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LIQUID HYDROGEN AS AN AUTOMOTIVE FUEL*

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ABSTRACT

Cryogenic liquid is the only form of hydrogen storage that is presently capable of competing with gasoline on the basis of weight and vehicle range; however, a larger volume is required and its extreme cold will require special considerations. At least six hydrogen fuel projects, involving six container designs and six vehicles, have used liquid hydrogen storage. Some of these projects used existing laboratory type containers while others involve containers designed especially for the project. Service (refueling) stations and bulk distribution systems can be built using present technology. These can be similar in concept to the present service stations and distribution systems. Vehicle refueling and bulk liquid hydrogen transfer will probably be computer controlled - automated as completely as possible. Liquid hydrogen can begin its entry into the automotive fuel picture as a fuel for fixed-base vehicles such as trucks, buses, taxis, etc., and expanded into the private sector as its availability increases.

*Work performed under the auspices of the U.S. Department of Energy.

Liquid Hydrogen as an Automotive Fuel

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Hydrogen is an excellent fuel; it will become the fuel in our future given (1) an incentive to change from the present hydrocarbon fuel, (2) an energy source to produce the hydrogen, (3) an engine to run on hydrogen, and (4) an on-board hydrogen storage system. The on-board hydrogen storage system is discussed here.

Hydrogen has a high gravimetric but a low volumetric heating value; consequently, hydrogen provides nearly 3 times the chemical energy of gasoline by weight, but only about 25% of the energy of gasoline by volume. Thus, a larger volume fuel tank is required for hydrogen than for gasoline, although the weight of the hydrogen is considerably less than gasoline for an equivalent energy storage. This hydrogen storage problem is being solved in various ways; however, only the liquid hydrogen storage method is addressed in this report.

Liquid hydrogen storage is now the only form that can compete with gasoline storage on the basis of weight and vehicle range; however, a large-volume, well-insulated storage container is required because liquid hydrogen is a cryogen of low density. The problems to be overcome for liquid hydrogen use are:

- (1) its volume requirement,
- (2) its extreme cold,
- (3) its high volatility, and
- (4) the additional energy (hence, expense) for its liquefaction.

This raises questions of safety and economics. If these questions are resolved, the use of liquid hydrogen for on-board fuel storage for the general public will then depend on successful demonstrations. For fleet operations (busses, trucks, taxis, trains, etc.) the safe use of liquid hydrogen is possible now because the transportation, handling, and storage of bulk quantities of liquid hydrogen for use anywhere within the continental United States has been demonstrated with an excellent safety record. In spite of the extra expense and energy requirements of liquefaction, there are numerous factors that could lead to the use of liquid hydrogen. These include:

- (1) the possible necessity to liquefy hydrogen for its shipment and distribution regardless of the type of on-board storage system;
- (2) the possibility that advanced engines can be built to take advantage of the use of hydrogen as a liquid;
- (3) the auxiliary use of the refrigeration capacity of liquid hydrogen for oxygen enrichment of the combustion air; and
- (4) the ancillary uses of liquid hydrogen (e.g. air conditioning).

Thus, the additional energy required for hydrogen liquefaction could be partially recovered or utilized.

At least six hydrogen fuel projects (involving 6 container designs and 6 vehicles) have involved liquid hydrogen storage. Some of these projects used existing laboratory type containers, some used adapted liquefied natural gas (LNG) containers, and others used containers designed especially for the project. These projects are summarized in Table 1 and described in more detail below.

Perris Smogless Automobile Association

The Perris Smogless Automobile Association, Perris, California, has operated several vehicles on hydrogen. Liquid hydrogen storage was used on a 1960 Ford F250 pickup truck with a standard 6-cylinder overhead-valve-type engine.¹

Liquid hydrogen was stored in two 0.15 m³ Linde LSH-150 Dewars while another 0.11 m³ Dewar (Linde LC-36) was used to store liquid oxygen. These Dewars were standard, commercially available, portable containers that were not modified in any way. The Dewars were located in the bed of the pickup truck. Approximately 25 hours of static engine operation and about 161 km (100 miles) of driving were accomplished on this vehicle. An estimate of 70.9 m/g (20 miles/pound) of hydrogen was reported¹ (m/g = meters/gram).

Billings Energy Research Corporation

The Billings Energy Research Corporation, Provo, Utah, has operated numerous engines and vehicles on hydrogen, initially using compressed gas storage. About 1973, however, cryogenic liquid, metallic hydride, and hybrid storage systems began to be used.² A 1973 Chevrolet Monte Carlo 2-door Sedan with an 8-cylinder engine was equipped with a hybrid cryogenic/hydride storage system.

The cryogenic liquid container (made by the Beech Aircraft Corporation of Boulder, Colorado) was a horizontal cylinder with a liquid hydrogen capacity of approximately 0.058 m³ (18 gallons) and held 3.77 kg (8.3#) of hydrogen.³ The Dewar was mounted in the vehicle's rear trunk compartment.

The liquid hydrogen container, a modified LNG container, had a maximum operating pressure of 517 kPa (75 psig) and had a boil-off rate of 4.9% per day, giving a lock-up time of 44 hours.⁶ Engineering models of this Dewar were subjected to extensive pressure cycling, rupture, vibration, and shock loading (up to 10 g's) to evaluate structural integrity. Five engineering models and ten prototype tanks were designed, fabricated, and tested in this development program.

When the vehicle was not in use, boil-off from the liquid hydrogen tank could be transferred to the metal hydride system and stored, or it could be vented to a catalytic device and reacted with air to form water so that hydrogen was never vented to the atmosphere.

Table I
Summary of Projects Using Liquid Hydrogen Storage

Project	Perris	Billings	LASL	UCLA	Musashi	DFVLR	DFVLR
Vehicle	1960 Ford Pickup	1973 Chevy Monte Carlo	1972 Dodge Pickup	Jeep	Datsun B210 Car	none	none
Dewar Manufacturer	Linde	Beech	MVE	MVE	Musashi	DFVLR	DFVLR
Dewar Shape	Vertical Cylinder	Horizontal Cylinder	Spherical	Spherical	Vertical Cylinder	Ellipsoidal	Ellipsoidal
Dewar Overall Dimensions (m)	0.51 o.d. 1.47 height	0.38 o.d. 1.02 long	0.86 o.d.	0.86 o.d.	0.51 o.d.	0.42x0.9	0.42x0.9
Dewar Liquid Volume (m ³)	0.15	0.07	0.19	0.19	0.23	0.15	0.12
Dewar Empty Weight (kg)	75	34	41.5	45.5	120	43	88
Dewar Filled Weight (kg)	85	38	58.0	58.6	135	54	97
Dewar Evaporative Loss (%/day)	2	4.9	3.3 (max)	5	2.5	3.5	7.5
Dewar Max Working Pr (kPa)	63.9	517	206.8	206.8	490	448	448
Dewar Material	Stainless Steel Carbon Steel	Stainless Steel Carbon Steel	Aluminum	Aluminum	Stainless steel	Aluminum	Stainless steel
Dewar Design Load (g's)			20	20	10	30	10
Lock-up Time (h)		44	28	< 24		48	

Fuel economy was reported to be 35.4 m/g (10 miles/lb) of hydrogen for "city driving," equivalent to 12.0 m/g (20 miles/gallon) of gasoline, with an 86% increase in energy conversion efficiency claimed for urban driving conditions.^{4,5} About 11,265 km (7,000 miles) were accumulated on the vehicle operating on hydrogen. This car was destroyed by fire that resulted from the failure of a component that was being tested in a cryogenic application.

Billings is also reported² to have modified a large Winnebago "motor home" to operate completely on hydrogen. The vehicle's 8 cylinder $7.21 \times 10^{-3} \text{ m}^3$ (440 in³) Dodge engine, Onan motor-generator, and all cooling and heating appliances were operated on hydrogen supplied from a cryogenic liquid hydrogen container specially modified for this application by the Linde Division of the Union Carbide Corporation.

Los Alamos Scientific Laboratory

A 1972 Dodge 1/2-ton pickup truck with a four speed transmission and a $5.21 \times 10^{-3} \text{ m}^3$ (318 in³) displacement V-8 engine was modified to operate on hydrogen as its fuel at the Los Alamos Scientific Laboratory, Los Alamos, NM.⁷

The liquid hydrogen container installed in this vehicle was a spherical Dewar with an o.d. of 0.854 m (34 in), a capacity of 0.19 m^3 (50 gal), and had a maximum working pressure of 207 kPa (30 psig). The Dewar was manufactured by the Minnesota Valley Engineering Company. The loss rate for this Dewar varied from 0.8% to 3.3% per day depending on the configuration of the top closure which provided liquid or gas withdrawal tubes, a heater, and instrumentation. The maximum working pressure and the maximum heat input rate resulted in a maximum lock-up time of approximately 1-1/4 days.

A mileage efficiency of 30 to 35 m/g (5 to 5.8 miles per gallon) of liquid hydrogen was obtained in operation at an average elevation of 2.1 km (7000 ft)

over a rather hilly road with up to 70% grades. The average of 32.5 m/g (5.4 miles per gallon) of liquid hydrogen corresponds to a 58% increased efficiency over the normal truck operation of 7.7 m/g (13 miles per gallon) of gasoline. With this fuel consumption the vehicle had a range in excess of 400 km (250 miles) with the 0.19-m³ (50-gal) Dewar.

UCLA

Several vehicles and engines have been operated on hydrogen using compressed gas, metallic hydride, and liquid hydrogen storage by researchers at UCLA.

A Dewar identical to that used at LASL was installed in a Jeep furnished to UCLA by the US Postal Service,^{8,9} giving the vehicle a range of about 724 km (450 miles).

This vehicle was involved in an accident⁹ without the liquid hydrogen becoming a major problem. The vehicle, with a full liquid hydrogen tank, was being towed on a trailer when a tire blowout on the trailer resulted in the trailer and Jeep overturning, coming to rest upside down. With liquid hydrogen in contact with the warm top portion of the Dewar, a rapid pressure rise occurred resulting in hydrogen being vented through the relief valve. The Dewar was manually vented several times to keep the Dewar pressure down. The Jeep was unchained from the trailer and manually turned upright. The Dewar then returned to normal operation. The vehicle was inspected with no damage to it or the hydrogen system found so it was driven from the accident scene.

While this incident does not prove that liquid hydrogen is absolutely safe, it does show that an accident involving liquid hydrogen is not necessarily catastrophic.

Musashi Institute of Technology

Experiments with several hydrogen fueled engines and vehicles have been made at the Musashi Institute of Technology, Tokyo, Japan, with at least one using liquid hydrogen storage.¹⁰

A Datsun B210 car with a 4 cylinder engine ($1.4 \times 10^{-3} \text{ m}^3$ total displacement) was equipped with a liquid hydrogen Dewar with a capacity of 0.23 m^3 (60 gallons). A Dewar of this size was installed to permit the vehicle to compete in the Student Engineered Economy Design (SEED) Rally 1975 in which a minimum range of 650 km (400 miles) was required.

The Dewar inner shell was an 800-mm-diameter, 2.5-mm-thick cylindrical section with 3-mm-thick hemispherical end caps of stainless steel with a working pressure of 490 kPa (71 psig). The outer shell was spaced 100 mm from the inner shell with a wall thickness of 5 mm and was made of aluminum alloy plates. The overall weight of the tank was 120 kg. The heat leak into the Dewar resulted in a boiloff loss of about 2.5% per day. Hydrogen gas was delivered to the engine cold (approximately 140 K) for increased performance and lower NO_x emissions.

The vehicle successfully completed the 2800 km (1740 miles) Rally.

DFVLR

The Institut für Technische Physik, Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt e. V. (DFVLR), in Stuttgart, Federal Republic of Germany, has developed and tested what is perhaps the most advanced of the liquid hydrogen containers designed especially for vehicle applications.^{11,12}

Two Dewars have been designed and tested; one fabricated of stainless steel with a capacity of 0.12 m^3 , and one of aluminum with a capacity of 0.15 m^3 . Both tanks are of a flat geometrical configuration with both the inner and outer shells being manufactured by welding two commercially

available caps together. The inner shell has no neck as does the MVE Dewar, but contains three 1/2" o.d. stainless steel connections with one for LH₂ refilling (also for LH₂ withdrawal), one for removal of gaseous hydrogen, and the other for safety relief valves. One of the tubes is also used for the electrical leads for liquid level sensors. The inner shell is supported from the outer shell by two glass reinforced epoxy resin cylinders (100 mm long, 1 mm wall thickness and about 50 mm between inner and outer shells). The inner shell is designed for a normal operating pressure of 448 kPa (65 psig). Aluminum plates are used to prevent stratification and sloshing.

Cooldown, boiloff (heat leak), and refueling tests have been conducted on these Dewars. Cooldown of a warm Dewar was achieved in less than 30 minutes and required about 0.02 m³ of LH₂. A refilling rate of about 0.015 m³/min of LH₂ was obtained. Later, refueling times of about 5 minutes were attained. The aluminum tank has a boiloff rate of 5200 mm³/d (3.5% per day) and the stainless steel tank has a boiloff rate of 9000 mm³/d (7.5% per day).

Refueling Station

Most of the projects mentioned above have used makeshift systems or methods for refueling their Dewars but eventually more realistic refueling stations will be required.

A refueling station design was proposed by Stewart and Edeskuty¹³ and described in more detail later.¹⁴ A completely automatic refueling station as shown in Fig. 1 would operate as follows.

discharge line or the level in the tank itself. Disconnect could then be made and the vehicle driven away.

The DFVLR has built and tested a semiautomatic refueling station that essentially accomplishes the above operations and is designed to be operated by untrained personnel.¹² Refueling times of about 5 minutes for Dewars with capacities of 0.12 to 0.15 m³ were obtained.

The layout of a liquid hydrogen service station with the LH₂ storage Dewars located 7.6 m (25 ft) from a roadway and 22.9 m (75 ft) from a building in accordance with existing safety standards is shown in Fig. 2.

A recent survey¹⁵ of liquid hydrogen container technology for highway vehicle fuel system applications included a preliminary cost estimate from several Dewar manufacturers for a LH₂ container suitable for use in an automobile. The cost estimate was based on the specifications listed in Table 2.

Cost estimates were received from three manufacturers as summarized in Table 3. These cost estimates (in 1977 dollars) were for complete liquid hydrogen fuel systems including controls, ancillaries, and gaging.

A liquid hydrogen production and distribution system can be developed based on the present, well-established facilities and equipment. A preliminary estimate of the total cost of a production and distribution system indicated that it would not greatly exceed the forecasted expenditure of the petroleum industry for new facilities during the same time period.¹³

Estimates for the cost of operating an automobile on hydrogen compared to gasoline vary from hydrogen costs being less than to several times that of gasoline.

Fig. 2. Layout of liquid-hydrogen service station.

Table 2

PRELIMINARY TECHNICAL SPECIFICATION FOR CONTAINER COST ESTIMATION

- Configuration: Horizontal cylinder
- Capacity: 0.19 m³ (50 gal)
- Nominal operating pressure: 345 kPa (50 psig)
- No-loss pressure lock-up time: 3 days
- Allowance for liquid level gaging
- Fill and vent connections: standard, to meet all governing regulations
- Construction: Sufficiently robust for road use

Table 3

U.S. PRODUCTION COST ESTIMATES FOR COMPLETE LIQUID HYDROGEN FUEL SYSTEM

Basis: 30,000 Units		Basis: 3 Lot Sizes*	
Company No. 1	\$1550	1,000	\$2200
Company No. 2	1500	10,000	1740
Company No. 3	900	100,000	1350
Average	\$1315		

*Company No. 1 estimates

Continued improvements in engine, vehicle container, and refueling station design and performance are expected. A well managed systems engineering approach would assure that an optimum vehicle, engine, storage tank, refueling, distribution, and production system develops.

Plans are in progress at LASL to install the aluminum DFVLR tank in a vehicle for operation on liquid hydrogen using presently available hardware and technology in a baseline hydrogen program that would provide a reference baseline for evaluation and comparison of future vehicles.

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