- Acceptance of the new fuel can be enhanced by routine use in a commercial environment.

The enduring funding of hydrogen technologies in the framework of this lead project is intended to contribute to the demonstration of the energetic application of hydrogen and to break ground for a fundamental broad application.

Worldwide as a first, besides hydrogen production and storage also the fully automatic refueling and operation of apron fleet vehicles is being tested under the safety requirements of an airport.

Important milestones in hydrogen technology have been set by the first publicly accessible automatic hydrogen refueling station for passenger cars, the refueling of apron hydrogen buses and the hydrogen production by means of a newly developed pressurized electrolyser.

2. GENERAL DESCRIPTION

2.1 Hydrogen supply pathways

The system comprises two parallel hydrogen supply paths, one for the refueling of three apron buses with gaseous hydrogen (GH2) and one for the refueling of passenger cars with liquid hydrogen (LH2). Gaseous hydrogen is produced autonomously on-site using high-pressure electrolysis. Liquid hydrogen is being delivered in trailers from a nearby liquefaction plant and stored in the LH2-storage tank of the station.

Refueling of passenger cars with liquid hydrogen is performed in a fully automatic way by means of a specially developed refueling robot. The LH2 refueling station is located outside the closed airport zones, open to the public.

Hydrogen from the electrolysis unit goes first into a hydride based intermediate storage unit. Together with a special heating/cooling system this unit provides the subsequent gas compressor with a constant inlet pressure even at varying hydrogen production rates from the electrolysis unit. The compressor raises the gas pressure to the level of the GH2 high-pressure storage unit, from where it can be transferred into the bus tanks via the GH2-Dispenser.

The link between liquid and gaseous supply paths guarantees the hydrogen supply for the buses in times of maintenance work on the hydrogen production path. In this case a high-pressure pump pressurizes subcooled liquid hydrogen coming from the LH2 storage tank up to the pressure of the GH2 high-pressure storage unit. After passing the LH2 vaporizer the warm high pressure gas can then be fed into the GH2 high-pressure storage unit.

The individual subsystems of the plant are integrated into a computerized central control unit. This control unit coordinates the various operational sequences of the subsystems and guarantees in conjunction with the hydrogen detector network the safe operation of the complete system.

2.2 Hydrogen powered vehicles

Two low-floor articulated buses built by MAN Utility Vehicles and another built by NEOPLAN are being operated on gaseous hydrogen with combustion engines. The hydrogen is stored in a roof-mounted gas tank consisting of 15 carbon-fiber pressure vessels manufactured by MAN-Technology. In the first two years the three buses have used about 40'000 kg of hydrogen, transporting passengers for 16 hours/day in the apron area, and covering a total distance of about 120'000 km.

With a research fleet of 15 BMW 750hL hydrogen vehicles, the BMW Group is the largest "customer" for liquid hydrogen in the plant. As a partner in the Munich Airport hydrogen project, BMW currently operates one vehicle in the Airport's Special Passenger Service for transporting people. However, this car is also used as a demonstration vehicle for numerous national and international visitor groups.

2.3 Project phases and time frame

The first phase of the project lasted from 1997-2000. The start of trial operations was marked on May 5, 1999, with the formal opening of the world's first public filling station for liquid and gaseous hydrogen with on-site hydrogen gas production in the presence of 13 CEOs of the participating companies together with the Bavarian Minister of Economics, Traffic and Technology, Dr. Otto Wiesheu. The total costs of this project are carried by the project partners and by the Free State of Bavaria, which provided 50% of the costs from public funds. The costs for the first two project phases were around DM 34 million (approximately US$ 20 million).

More than 10'000 visitors from all over the world have demonstrated that it is worthwhile to promote the hydrogen technology and to increase the acceptance by day to day use in commercial surroundings, and that this is an efficient way to increase its acceptance.

The positive results and experiences have led to the decision to continue the project and to include additional and more advanced components. The main new components are:

- a steam reforming facility to produce hydrogen from natural gas
- two fuel cell passenger buses
- a forklift truck operating with a fuel cell and an electric engine
- hydrogen storage at elevated pressure level of 35 MPa (350 bar)

Table 1: Main goals of the four project phases

Phase 1 (1.1.97-31.12.00): operation of a BMW passenger car (later on several cars) using liquid hydrogen direct refueling via worldwide first cryogenic LH2 robot refueling station open to the public gasifying LH2 for use in three articulated buses (2 MAN and 1 Neoplan) with internal combustion engines and compressed gaseous hydrogen storage.
Phase 2 (1.1.01-31.12.02): hydrogen production infrastructure via advanced high performance electrolyser using economic surplus grid electricity feeding consumers via compressed gaseous hydrogen.
Phase 3 (1.1.03-31.12.04): onsite hydrogen production from natural gas by steam reforming construction of two passenger buses with fuel cells and electric engines, including trial operation on the airport apron construction and operation of a forklift truck fuelled by a fuel cell and an electric engine Integration of a public 350 bar hydrogen refueling dispenser into the existing filling station.
Phase 4 (1.1.05-31.12.06): operation of the fuel cell buses in public transport around the airport evaluation of technical performance data for all components of the system adaptation of system integration to technical improvements of components determination and improvement of economical performance

An overview of the entire project is shown in Figure 1, and the main goals of the four project phases are summarized in Table 1. In all four phases the State Government of Bavaria supports the project.

2.4 Partners and responsibilities

The hydrogen project at Munich Airport has been realized by ARGEMUC (ArbeitsGEmeinschaft Flughafen MUenChen), a consortium comprising the companies listed in Table 2, which also displays their main responsibilities. Most of the original project partners are participating in Phase 2 of the project as well. The new project partners, who joined the project in Phase 2, are also listed in the table.

Table 2: Industrial partners and main responsibilities

Partners in project phase 1	**Tasks**
ARAL	Filling stations and infrastructure
BMW	Liquid hydrogen fuelled personal cars
Munich Airport, FMG	Operations
Gesellschaft für Hochleistungselektrolyseure, GHW	High-performance pressurized electrolyser
Grimm Labortechnik	Hydrogen sensors
Isar Amper Werke AG, IAW	Production and distribution of electricity
Howaldtswerke-Deutsche Werft, HDW	Downstream GH2 purification and drying plant storage in metal hydrides
Linde AG	Liquid hydrogen production and delivery
MAN Utility vehicles, MAN-N	Low-floor articulated buses
MAN Technology, MAN-T	GH2 storage systems for buses
Mannesmann Demag Energie- und Umwelttechnik	Hydrogen storage cylinders and dispenser
Gottlob Auwärter GmbH , NEOPLAN	Low-floor articulated buses
Siemens AG	Master control and measurement system
TÜV Süddeutschland	Safety aspects
Additional partners in phase 2:	
BAYERNGAS / Linde	Steam reforming facility
E.ON	Production and distribution of electricity
PROTON MOTOR Fuel Cell GmbH	Fuel cells for the forklift truck
ET Energie Technologie	Project management, interface coordination

In order to ensure a comprehensive overview of the integrity of the system at all times, hydrogen sensors manufactured by Grimm Labortechnik are installed at all safety-relevant locations. Any leak or fault in the individual subsystems are reported via a master control and measurement system to the airport central control/fire brigade as well as to the system operator by ISDN.

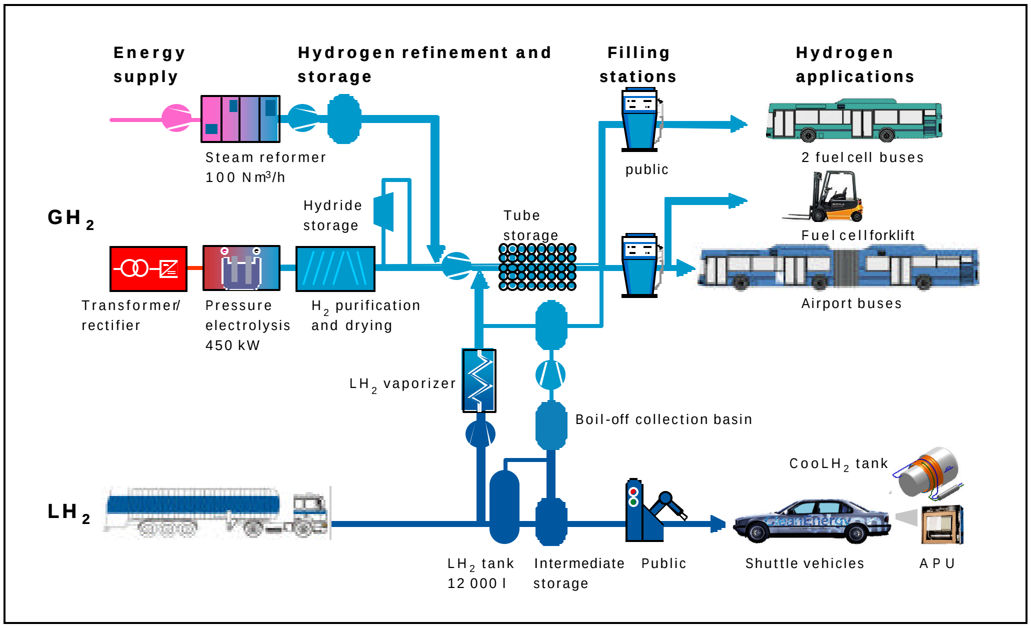

Figure 1: Overview of the hydrogen project at Munich International Airport

3. DESCRIPTION OF COMPONENTS

3.1 Hydrogen production and supply

In a feasibility study carried out by DASA (DaimlerChrysler Aerospace AG, now integrated in European Aeronautic Defence and Space Company EADS), several scenarios for the production of hydrogen were investigated: LH2 delivery from existing refinery surplus H2, plasma arc splitting of natural gas into H2 and carbon black by use of electricity (Kværner process) and ambient and high pressure electrolysis units for H2 production from off peak grid electricity, and PV electricity. The Kværner process showed the highest overall energy efficiencies but was not regarded as flexible enough for a step-by-step project build-up. Liquid hydrogen supply delivered in tankers and onsite production by high pressure electrolysis were thus selected for the first phase of the project, and production from natural gas in a steam reforming facility for later stages.

3.1.1 High-performance electrolyser

The GHW 3 MPa (30 bar) pressure electrolyser was developed specifically for the decentralized production of hydrogen. Connected up to the existing power network, hydrogen for the use as vehicle fuel, electricity storage media and for the manufacture of synthetic fuels can be produced practically at any place of demand. Its ability to cover a working range of 10 to about 150 % of the nominal load and its speed of varying the load, make the GHW electrolyser suitable for use as a frequency control unit within the power network and for the power management of suppliers of electricity.

Furthermore power networks with a sufficiently installed electrolyser capacity become more tolerant to fluctuating renewable energy. The properties of the GHW electrolyser allow the separation of electricity generation from demand and thus low price power potentials to be utilized.

Some of the outstanding features of the GHW electrolyser are the excellent level of efficiency, the very high purity of the gases produced, the wide range of load variability, the speed of changing the load and the operating pressure of 3 MPa (30 bar).

The electrolysis plant at Munich Airport has a capacity of approx. 450 kW. In two adjacent cell blocks of approx. 225 kW each, each of which is located in a 3 MPa pressure vessel, a total of approx. 94 m^3 H_2 and approx. 47 m^3 O_2 per hour are produced at the nominal load. The oxygen is released into the atmosphere, and the hydrogen is delivered (at 3 MPa) to HDW's gas purification, drying and hydride storage system and stored; or, after purification and drying, it is sent via a by-pass line direct to the membrane compressor. The electrolysis plant is monitored remotely and designed for unsupervised automatic operation. An ISDN connection allows distant intervention into the plants functions.

In GHW's electrolysis plant at Munich Airport, a number of major innovative plant component systems and operating functions were realized for the first time. The high-speed pressure relief in the event of an emergency cut out, for example, is a patent pending innovation, which takes the special requirements of the Airport into consideration. The system design and functions were realized on the basis of a safety study, with the assistance of the TÜV authorities, amongst others. MTU Friedrichshafen GmbH was not only the supplier of the key technology, but is also the operator of the system.

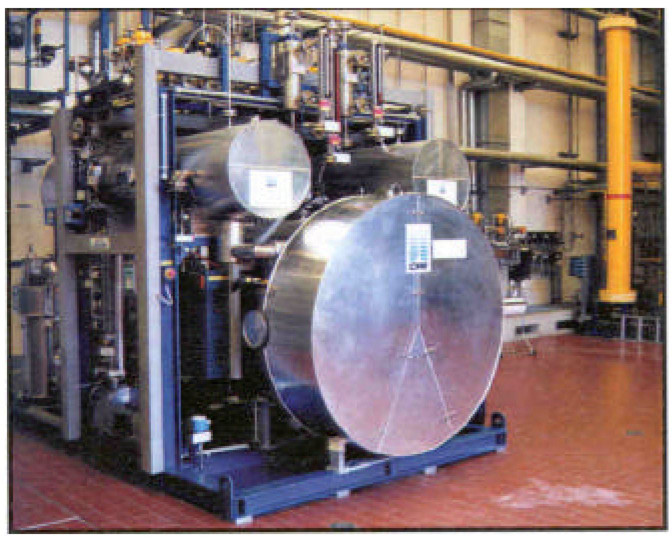

Figure 2: The interior of the GHW electrolyser

To improve plant reliability and performance, many modifications to the process, the system and to individual components were carried out, and these have been documented in detail.

The project has enabled important technological progress to be made and has produced valuable results that can be applied for new projects. As far as saving energy is concerned, a connecting pipe to the compressor had been installed, to by-pass the hydrogen around the hydride storage unit during normal operation. In this manner the need for cooling and heating of the hydride storage unit is avoided.

3.1.2 Steam Reformer

The construction of a steam reformer created an additional means of producing hydrogen. This facility, which went into operation in December 2003, uses a pressurized catalytic process under which steam is injected to convert natural gas into synthetic gas (hydrogen, carbon monoxide, carbon dioxide, steam and methane). In subsequent process steps, the synthetic gas is concentrated and the hydrogen is purified using pressure swing adsorption. The hydrogen generation facility is designed for fully automated operation with minimal human monitoring and maintenance work. A mixture of steam and hydrocarbon is heated to very high temperatures in tubes fitted with catalytic converters, yielding synthetic gases rich in hydrogen and carbon monoxide. The steam reformer in use can deliver up to 100 Nm^3 of hydrogen per hour. After purification and drying, the hydrogen is stored in a hydride storage tank. The storage facility stores 2,000 m^3 at a pressure of 3 MPa (30 bar). It feeds a membrane compressor, which compresses the hydrogen from 3 MPa to 35 MPa and fills the downstream high-pressure storage facility. The highly compressed hydrogen is stored in five storage cylinders with a total volume of 10 m^3. At a maximum operating pressure of 35 MPa, this means that 3,500 m^3 of hydrogen can be stored. The buses are fueled with hydrogen gas from the high-pressure storage facility using a specially designed dispenser. The capacity of the facility is designed for a single day's consumption.

Linde is responsible for the construction and operation of the steam reformers. Bayerngas delivers the natural gas as feed.

3.1.3 Liquid hydrogen supply

Hydrogen is stored in vehicles in two aggregate states: liquid frozen in thermally insulated tanks or in gaseous form in high-pressure cylinders. The liquid hydrogen filling station at Munich Airport can supply both systems. For this, liquid hydrogen is delivered in tanker vehicles from the Linde hydrogen plant in Ingolstadt and filled into a 12,000 l tank (see Figure 3).

Figure 3: Linde liquid hydrogen tank plant

Cars are filled directly with liquid hydrogen using a robot filling pump.

As a backup for GH2 production, the liquid hydrogen is vaporized and compressed to 35 MPa (350 bar) using a piston pump, vaporized and stored in large high-pressure cylinders in gaseous form at ambient temperature for the next time that the buses need filling with hydrogen.

In addition to refueling with liquid hydrogen, the filling station at the airport also has facilities for refueling apron buses with gaseous hydrogen. The hydrogen gas is generated on site by electrolysis and compressed to a pressure of 35 MPa.

In its two years of operation, the filling station has impressively demonstrated its reliability with both systems. Hydrogen filling operations have been carried out on both buses and cars thousands of times without any incident. The robot pump for liquid hydrogen has attracted the particular attention of the visitors.

3.1.3.1 Liquid hydrogen robot dispenser

The liquid hydrogen (LH2) filling of the cars is carried out automatically at the plant by a tank robot. ARAL and BMW are responsible for the supply of the robotic systems and Linde is responsible for supplying the liquid hydrogen lines and the LH2 coupling. The safety authority TÜV Süddeutschland is in charge of the necessary procedures for the acceptance of the station and the safety-related interfaces between the robotics, the liquid hydrogen lines and the LH2 coupling.

The aim of this part of the project is to modify the ARAL tank-filling robots for conventional fuels to the requirements of hydrogen.

The robotics system is installed above the carriageway on an island in an above-ground level version. The movement mechanism can be moved in four axes, so that the end effector (end point of the robot arm) can be moved freely in a limited working area (1000x800x200 mm).

The LH2 coupling, various operating elements for the coupling, the docking sensor system and the mechanism for opening and closing the tank flap are installed at the end effector.

The LH2 hose runs externally and the electric cables and other control lines run inside the robot arm to the end effector.

The tank-filling process is divided into the following steps:

- access to filling position cleared by a traffic light system
- vehicle recognition and customer authorization by the filling card
- docking process and filling of tank
- undocking process, issue of receipt and exit

Mechanical claddings, which activate safety-oriented switch elements in the event of a collision, meet the requirements for the protection and safety of users. In addition, gas sensors on the robot and underneath the filling station roof check that the robotics system is operating safely.

Figure 4: Liquid hydrogen robot dispenser

In the first project phase, the filling robot carried out 500 filling operations. The time taken to fill a tank with a volume of 125 l is approximately three minutes. The use of the cold drawable Linde coupling means that it is possible to fill several vehicles consecutively without any problem.

In the next project phase, the movement mechanics of the robot will be modified to the meet the requirements of the next generation of vehicles. In addition, improvements will be made to the coupling system to increase practicality. The results achieved so far will be incorporated directly into the further development of the components.

3.2 Storage and distribution of hydrogen

3.2.1 Hydrogen drying, purification and hydride storage

Howaldtswerke Deutsche Werft (HDW) took over hydrogen purification and hydrogen storage in metal hydride within this project. The plant is the connecting link between the electrolyser the compressor and the high-pressure storage unit. The electrolytically produced hydrogen basically passes through the purification plant. Aerosols are removed from the flow of gas in a filter and the very low quantities of residual oxygen, contained in the hydrogen, are converted by a catalytic reaction to water, using a catalyst containing precious metal.

The metal hydride storage units consist of coaxial pipes, which contain the metal hydride in the inner pipe. In the areas between the inner and outer pipe flows the cooling or heating water, which transports the heat energy for the charging and discharging process. Depending on the "concentration pressure isotherms", large quantities of hydrogen can be stored in a metal hydride.

The pressure and filling levels are adjusted by controlling the temperature. If hydrogen is to be discharged to the high-pressure compressor, the temperature in the hydride storage unit is increased so as to ensure that the compressor entry pressure is always approx. 3 MPa irrespective of the fill level of the hydride storage unit. This allows the compressor to be operated effectively and in a way that saves energy.

The hydride storage units are grouped together in two groups, which can be charged and discharged alternately. If necessary, the storage units can also be operated parallel. Depending on the method of operation, the hydride storage units can take up to 2,000 m^3 of hydrogen. Using a bypass line, the hydrogen produced in the electrolysis plant can be forwarded after purification directly to the compressor. In this way, the hydride storage unit serves as a store for hydrogen, which can be used if required. Since constant charging and discharging is avoided and thus the cooling and heating of the hydride storage unit energy will be saved, which further improves the efficiency of the entire system.

The measuring and control equipment was also developed by HDW. It aims to provide for a fully automated operation of the hydrogen gas line after the electrolyser. The plant is designed in such a way that operation can be remotely monitored by means of an ISDN connection, which allows intervention in the plant's functions.

Since HDW left the ARGE MUC consortium after the end of the first phase of the project, GHW has taken over the plants and guarantees further operation through MTU Friedrichshafen GmbH.

3.2.2 Compressor and gas storage cylinders

A two-stage horizontal membrane compressor is used to compress the gaseous hydrogen to the storage pressure of 35 MPa. The required inlet pressure is 1.5 to 3 MPa.

The purified hydrogen gas is supplied from the hydride storage cylinders with the process data required for the compressor.

The delivery rate of the compressor is 125 m^3 at an inlet pressure of 3 MPa. The maximum outlet pressure is 40 MPa.

The compressor and gas store are installed in a housing to protect them from the elements.

The high-pressure storage cylinder consists of five vessels (see Table 3).

Table 3: Specifications of high-pressure storage cylinders

outside diameter:	559 mm
wall thickness:	27.0 mm
length:	10,870 mm
Weight:	4,500 kg
Operating pressure:	35 MPa

The cylinder is supplied as a module with complete pipework. The high-pressure storage cylinder is manufactured and supplied by Mannesmann Cylinder Systems, Dinslaken. The storage volume is divided into three banks (low-pressure 6 m^3, medium-pressure and high-pressure 2 m^3 each). Each storage bank is charged to a pressure of 35 MPa. The logistic division into three banks (priority switching) is required for rapid fuelling. A priority switch ensures that a high differential pressure always exists between the vessels of the gas storage system and the vehicle tank during filling. This results in faster refueling.

The high-performance electronic dispenser controls the automatic sequence switch that opens and closes the valve system in accordance with the three-bank strategy.

The hydrogen discharged from the hydride storage plant is compressed to 25 MPa by a high-pressure compressor and filled into the high-pressure storage plant. The highly compressed gaseous hydrogen is stored in five storage cylinders, each with a capacity of 10 m^3. Following this, the hydrogen gas is passed to the buses using a hydrogen pump developed by ARAL and Mannesmann. The high-pressure capacity is designed to last for an entire day.

In the next stages of the project, it is planned to reach a filling pressure of nearly 35 MPa for the new fuel cell buses.

To continue the joint ARGEMUC project, Bayerngas took over the operation of the system elements for the compression and storage of gaseous hydrogen (GH2) including the hydrogen gas pump.

3.2.3 Gaseous hydrogen dispenser

The airport buses are filled with hydrogen using a filling station pump, which was developed by ARAL and Mannesmann DEMAG jointly. In this work, Mannesmann was responsible for the gas technology and ARAL for the housing, the display module, the card reader and the link to the TMS (filling station management system).

In the continuation of the project, Bayerngas took over the Mannesmann DEMAG AG plant components. The pump design followed the design of the conventional gas pumps at ARAL filling stations, with some modifications made due to the special official requirements.

The integrated information technology has to fulfill the following tasks:

- Metering and totaling
- Sequence control of 3 bank memory modules
- Pressure and temperature compensation
- Safety cutout in the event of an overfill or overflow
- Connection possibility of teleservice to a serial interface

For the filling process, the elastic hose line from the gas pump with the filler nozzle is connected to the vehicle gas tank and locked. To start the automatic filling process, a lever must be operated. The main valve of the gas pump is opened and the compressed GH2 flows into the vehicle's tank.

The flow of the gas is monitored via the flow volume meter built into the gas pump.

The filling process is automatically finished once the filling pressure in the vehicle tank calculated by the temperature compensation unit has been reached.

The amount of gas supplied (kg), the final price (€) and the price per unit supplied (€/kg) are displayed at the gas pump via the electronic display.

In a second project phase, a further GH2 gas pump will be added to the hydrogen station; this pump will be located in the public area of the Airport and buses and cars will be able to use it to fill with hydrogen. A further technical advance is the raising of the pressure level from 25 to 35 MPa filling pressure in the hydrogen storage units of the vehicles. The other functional features and operation will be the same. The design will once again be based on ARAL pumps for conventional fuels. ARAL is responsible for the development of the 35 MPa hydrogen pump.

3.3 Hydrogen vehicles

3.3.1 Low-floor articulated buses powered by hydrogen

In the first phase of the ARGEMUC hydrogen project, two low-floor articulated buses were developed and built by MAN and one articulated bus by NEOPLAN. All of the buses are powered by a flat in-line 6-cylinder hydrogen engine with an output of 140 kW (190 hp). The engine is supplied with gaseous hydrogen, which is generated at Munich Airport by power electrolysis and kept in stationary hydride or pressurized storage containers. The 15 aluminum containers required, with full carbon wrapping, are mounted on the roof of the vehicle, allowing a desired range from Munich Airport of 150 km. Filling a vehicle completely only takes a few minutes. The articulated buses have been traveling on the apron since May 1999, covering about 187'000 km (117'000 miles) in their three-year operating period. The main technical characteristics of the buses and of the hydrogen ignition engines are given in Table 4.

Table 4: Technical data of low-floor articulated buses and engines:

Low-floor buses		
type	MAN	A 23
	NEOPLAN	Centroliner N 4421/Hydrogen
length		18 m
height		3.3 m
total weight		28 t
hydrogen storage volume		2,580 l
Hydrogen engine		
type		H2866UH01
		6-cylinder in-line engine, 4-stroke cycle
power		140 kW max
torque		700 Nm max. at 1200 rpm
piston displacement		12 l
engine control		MOTRONIC Lambda-controlled, catalytic converter
Hydrogen tank		15 tanks, aluminum wrapped
overall volume		2580 l
overall energy content		1670 kWh
operating pressure		25 MPa

In the second phase of the Munich Airport hydrogen project MAN has set the following goals:

- Continuation of the operation of the two low-floor articulated buses with hydrogen engines and 25 MPa storage in the airport apron area, accompanied by further system optimization;
- Development of a turbo-charged hydrogen ignition engine;
- Development of two low-floor buses with PEM fuel cells and hydrogen storage at 35 MPa.

Figure 5: MAN low-floor articulated bus

Project phase 2 was started in mid-2001. Operation of the articulated buses on the apron is continued in the subsequent phases of the project. As part of the further development of the hydrogen drive train, detailed improvements are planned both to the engine and to the gas line. The articulated buses will continue to be filled with gas on the apron using 25 MPa compressed hydrogen.

In a further stage, a turbo-charged MAN hydrogen lean-mix engine H 2866 LUH with an output of more than 200 kW will be developed and tested.

3.3.2 On-board hydrogen storage systems for buses

Every bus is fitted with two roof storage systems, which store hydrogen in a total of 15 pressurized gas containers (total volume of 2,580 l) and a maximum pressure of 25 MPa (250 bar). The technical data of the single cylinders are given in Table 5. Each container consists of a thin, seamless aluminum liner and a wrapping made from carbon fiber reinforced plastic. All containers have a connection thread at their ends for the connection of pipes or shutoff valves.

Table 5: Technical data and characteristics of the gas storage cylinders

capacity	172	l
length	1880	mm
diameter	386	mm
weight	62	kg
maximum operating pressure at 15ºC	25	MPa

The gas storage systems are completely mounted and connected on aluminum frames with neoprene rests and neoprene-padded strap attachment for six and nine GH2 tanks. The welded seams have been inspected for cracks. The aluminum frame has been powder-coated in compliance with MAN specifications M3018-3 RAL 9005 The Dynetek aluminum composite pressurized gas vessel is certified and fitted with fuse protection.

Tests for the type approval of the containers under the supervision of the safety authority TÜV Süddeutschland have been successfully concluded.

3.3.3 Low-floor fuel cell buses

One of the main highlights is the development of two MAN low-floor buses with fuel cell drive. These buses are to undergo trial operation initially on the apron. The development objective is to test how far this innovative drive technology will succeed in operating use at an airport. Other uses for the fuel cell buses on public transport lines around the airport are planned. A public filling station is planned for filling up the fuel cell buses, which will have hydrogen storage systems with a 35 MPa (350 bar) filling pressure. The buses are based on the newest version of the type A21 low-floor bus. The main characteristics are summarized in Table 6.

Table 6: Technical characteristics of the low-floor fuel cell bus:

Vehicle	type	NL 163	
	lenght	12	m
	height	3.4	m
	total weight	18	t
	range	> 250	km
Hydrogen engine	net power available for propulsion	> 150	kW el
	fuel cell voltage	400-600	V
	rated velocity	80	km/h
Hydrogen storage	maximum pressure	35	MPa

In the case of low-floor city buses there is very limited space to locate components under the floor. In order to keep the desired transport capacity the fuel storage system as well as the cooling system are located on the roofs.

3.3.4 Forklift truck

For the Munich Airport hydrogen project, the company Proton-Motor GmbH is developing and building a fuel cell for a forklift truck to be supplied by Still GmbH (part of Linde Material Handling Division). The hydrogen supply system is provided by Linde.

The Cargogate airfreight company, a 100% subsidiary of Flughafen München GmbH (FMG), will use this vehicle. By replacing the traditional battery, the forklift truck can be filled with hydrogen in minutes, just like a passenger car, at the nearby H_2 filling station. The hydrogen storage container will be a pressurized container (up to 35 MPa) with a capacity of up to three kilograms of hydrogen. This corresponds to around 100 kWh of electricity of ten liters of diesel, allowing the forklift to be used over a total eight-hour work shift.

Because it is incorporated into the operating fleet of 30 forklifts, it is possible to test the suitability of the fuel cell system for everyday use. A high-performance cell type with a continuous electrical output of 14 kW carries out the more demanding movement and lifting tasks. In addition, the system incorporates an electrical energy storage unit, which absorbs the braking energy of the vehicle and provides the necessary peak acceleration output of 24 kW.

Figure 6: Forklift truck and associated PowerPack

4. OPERATIONAL EXPERIENCE

The field test has proven the technical functions of the whole system. Data concerning the reliability and the economic efficiency are being evaluated and will be made available in 2005.

4.1 Liquid hydrogen vehicles with hydrogen combustion engines

The fuel tank of the BMW 750hL vehicle holds approximately 125 l of liquid hydrogen, corresponding to a driving range of over 300 km (190 mi). The hydrogen combustion engine accelerates the vehicles to over 200 km/h (125 mi/h). The hydrogen is burnt in the engine with excess air. This concept lowers the flame temperature in the combustion area to below the critical limit above which nitrogen oxides are created. Even without additional waste gas processing by catalytic converters, hydrogen engines thus run practically without emissions. The BMW 750hL can either be filled automatically at the filling station at Munich Airport or manually at BMW AG's factory site.

So far, over 600 filling operations have been carried out, involving around 30,000 liters of liquid hydrogen. At the beginning of the project, only one vehicle could be filled at the robot filling station, but the gradual expansion of the BMW research fleet proved that fleeting filling operations can also easily be carried out at the filling station. It became clear that the design of the plant offers customers a high level of user-friendliness. This is an important discovery on the way to successfully developing a filling station network throughout Germany.

In addition to being able to test and fill the vehicles under working conditions, the Munich Airport hydrogen project offers further test opportunities for the BMW Group. The operation of the vehicles at Munich Airport can provide information that can be used for the improved servicing of conventional vehicles. For example, service-related data are recorded in the hydrogen car and transmitted if necessary via mobile radio to the BMW service center. The emergency service is thus precisely informed about the vehicle status and position and Customer Service can - if necessary - react immediately. On board the BMW hydrogen vehicles, a PEM fuel cell is provided for the on-board power supply, which is used as a battery substitute (Auxiliary Power Unit, APU). It provides an output of up to 5 kW. As a further development, the integration of a new larger tank system with a capacity of 170 liters is planned.

4.2 Infrastructure, auxiliary and supply systems

Within the framework of the project, ARAL AG is responsible for producing the entire infrastructure. The aim in planning and implementing the building measures was to take over, as far as possible, the standardized design of conventional ARAL filling stations. Special requirements on the part of the partners involved for the installation of system components, compliance with safety regulations and connections to the road network were linked with the standard components and taken into account during implementation.

The following components were realized by ARAL at the hydrogen filling station:

- filling station building to house the electrical distribution system, the control panels, the primary Instrumentation and Control (PIC~, the fire alarm sub-board and the instrument air supply system
- filling position roofing for the GH2 gas pump (station roof) and the LH2 filling robots (roof canopy).
- carriageway and pedestrian way surface including lighting of the filling positions
- auxiliary, secondary and supply systems (e.g. fire alarm, instrument air supply, electrical distribution).

The building measures were started at the end of April 1998, when the building approval was granted and were completed on schedule in August of the same year.

The filling station infrastructure will be expanded in the next project phase. A second hydrogen production unit (steam reformer) and a second dispenser unit for pressurized hydrogen will then be integrated into the existing filling station layout.

Figure 7: Liquid hydrogen filling station

5. INTEGRATION OF COMPONENTS

5.1 Instrumentation and control

By providing the PIC (primary instrumentation and control) DCS (Digital Control System) in this project, the Automation & Drives division at Siemens AG, the market leaders in automation technology, is making a major contribution to the testing and introduction of this environmentally friendly technology.

The new process control system SIMATIC PCS 7 is being used here.

The particular distributed system structure of the hydrogen filling station makes places tough demands on data transfer and the transfer media required for it. Fiber optic technologies were used for the communication connection between the individual automation systems.

PROFIBUS, the leading field bus system in Europe, is used for the exchange of information between the system elements and the higher-level Siemens process control system PCS 7.

The operator stations of the SIMATIC PCS 7 process control system are the "window" to the entire hydrogen system and present the process sequences, statuses states and reports from the connected part-systems in a way that is clear and easy to understand.

This system is connected to Munich Airport's central airport control system. In this way, the replacement personnel of the central airport control system can be provided with all the necessary information so that the safe operation of the system can be guaranteed at all times, even from a distance.

In addition to the instrumentation automation and control, Siemens supplies the project with systems for safety technology. All safety-relevant signals such as the emergency cutout shut-down, gas alarm or fire alarm are incorporated into this control and forwarded to Central Information Automation and Control or to Munich Airport's Central Fire Brigade unit.

The operating period so far has shown that the system configuration chosen, and the automation concept in use allow 24 h safe and unmanned operation.

The solution chosen, using the SIMATIC PCS 7 control system, has proved to be a pioneering automation concept, which can be taken as a reference for the commercial use of further hydrogen filling stations.

5.2 Hydrogen monitoring system

GRIMM Labortechnik supplied the hydrogen monitoring system. It consists of twelve sensors, a receiver and an evaluator unit for warning and alarm output. The system monitors the entire hydrogen process chain from production to storage to transport as well as the distribution, utilization and refueling processes. Any leak or fault in the individual subsystems are reported via a master control and measurement system to the airport central control/fire brigade as well as to the system operator by ISDN.

The hydrogen sensors operate on an electrochemical basis like mini fuel cells. The sensors are used for monitoring workplace concentrations during the production, storage and processing of industrial gases as well as for continuous safety checks and monitoring of the lower explosion limit. A novelty is the multi-sensor concept of the universal gas sensors and transmitters, whereby the transmitter can be used for any gas sensor. The universal transmitter recognizes the type and measurement range of the integrated sensor.

The monitoring system was adapted to the requirements of the hydrogen project and-particularly in the robot arm-was developed as part of the safety concept for the LH2 dispenser robot. TÜV Süddeutschland inspected the system.

5.3 Interface coordination

Within the scope of the Munich Airport hydrogen project, ET-EnergieTechnologie (Gesellschaft für innovative Energie- und Wasserstoff-Technologie mbH), on the basis of its management and engineering experience, took over the project management and higher level interface coordination between the partners in the consortium in order to optimize the services being provided. The tasks of ET project management include:

- Classic management activities such as the provision and supervision of timetables, reporting to the Ministry and within the partner companies, convening the meetings of the authorized representatives and ensuring that their resolutions are implemented
- Technical project management such as recording the performance data of all the partners in the consortium, interface coordination and the implementation, if necessary, of suitable measures in the event of technical or deadline problems on the part of a partner or supplier, and coordinating the acceptance and commissioning of systems on site
- General coordination tasks such as the working out of conflict solutions if company strategies and procedures diverge in relation to the project objective, the introduction of measures to handle any damages and working out rescue solutions if anything occurs which could endanger part of the project.

In these project management tasks, ET-EnergieTechnologie makes use of its widely based technical knowledge, acquired over many years, in the hydrogen sector and its experience in cooperation with system operators, small and medium-sized enterprises (SME) and universities and research institutions.

6. SAFETY ASPECTS

The production, storage and application of gases such as hydrogen are technologies that have been proved reliable over decades. However, the innovative components used within the scope of the hydrogen project at Munich Airport, , and the special nature of the environment require specially modified safety technology. TÜV Süddeutschland has therefore been involved as the project safety consultant during the planning, setting up and operational phases.

The safety technology needs have to meet particular challenges due to the many different links between the systems for automatic hydrogen production and storage, and also due to the testing of technologies such as filling passenger car tanks with liquid hydrogen by robot and the special conditions of use for H2 vehicles around the airport apron.

The aim of providing support for this project is to exclude potential environmentally related and operational sources of danger from the beginning through the appropriate design of the system technology. As far as safety is concerned, the relevant operating and environmental sources of danger were analyzed and the protection objects for the entire system and for vehicle use were discussed. The evaluation was based on the regulations and guidelines to be applied wherever hydrogen is used.

The individual H2 carrying elements were systematically examined during the planning phase, for inadmissible conditions inside the systems, for example, for possible faults in the supply of the energy and the medium, or for possible leaks in walls following mechanical damage, corrosion, wear, etc.

The possible effects of an H2 leak after a fault were also examined. The aim was to prove that that safety concept or the proposed precautionary measures would prevent the stationary plant and the hydrogen vehicles causing any serious damage and to ensure that sufficient measures had been taken to keep the effects of H2 leaks to a minimum.

On the basis of the evaluation of the possible hazard potential, technical or organizational measures were proposed to the consortium partners to prevent or limit leaks, ignitable mixtures and fires.

The construction of the components and systems was compared on site with the documents that had been reviewed. In addition, safety-related functional tests were also carried out.

Naturally, in a demonstration project like this, the procedure described here in brief is associated with several repeated stages, depending on the progress of the planning, rather than running on a linear basis.

The operating time to date shows that the safety concept has been successful. At the same time, there is still room for technical and economical optimization in critical components of the hydrogen production and implementation process.

7. FUTURE PLANS

The main goal of Phase 4 of the project (2005-2006) is the continuous operation and evaluation of the whole system. This will lead to technical improvements of many of the components. Some of these intentions are described in this section, but all the partners will be involved in continuous and mutually influenced improvements.

7.1 Pressure module electrolyser

GHW is currently developing an innovative Pressure Module Electrolyser (PME, patent pending) in the MW power range for the energy hydrogen markets. With the PME, GHW is aiming for considerably cutting the investment and operating cost and improving reliability to achieve stand alone operation.

As stated above, the controllable pressurized alkaline electrolysis is a very suitable approach to a technical solution for favorable mass production of energy hydrogen is. At a high service pressure of up to 3 MPa and with its broad working range, the system is quickly controllable and can thus be flexibly adjusted to different loads.

Dispensing with electrolyte pumps and integrating all of the pressure-bearing functional units into a common pressure vessel open up further potentials for increasing efficiency and cost reduction. This approach to a solution is currently being pursued by GHW together with its partners MTU Friedrichshafen GmbH, Norsk Hydro ASA and Vattenfall Europe AG company. The Pressure Module Electrolyser concept (PME) will take up only one third to one quarter of the space required by a unit with the same capacity operated at atmospheric pressure and will have a considerably lower power consumption. A target price for the construction of systems in the MW range is in the order of € 400/kW. This type of unit would be within the range of the most favorably priced conventional atmospheric pressure units.

GHW will become increasingly active in the establishment of a hydrogen infrastructure on the basis of its electrolysis systems and will, together with project partners, be offering the technology for total hydrogen filling stations right through to the delivery of certified green electricity.

7.2 Liquid hydrogen supply

All the original project goals with respect to liquid hydrogen supply and tanking facility have been successfully achieved. In the next phase, the coupling and vehicle tank for liquid hydrogen will be further developed from demonstration to series operation. In addition, the coupling will be smaller and lighter, which means that it will be easier to use in manual operation too. As far as the cryogenic tanks are concerned, two new developments are in sight:

- modification of the tank shape for better adaptation to the vehicle, and
- extension of idling time

As an energy medium, hydrogen in liquid form has a much higher energy density than gaseous hydrogen. This means that LH2 can provide fuel for similar distances to those provided by conventional fuels. However, after just a few days of idling time, the tank loses hydrogen, which is blown out via safety vales, due to the effects of heat.

A new patented Linde tank system extends the idling time of the vehicle without hydrogen evaporation loses by around ten days, thus reducing the problem of the effect of heat during long idling times to a minimum. The cold contained in the liquid hydrogen had not been used before; in fact, it had actually been destroyed before use in a cold-water heat exchanger.

In the new system, the cold in the hydrogen is used to liquefy ambient air that has been sucked in and dried. The liquid air (-191°C) flows through a condensing jacket that encloses the inner tank and, as in a refrigerator, protects the hydrogen against the ambient warmth. Every time a new journey is started, the "refrigerator' is filled again with liquid air, and the tank once again has a standing time of more than 14 days.

7.3 Primary energy

The utility company E.ON Energie is providing Munich Airport with the electricity for the decentralized production of hydrogen as an energy carrier on particularly favorable terms.

Involvement in the project offers E.ON Energie the opportunity to gather further experience in the conversion of electrical energy to chemically bound energy for the purposes of storing energy, and to further explore the early adjustment of the production and distribution structure required by the new technologies. As electrical energy is increasingly produced from renewable sources, which are not always available in parallel with demand, such as the solar and wind, the storage of energy becomes more and more important.

The production of hydrogen using electrolysis represents this type of particularly innovative use of power from periods in the day with a low consumption or a surplus generation from renewable sources: electricity from the supply network is locally converted into direct current to produce hydrogen and oxygen from water in the electrolyser. Gaseous hydrogen is stored under pressure; compression is also driven by electrical energy.

The project provides an opportunity to carry out a more in-depth examination of the dynamic behavior of water electrolysis units. These results can be used to maintain network stability in more distributed generation systems.

8. CONCLUSIONS

The first five years of the field study at Munich Airport are over. The production and storage of gaseous hydrogen has now become routine.

Although the refueling of the GH_2 low-floor buses, which are used for transportation at the airport, is seen as a spectacular event, generating interest around the world, the actual process has become an everyday task. This is illustrated by the more than 8,000 problem-free refueling operations.

After a five-year operating phase, the buses have driven more than 350,000 km (220,000 mi). The cars, which are refueled with liquid hydrogen, have driven more than 170,000 km (100,000 mi) during that period.

During the first and second project phases, more than 13,000 visitors from around the world have learned about our project so far. In addition to 600 tours for specialists at the filling station, more than 220 presentations have taken place in Germany and abroad.

The results obtained since the opening date on May 5th, 1999, have shown that the main objectives of the project have clearly been achieved:

- operational use of hydrogen
- presentation of an enclosed hydrogen circuit from generation to use as an autonomous unit
- demonstration of the reliability of today's hydrogen technologies
- determination of the general requirements for the commercial use of hydrogen
- development and implementation of safety requirements in dealing with hydrogen

The continuation and expansion of this project using increasingly advanced hydrogen technologies is a necessary and appropriate reaction to the increasing pressure of environmental pollution and dwindling resources.

9. CONTACT INFORMATION

Wolfgang Burmeister has been designated by ARGEMUC to be responsible for press and public relations. He will either answer questions directly or forward them to the appropriate partners.

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