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REFUELING SYSTEM 2

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OPERATING EXPERIENCE WITH A LIQUID-HYDROGEN FUELED BUICK AND REFUELING SYSTEM¹

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ABSTRACT

An investigation of liquid-hydrogen storage and refueling systems for vehicular applications was made in a recently completed project. The vehicle used in the project was a 1979 Buick Century sedan with a 3.8-L displacement turbocharged V6 engine and an automatic transmission. The vehicle had a fuel economy for driving in the high altitude Los Alamos area that was equivalent to 2.4 km/L of liquid hydrogen or 8.9 km/L of gasoline on an equivalent energy basis. About 22% less energy was required using hydrogen rather than gasoline to go a given distance based on the Environmental Protection Agency estimate of 7.2 km/L of gasoline for this vehicle. At the end of the project the engine had been operated for 138 hours and the car driven 3633 km during the 17 months that the vehicle was operated on hydrogen. Two types of onboard liquid-hydrogen storage tanks were tested in the vehicle: the first was an aluminum Dewar with a liquid-hydrogen capacity of 110 L; the second was a Dewar with an aluminum outer vessel, two copper vapor-cooled thermal radiation shields, and a stainless steel inner vessel with a liquid-hydrogen capacity of 155 L. The Buick had an unrefueled range of about 274 km with the first liquid-hydrogen tank and about 362 km with the second. The Buick was fueled at least 65 times involving a minimum of 8.1 kL of liquid hydrogen using various liquid-hydrogen storage Dewars at Los Alamos and a semiautomatic refueling station. A refueling time of nine minutes was achieved, and liquid-hydrogen losses during refueling were measured. The project has demonstrated that liquid-hydrogen storage onboard a vehicle, and its refueling, can be accomplished over an extended period without any major difficulties; nevertheless, appropriate testing is still needed to quantitatively address the question of safety for liquid-hydrogen storage onboard a vehicle.

KEYWORDS

Liquid hydrogen; hydrogen-fueled highway vehicles; alternative transportation fuel; cryogenic containers; hydrogen fuel; liquid-hydrogen refueling; liquid-hydrogen onboard storage.

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INTRODUCTION

With funding from the Office of Vehicle and Engine Research and Development of the U.S. Department of Energy (DOE), the Los Alamos National Laboratory has conducted a 2-1/2 year baseline experimental vehicle project to evaluate and document representative state-of-the-art capabilities in engine conversion for hydrogen operation, liquid-hydrogen onboard storage, and liquid-hydrogen refueling. The project was accomplished as a part of the Alternative Fuels Utilization Program of the DOE (Anon., 1978). The primary emphasis of the project was on the liquid-hydrogen onboard storage and refueling; the engine conversion and vehicle performance and operation was secondary. The major objectives of the project included:

- o investigate the problems involved in the onboard storage of liquid-hydrogen;
- o investigate the problems involved in fueling vehicles with liquid-hydrogen;
- o develop a liquid-hydrogen refueling system that can be operated by personnel with minimal special training;
- o develop an automobile of conventional appearance and performance operating on liquid hydrogen;
- o provide a baseline vehicle using state-of-the-art equipment with which to compare and evaluate future improvements in vehicle performance, liquid-hydrogen storage systems, other hydrogen storage methods, and other synthetic fuels storage methods; and
- o provide a general background of information on liquid-hydrogen onboard storage and refueling for other projects (such as busses, trucks, or trains) involving liquid hydrogen.

Numerous studies (Escher, 1979; Donnelly and colleagues, 1979) have recognized the onboard storage of hydrogen is a major obstacle in the use of hydrogen as a transportation fuel as exemplified by the following quotation from Bidwell (1978): "The most significant deterrent to the use of hydrogen for vehicular energy is the onboard storage problem." The need for additional work on the refueling aspects of the use of hydrogen as a fuel, especially for liquid hydrogen, has also been recognized. In addition to the Laboratory and the DOE, this cooperative project also involved the joint efforts of the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) of the Federal Republic of Germany, and the State of New Mexico through the New Mexico Energy Institute (NMEI). The NMEI provided the vehicle, a 1979 Buick Century sedan, for the project. The DFVLR provided the first liquid-hydrogen tank and a semiautomatic refueling station. The DFVLR and Los Alamos jointly designed and fabricated the second liquid-hydrogen tank used in the project. Project management and coordination was provided by the Laboratory. The Laboratory also installed the liquid-hydrogen tanks and ancillary equipment in the car and made road tests of the vehicle. The initial vehicle and engine modifications for operation on hydrogen rather than gasoline were subcontracted by the Laboratory to the Billings Energy Corporation (BEC).

ONBOARD LIQUID-HYDROGEN STORAGE AND ENGINE FUEL DELIVERY SYSTEM

Previous programs involving the onboard storage of liquid hydrogen have used various types of containers; some used commercially available, laboratory type Dewars; others adapted liquefied natural gas tanks; and some used containers that were designed specifically for the project (Stewart, 1980). The need for additional efforts to develop a satisfactory onboard liquid-hydrogen storage system that is integrated with the engine fuel system has been recognized and recommended (Escher, 1975). The use of a readily available Dewar which had been designed specifically for automotive use permitted a direct evaluation and documentation of the state-of-the-art capabilities in onboard liquid-hydrogen storage. The fabrication of a Dewar specifically for this project provided the

opportunity for an improved Dewar to be included in the evaluation and documentation efforts.

Liquid-Hydrogen Onboard Storage Tank A

When this project began, the DFVLR had already built and had made some limited tests of a vehicle liquid-hydrogen Dewar (VLHD) for a project that did not materialize. Consequently, the DFVLR was willing to provide the Dewar for this project although its particular shape was not necessarily optimum for the vehicle used in the project. This tank has been referred to as DFVLR tank II in many previous references; in this report it will be referred to as VLHD-A. The design of VLHD-A was based on the experience gained by the DFVLR in the design, fabrication, and testing of a previous Dewar for vehicular applications (Escher, 1975; Peschka and Carpetis, 1976). The VLHD-A was a conventional dual-shell Dewar vessel as described in detail previously (Escher, 1979; Peschka, 1980; Peschka and Carpetis, 1980; Peschka, Edeskuty, and Stewart, 1980; Stewart, 1980; Stewart and Escher, 1981). The VLHD-A is shown installed in the trunk of the experimental vehicle in Fig. 1 and its major features are summarized in Table 1 with a limited comparison with the vehicle's original gasoline tank.

Engine Fuel Delivery System for VLHD-A

The hydrogen delivery system included components (such as solenoid valves, relief valves, manually operated valves, and instrumentation) for the transfer of hydrogen from the VLHD-A to the engine, and for other needs such as hydrogen venting. A schematic of the engine fuel delivery system for VLHD-A is shown in Fig. 2; some of its components can be seen in Fig. 1 on the top rear part of the tank as it was installed in the car. An indicator/controller, provided by the DFVLR, was installed in the vehicle for access by the driver to give an indication of the liquid level and the pressure in the VLHD-A, and to control solenoid valves SV1, SV2, and SV3. Hydrogen for the engine was withdrawn from VLHD-A from either the liquid or the gaseous phase depending on the pressure within the tank. The VLHD-A pressure (and thus, the Fisher regulator inlet pressure at the engine) could be increased during driving by adjusting the controls for solenoid valves SV1 and SV2 on the indicator/controller. The cold, 20 K, hydrogen (gas or liquid) removed from the VLHD-A was warmed in a heat exchanger (using hot water from the engine cooling system) before it was delivered to the engine. Hydrogen could be vented from the system manually, remotely (through SV3 operated by the indicator/controller), or automatically through the various relief valves in the system if the pressure exceeded the preset value for the relief valves. The hydrogen gas was vented through a line at the rear of the vehicle. When a significant amount of hydrogen was to be vented this line was connected to a vent stack to disperse the hydrogen safely.

Operational Difficulties Encountered with VLHD-A

One of the main operational difficulties encountered with the VLHD-A involved the integral water/hydrogen heat exchanger: water in the heat exchanger would freeze during several conditions at one extreme, and the hydrogen would be overheated at the other extreme. The only way to vent hydrogen from the tank, other than through the gaseous-hydrogen return bayonet, was through the heat exchanger and if the engine was not running at least at a fast idle, the cold hydrogen gas being vented would freeze all of the water/ethylene glycol mixture in the heat exchanger. This condition was not desirable because the expansion of the water/ethylene glycol

Fig. 1. VLHD-A and engine fuel delivery system components installed in the trunk of the experimental vehicle.

Fig. 2. VLHD-A engine fuel delivery system schematic.

mixture could have caused a leak to develop, also the vehicle could not be operated until the frozen water/ethylene glycol mixture melted--a very slow process. Situations also arose in which the water/glycol mixture would freeze while the vehicle was being driven. When this happened very cold hydrogen gas was delivered to the engine; an unsatisfactory condition because the Fisher regulator, the Impco gas mixer, and various other parts in the engine fuel systems were not designed for such low temperatures. The water flow to the heat exchanger could not be in parallel with the heater because most of the flow would pass through the heater resulting in an insufficient flow through the heat exchanger to prevent freezing of the water/ethylene glycol mixture. It is also possible that an insulating layer of ice was formed around the liquid-hydrogen line so that the hydrogen was not warmed as it should have been during prolonged operation in the liquid-hydrogen withdrawal mode. At the other extreme, when the water flow to the heat exchanger was unrestricted, the hydrogen was overheated and was delivered to the engine at a temperature much higher than desired. This would affect the vehicle's performance because the hydrogen would be less dense at the higher temperature reducing the energy content per intake stroke. A control valve was installed in the water line with its control sensor installed in the hydrogen line at the engine in an attempt to control the water flowrate to maintain a constant hydrogen temperature at the engine. However, this effort was not very successful because the valve did not provide the minimum flow rate under all conditions to prevent freezing of the water/ethylene glycol mixture.

Another difficulty involved the lack of a bypass valve to permit the liquid-hydrogen fill line to be cooled down without flowing warm hydrogen gas through a cold tank and vaporizing some part of any liquid hydrogen remaining in the tank at the start of a refueling operation.

The VLHD-A did not have any internal means of increasing the pressure in the tank. This made it difficult to obtain operating pressure under certain circumstances such as when the tank was only partially full and had been vented to ambient pressure.

Liquid-Hydrogen Onboard Storage Tank B

The second vehicle liquid-hydrogen Dewar (VLHD-B) used in the project was built jointly by the DFVLR and Los Alamos to overcome some of the disadvantages (such as the high heat leak into the liquid hydrogen) of the first Dewar, and to incorporate more advanced cryogenic engineering techniques. The VLHD-B was a cylindrical, dual-shell Dewar vessel with two gas-cooled copper thermal radiation shields as shown in Fig. 3 and described previously by Peschka, Idecky, and Stewart (1980). Heat leak into the inner vessel caused the liquid hydrogen to boil; the cold hydrogen gas generated by this boiling was used to cool the two copper thermal radiation shields which reduced the heat leak into the inner vessel. The VLHD-B is shown installed in the trunk of the experimental vehicle in Fig. 4 and its major features are summarized in Table I.

Engine Fuel Delivery System for VLHD-B

The hydrogen delivery system from the tank to the engine included components (such as solenoid valves, relief valves, manually operated valves, and instrumentation) for the transfer of hydrogen from the VLHD-B to the engine, and for other needs such as hydrogen venting. A schematic of the engine fuel delivery system for VLHD-B is shown in Fig. 5 and many of the components in the system are shown in

Fig. 6. The indicator/controller (provided by the DFVLR) for indicating the VLHD-B liquid level and pressure, controlling solenoid valves SV1 and SV2, and controlling the heaters in the tank is shown installed in the car for access by the driver in Fig. 7. The cold, 20 K, hydrogen (gas or liquid) removed from the VLHD-B was warmed (using ambient air) in the fin-tube heat exchanger shown in Fig. 6 before it was delivered to the engine. Therefore, the hydrogen temperature at the engine was always less than the ambient air temperature. During normal operation with an ambient temperature of 283 K, the hydrogen temperature at the outlet of the heat exchanger was about 240 K, but under continuous, heavy engine loading (climbing a long steep hill, for example) the temperature dropped to 180 K.

TABLE 1 Summary of VLHD Features

	<u>VLHD-A</u>	<u>VLHD-B</u>	<u>Original Gasoline Tank</u>
Outside diameter, m	0.9	0.712	---
Overall length, m	0.66 ^a	1.22 ^b	---
Empty weight, kg	83.6	156.4	13.6
Filled weight, kg	91.8	167	63.0
Maximum working pressure, kPa absolute	448	448	---
Liquid volume, L	110	155	68.5
Energy stored, GJ	0.97	1.30	2.2
Heat leak, W	4	?	---
Boiloff rate, %/day	10 ^c	4 ^c	---
Loss rate for vented tank, L/day	11	6.2	---
Pressure build-up rate, kPa/h	21 - 45.5 ^d	4.3 - 4.6 ^d	---
Lock-up time, h	10 - 21 ^d	45 - 48 ^{d,e}	---
Volumetric efficiency	0.35	0.42	---

^aVertical.

^bHorizontal.

^cBased on the total liquid volume of 110 L for VLHD-A or 155 L for VLHD-B.

^dDepends upon the liquid-level in the VLHD.

^eFor a pressure of 310 kPa absolute. About 60 h could be obtained by using the maximum working pressure of 448 kPa absolute.

Operational Difficulties Encountered with VLHD-B

One difficulty encountered with the VLHD-B was that the liquid-hydrogen fill, gaseous-hydrogen return, and bypass valves tended to freeze in the open position during refueling. The reason for these valves freezing is not known; they worked satisfactorily when tested with liquid nitrogen at the DFVLR before their use in the Dewar. Another difficulty encountered was that the hydrogen/air heat exchanger had insufficient heat transfer because under prolonged operation of the vehicle at full load the hydrogen temperature at the engine was lower than desired.

Fig. 3. Cross-section of VLHD-B.

Fig. 4. VLHD-B installed in the trunk of the experimental vehicle.

Fig. 5. VLHB-B engine fuel delivery system schematic.

Fig. 6. VLHB-B and engine fuel delivery system components.

for this engine conversion. Two other difficulties experienced involved the indicator/controller: the pressure and liquid level LCD was difficult to read in bright light; and, the capacitive liquid-level circuit was very temperature sensitive so that ambient temperature changes during the day cause a considerable change in the liquid-level indication. However, the liquid level indication was reasonably steady while the vehicle was in motion and did not seem to be adversely affected by fuel sloshing.

Improvements Possible in the VLHDs and Engine Fuel Delivery Systems

Many of the possible improvements in the VLHD-A were incorporated in the VLHD-B; including an increased liquid-hydrogen capacity, a lower heat leak, an internal heater, and a heat exchanger which was separate from the tank and would not freeze. Improvements that are possible in the VLHD-B include:

- o relocate the bypass valve connections;
- o correct the valve freezing problem;
- o reduce the tank weight;
- o increase the heat exchanger heat transfer;
- o revise the liquid-level indicator circuit to make it less temperature sensitive; and
- o replace the pressure and liquid level LCD with one that is more readable.

The preferred location for the bypass valve connections to the fill and return lines is between the bayonets and the fill and return valves, and not its actual location between the fill and return valves and the tank (see Fig. 3) which was imposed by space limitations within the valve chamber. The freezing problem with the liquid-hydrogen fill valve, gaseous-hydrogen return valve, and the bypass valve can be eliminated. The manual valves could be replaced with solenoid valves which would simplify the plumbing inside the valve chamber. A liquid sensor could be located in the gaseous hydrogen return line such that liquid could be detected during cooldown for refueling, and when the tank was full.

Fig. 7. VLHD-B indicator/controller installed in the car.

The weight of the VLHD-B could be reduced by 52.6 kg by using an aluminum alloy instead of stainless steel for the inner vessel and instead of copper for the thermal radiation shields. It may also be possible to eliminate one of the thermal radiation shields without affecting the heat leak into the liquid hydrogen and reduce the weight by 22.3 kg for a copper, or 6.8 kg for an aluminum, outer shield.

The liquid-level circuit could be improved by using a less temperature sensitive reference capacitor in the circuit.

The heat transfer capability of the hydrogen/air heat exchanger could be increased by adding an air blower or more sections of the heat exchanger tubing, but a more significant improvement would be to use the refrigeration capacity of the liquid hydrogen in a beneficial manner (for examples: air conditioning; cool the intake air; and cool the turbocharger discharge to the intake manifold).

An improved method for hydrogen venting is also possible by venting the hydrogen through a catalytic converter or a burner (in which the hydrogen is reacted with oxygen to form water), or through a mixer in which the hydrogen is mixed with sufficient air so that the mixture is below the combustible limit. The mixer type vent is used in some applications (Foster and Escher, 1976) but would not be appropriate for a vehicle that would be parked in an enclosed space because of the potential for the hydrogen concentration to increase to the combustible level. The catalytic converter systems that are presently available have been found to be unreliable (Peschka, 1981; Woolley and Davis, 1979). A preferable improvement would be to collect any vented hydrogen (in a metal hydride tank, for example) for use later, or to use the hydrogen in a beneficial manner [for example, to operate a fuel cell which could replace the alternator (Peschka, 1981; Stewart and Eades, 1974)].

The volumetric efficiency of the two tanks (0.35 and 0.42 for VLHD-A and VLHD-B, respectively) could probably be increased. The spherical tank used in an earlier project at Los Alamos (Stewart and colleagues, 1975) had a volumetric efficiency of about 0.55.

Many of the components in the engine fuel delivery systems were installed to provide more operational flexibility and control in this experimental project; these components could be eliminated to provide a simpler, less expensive system for nonexperimental applications. Likewise, both the size of the control unit and the number of controls could be reduced and the unit installed in the vehicle's instrumentation console.

LIQUID-HYDROGEN REFUELING

DFVLR/Los Alamos Liquid-Hydrogen Refueling System

Most of the projects involved in the use of liquid hydrogen as a fuel, summarized by Stewart (1980), used or adapted commercially available components with makeshift systems or methods for refueling the VLHD onboard their vehicle. The DFVLR was the first to build a special system for vehicle refueling. The DFVLR has built two semiautomatic refueling stations which were designed to be operated by personnel with little or no special training: the first (unit 1) for use in their program and the second (unit 2) for use in the joint DFVLR/Los Alamos project.

The DFVLR refueling concept has been described in detail previously (Escher, 1979; Peschka, 1980; Peschka and Carpetis, 1980; Peschka, Edeskuty, and Stewart, 1980; Stewart and Escher, 1981) but only the unit 2 refueling station (U2RS) was used in the joint DFVLR/Los Alamos project.

A typical arrangement for refueling using the U2RS is shown in Fig. 8 where the U2RS is shown connected to a 500-L bulk liquid-hydrogen storage Dewar (BLHSD) and to the VLHD by the appropriate transfer lines. The U2RS was used with any of several different BLHSDs at Los Alamos to fill the VLHD in the experimental vehicle. The BLHSDs could be connected directly to the VLHD, and liquid-hydrogen refueling could be accomplished without the U2RS; in fact, this arrangement was used extensively because of the lower liquid-hydrogen losses. A typical refueling operation using the U2RS has been described in detail previously (Peschka, Edeskuty, and Stewart, 1980; Stewart and Escher, 1981).

Refueling Performance and Operating Experience

A series of tests was conducted to determine the extent of the liquid hydrogen losses that occur during a refueling operation, and to determine optimum conditions and transfer procedures using various arrangements of the VLHD-A (before it was installed in the vehicle), various BLHSDs, and the U2RS. Tests were made both with and without the U2RS. In these transfer tests the pressure in the BLHSD was varied from 22.7 to 172.4 kPa gauge. The corresponding transfer times ranged from 45 to 9 minutes to fill the VLHD-A with corresponding liquid-hydrogen transfer rates from 1.8 to 14.5 g/s. During these tests the most efficient transfer to a cold VLHD-A involved a liquid-hydrogen loss of 9.1 L for a refueling efficiency of 92% without the U2RS. With the U2RS the liquid-hydrogen loss was 15.7 L for an efficiency of 88%. For a warm VLHD-A and with the U2RS the liquid hydrogen loss was 30 L and the refueling efficiency was 79%. The VLHD-B was refueled without the U2RS with an efficiency of about 91% for a cold VLHD-B and about 79% for a warm VLHD-B. The refueling time and losses achieved during these tests have been described previously (Peschka, Edeskuty, and Stewart, 1980). Although several possibilities for reducing these losses were identified (such as

Fig. 8. Refueling operation with a 500-L BLHSD.

reducing the heat leak) the major losses appear to be from such miscellaneous factors as flashing and these factors should be examined in greater detail to determine how these losses could be reduced. A total transfer time of five minutes appears to be possible with a properly designed system without requiring a high storage tank pressure nor a liquid-hydrogen pump. The vehicle was refueled with liquid hydrogen at least 65 times, including some at locations away from Los Alamos such as Albuquerque, New Mexico and Independence, Missouri. A total of at least 8.1 kL of liquid hydrogen were involved in the total refueling operations.

VEHICLE

A 1979 Buick Century four-door sedan (Fig. 9) with a 3.8-L displacement turbo-charged V6 engine, an automatic transmission, and air conditioning was provided for the project by the NMEI. The engine conversion involved hydrogen and water induction to the engine; hydrogen through an Impco gas mixer, and water (for backfire and NO_x control) through the stock gasoline fuel pump and carburetor. Modifications to the vehicle and the engine have been described in detail previously (Peschka, Edeskuty, and Stewart, 1980; Stewart and Escher, 1981). The vehicle was operated on hydrogen as a fuel for 17 months. The engine was operated for 138 hours and the car driven a distance of 3633 km on hydrogen without any major difficulty. The vehicle had a fuel economy for driving in the high altitude Los Alamos area that was equivalent to 2.4 km/L of liquid hydrogen or 8.9 km/L of gasoline on an equivalent energy basis. About 22% less energy was required using hydrogen rather than gasoline to go a given distance based on the Environmental Protection Agency estimate of 7.2 km/L of gasoline for this vehicle. The vehicle experienced an occasional backfire during its operation; this occurred most frequently when starting the engine. The characteristics, performance and operation of the vehicle on hydrogen are summarized and compared with gasoline in Table 2.

Although an increase in fuel economy was achieved, the vehicle had less power operating on hydrogen than it did on gasoline² as shown by an increase in the time required to accelerate from 0 to 80.5 km/h. The acceleration data (speed as a function of time) for various configurations and conditions in which the vehicle was tested are shown in Fig. 10. In Independence, Missouri (elevation 229 m) the 0 to 80.5 km/h acceleration time was about 16.8 s (point 5, Fig. 10), compared to 24.8 s (end point of curve 3) in Los Alamos, New Mexico (elevation 2225 m)--about twice the acceleration time expected when operating on gasoline. As shown by curves 1 and 3 of Fig. 10, the turbocharger, although not properly sized for operating on hydrogen,³ did provide some additional power which reduced the 0 to

²An overall loss of power results when gasoline-fueled engines are converted to aspirated gaseous fuels because of the air-charge displacement by a gaseous fuel with less energy per unit volume than a liquid fuel. This loss of power is about 5-10% for LPG and natural gas and about 20% for hydrogen. There are several ways that this loss of power can be averted but these were beyond the scope of this project since the project did not involve attempting to advance the state-of-the-art in engine conversion.

³The stock turbocharger on the engine was not changed, and as a result of its not being properly sized for hydrogen, a maximum boost pressure of 13.6 kPa gage at Los Alamos, and 34.5 kPa gage at Independence, Missouri was achieved; a maximum boost pressure of 65.5 kPa gage is possible when gasoline is used as the fuel. A slight increase in the turbocharger boost pressure was obtained with the addition of ethanol, about 22% by volume, to the water induction system to prevent freezing during the winter.

TABLE 2 Summary of Vehicle Characteristics, Performance, and
Operation on Liquid Hydrogen

	<u>Hydrogen</u>	<u>Gasoline</u>
0 to 80.5 km/h acceleration time, s	16.8 ^a , 24.8 ^b	14.4 ^c
Fuel economy, km/L	2.42 ^d	7.23 ^e
gasoline equivalent, km/L	8.93 ^f	
NO _x production, g/km	0.04, 3.79	0.37 - 0.5 ^h
Maximum range, km	274, 362 ^{d, i}	483
Curb weight, kg	1610, 1715 ⁱ	1520
Total distance driven on hydrogen, km	3633	--
Water use, km/L	9.1	--

^a In Independence, Missouri (elevation 229 m).

^b In Los Alamos, New Mexico (elevation 2225 m).

^c At Los Alamos in a similarly equipped Buick Regal.

^d Open-road driving around Los Alamos, Santa Fe, and Albuquerque.

^e Environmental Protection Agency estimate.

^f On an equivalent energy per distance basis.

^g At idle and full load, not an average value over a standard driving cycle.

^h Data provided by manufacturer for the average achieved in operation over a standard driving cycle.

ⁱ VLHD-A and VLHD-B respectively.

80.5 km/h acceleration time from 31.8 s without the turbocharger to 24.8 s with the turbocharger. The 0 to 80.5 km/h acceleration time was about 19.8 s in operation with the turbocharger and an ethanol/water mix in the water induction system. The effect of a higher VLHD pressure is shown by point 2 and the end point of curve 3; increasing the VLHD pressure from about 100 kPa absolute to 240 kPa absolute decreased the 0 to 80.5 km/h acceleration time by 3.2 s (from 28 s to 24.8 s). Acceleration tests were made on a similarly equipped 1978 Buick Regal Sports Coupe (turbocharged 3.8-L V6 engine and a weight of 1556 kg) for comparison with the hydrogen-fueled Buick Century. The gasoline-fueled Buick Regal was able to accelerate from 0 to 80.5 km/h in 14.4 s (point 6, Fig. 10) in contrast to the 24.8 s acceleration time for the hydrogen-fueled Buick Century with a weight of 1610 kg. According to manufacturer's data, the experimental vehicle should have had a 0 to 96.5 km/h acceleration time of about 12.4 s (point 7, Fig. 10) at sea level.

Instrumentation was installed in the engine fuel delivery system to determine its operating characteristics during various driving situations. Pressure transducers were installed to indicate the Dewar pressure, the Fisher regulator inlet pressure, and the Fisher regulator outlet pressure (the Impco gas mixer inlet pressure), and a Hastings mass flowmeter was installed downstream of the hydrogen shut-off valve to monitor the hydrogen flow. Data were obtained for three modes of operation:

- o driving at constant speeds from 32.2 to 80.5 km/h over several roads in Los Alamos;
- o acceleration from 0 to 80.5 km/h; and
- o steady grade hill climb in which the engine was maintained fully loaded long enough to develop and sustain its peak power.

During these three modes of operation, data were obtained under different ambient conditions and with various pressures in the VLHD-A (none of these tests were made with VLHD-B).

During the constant speed tests the pressure drop from VLHD-A to the Fisher regulator inlet varied from 4.1 to 9.7 kPa with VLHD-A pressures ranging from 42.7 to 206.8 kPa gage and hydrogen flowrates⁴ ranging from 4.48 to 10.1 dm³/s. The Fisher regulator outlet pressure varied from 1.04 to 1.49 kPa gage during these tests. The hydrogen flowrate data are shown in Fig. 11 as a function of the vehicle speed. The average of the flowrate values for uphill and downhill driving is shown by the solid line in Fig. 11. An extrapolation of this line to higher and lower vehicle speeds is shown by the dashed extensions of the solid line. The energy use (determined from the hydrogen flowrate) as a function of the constant vehicle speed is shown in Fig. 12.

During the acceleration tests from 0 to 80.5 km/h the pressure drop from the VLHD-A to the Fisher regulator inlet varied from 2.76 to 18.6 kPa with VLHD-A pressures ranging from 46.2 to 137.9 kPa gage and hydrogen flowrates⁴ from 3.73 to 20.63 dm³/s. The Fisher regulator output pressure varied from less than 0 to 1.48 kPa gage during these tests. The chart recordings for a typical acceleration test with an almost constant VLHD-A pressure is shown in Fig. 13. The pertinent data from Fig. 13 are summarized in Table 3. The VLHD-A pressure was maintained by solenoid valves SV1 and SV2 (see Fig. 3) automatically switching the hydrogen flow from the liquid and gaseous phases to maintain an almost constant VLHD-A pressure. Although the Fisher regulator inlet pressure was relatively constant as the hydrogen flowrate rapidly increased from Point A to B (see Fig. 13), the regulator outlet pressure dropped considerably, in fact, when the regulator inlet

⁴Referenced to a temperature and pressure of 293 K and 101.3 kPa absolute. Values above 11.8 dm³/s are extrapolated.

Fig. 10. Speed as a function of time for the test vehicle.
Curve 1 -- without turbocharger and Dewar pressure ~ 240 kPa.
Point 2 -- with turbocharger and Dewar pressure ~ 100 kPa.
Curve 3 -- with turbocharger and Dewar pressure ~ 240 kPa.
Curve 4 -- with turbocharger and ethanol in water.
Point 5 -- with turbocharger in Independence, Missouri.
Point 6 -- similarly equipped Buick Regal in Los Alamos.
Point 7 -- manufacturer's data for Buick Century with turbocharger at sea level.

Fig. 11. Hydrogen flowrate as a function of the constant vehicle speed. The solid triangles indicate data taken on the road near the Los Alamos airport (the most level road available).

Fig. 12. Energy use as a function of the constant vehicle speed.

Fig. 13. Hydrogen pressure and flow data for acceleration from 0 to 80.5 km/h with an almost constant VLHD-A pressure of 134.4 kPa gage during the downhill test and about 120.7 kPa gage during the uphill test. Point A is the starting point (0 km/h); the Buick automatically shifted from first to second gear at Point B; and, the acceleration test was terminated when a speed of 80.5 km/h was reached at Point C.

pressure was less than about 68.9 kPa gage at Point A, the regulator outlet pressure dropped to 0 kPa gage, or less, when the hydrogen flowrate was high. The time from point A to C was 28 s (downhill) and 35.7 s (uphill) for an average time of 31.9 s for the test shown in Fig. 13.

Flow and pressure data were taken while accelerating the experimental vehicle from a standing start up a long steady grade of about 5.7% in first gear to maintain the engine fully loaded long enough to develop and sustain its peak power. During these tests the pressure drop from VLHD-A to the Fisher regulator inlet varied from 2.8 to 19.3 kPa with VLHD-A pressures ranging from 37.9 to 236.5 kPa gage and hydrogen flowrates⁴ from 3.45 to 20.53 dm³/s. The Fisher regulator output pressure varied from less than 0 to 1.59 kPa gage during these tests. A typical chart recording of the data for the hill climb tests is shown in Fig. 14. The pertinent data from Fig. 14 are summarized in Table 3. The hill climb test was started at an elevation of about 2280 m and was stopped at about 2353 m; a climb of about 73 m in a distance of about 1290 m.

The effect of the automatic switching of solenoid valves SV1 and SV2 to remove hydrogen from the gaseous or liquid phases to maintain the desired VLHD-A pressure is shown in Fig. 14. A considerable oscillation in the Fisher regulator inlet and outlet pressures developed whenever liquid hydrogen was taken from VLHD-A (i.e., when solenoid valve SV2 was open and SV1 was closed). As shown in Fig. 14, the VLHD-A pressure and the Fisher regulator inlet pressure could be increased during driving by adjusting the controls for solenoid valves SV1 and SV2.

The data from the acceleration and hill climb tests show that the Fisher regulator outlet pressure dropped drastically under conditions requiring a high hydrogen flowrate, but this could have been due partially to the location and manner in which the pressure measurement was made. A drop in the regulator outlet pressure during high hydrogen flowrates would result in a drop in the hydrogen pressure at the Impeco gas mixer and cause the fuel/air mixture to become lean which would reduce the maximum output power.

The pressure drop from the VLHD-A to the regulator inlet (less than 20.7 kPa) was not significant except at low VLHD-A pressures (less than about 68.9 kPa gage).

Because of the concern over the potential for water/oil emulsions and possible corrosive acid formation in the engine, the oil was changed and analyzed several times in the beginning of the project. A standard 10W-40 grade oil was used in the engine. The first oil sample, taken shortly after operation on hydrogen began, appeared very black in color. One part of this oil sample was ashed in a muffle furnace and an emission spectrographic analysis made of the ash at Los Alamos, and a standard commercial oil analysis was made on the other part of the sample by a commercial company in Albuquerque. Most noticeable in the Los Alamos analysis was a significant amount of extremely fine black particulate matter made of particles which measured about 3 μ m on a photomicrograph. Most of this material burned away at an elevated temperature and, thus, was believed to be carbon black; probably a result of the carbon build-up in the engine from its initial operation on gasoline. The vehicle had been driven about 7080 km on gasoline before its conversion to hydrogen. The standard commercial analysis revealed excessive wear which was attributed primarily to silicon (possibly from dirt), and a 5% water content in the oil. The next three oil samples were taken after a crankcase ventilation system had been installed by BEC, after the engine had been operated for 25 h and the vehicle driven 665 km in Los Alamos. These

TABLE 3 Typical Acceleration and Hill Climb Test Data

	Hydrogen Flowrate ⁴ (dm ³ /s)	Dewar Pressure (kPa)	Regulator Pressure	
			Inlet (kPa)	Outlet (kPa)
Acceleration Test (Fig. 22)				
Downhill				
Point A	5.19	116.5	110.3	1.35
Point B	20.0	123.4	105.5	0.24
Point C	16.9	123.4	112.4	0.72
Uphill				
Point A	4.39	135.1	128.2	1.47
Point B	20.6	131.0	114.5	0.20
Point C	16.7	133.1	119.3	0.69
Hill Climb Test (Fig. 23)				
Point A	3.45	124.1	121.3	1.48
Point B	20.5	153.1	140.7	0.39
Point C	14.2	105.5	93.8	0.47

Fig. 14. Hydrogen pressure and flow data for a hill climb test with a decreasing, then an increasing, VLHD-A pressure. Point A is the starting point (0 km/h); Point B is the termination of the test near the top of the hill; Point C is the switchover from gaseous-hydrogen to liquid-hydrogen withdrawal from the VLHD-A.

three samples were analyzed only by the commercial company in Albuquerque. A 1% water content was reported in the first analysis, but none in the second or third. The common wear indicators (iron, chrome, lead, etc.) were such that no unusual or excessive wear was indicated in the analyses of these three samples. Consequently, no additional oil samples were taken for analysis and the oil change frequency was increased to the normal manufacturer's recommendation.

After the engine had been operated on hydrogen for 25 h and the vehicle driven 665 km in Los Alamos, the Impco gas mixer and the Rochester carburetor were removed to inspect for corrosion and to seal the idle jets in the Rochester carburetor so that no water would be used when the engine was idling. Some evidence of corrosion (such as rusty screws) was found in the Rochester carburetor, but more significantly, melted metal around the two venturi and on the top of the carburetor was found as shown in Fig. 15. This melted metal indicated that a fire had occurred in the carburetor. Consequently, the turbocharger was disassembled and the compressor turbine was found damaged. The leading edges of the turbine blades were very rough (bent, dented, and pitted). This damage was even more extensive than that found again later in the project and shown in Fig. 16. Although this damage to the turbocharger could have been caused by molten metal parts from the Rochester carburetor, it is more likely that the damage was caused by water droplets from the water induction system. Also at this time both rocker-arm covers were removed and a heavy, white, cream-like substance was found inside both covers as shown in Fig. 17, but it was more extensive in the left cover (which had had a port open to the air). This substance was thought to be a water-oil emulsion. A small quantity of water was found inside both covers. A litmus paper test of the water gave a pH of 6.5, just slightly acidic. Water and some minor rusting of the heads was found as shown in Fig. 17. At the end of the project, the left rocker-arm cover was removed again; but no water, rusting, or any of the cream-like substance was found on the left head or the rocker-arm cover as shown in Fig. 18.

SUMMARY OF MAJOR ACHIEVEMENTS

Most of the major objectives of the project were accomplished; however, several of the less important objectives were only partially completed. The failure to achieve a satisfactory vehicle acceleration capability was disappointing and in some cases this lack of performance did detract attention from the major objectives and accomplishments of the project. Another disappointment was that engine backfiring was never completely eliminated. Major achievements of the project include the following.

- o A documented (with technical data) baseline vehicle was established.
- o A liquid-hydrogen-fueled mid-size sedan was operated for 17 months and was driven for 3633 km on public roads.
- o Two different types of liquid-hydrogen onboard storage tanks were tested under actual on-the-road, operating conditions.
- o Refueling of the vehicle was accomplished more than 65 times involving a minimum of 8.1 kL of liquid hydrogen.
- o Data on refueling time and efficiency (or losses) were obtained.
- o Data on vehicle performance and efficiency were obtained.

RECOMMENDATIONS

The following recommendations are based on the experience gained during this program.

- o A fully integrated liquid-hydrogen bulk storage, refueling, and onboard storage system should be fabricated and tested. This should be a completely

Fig. 15. Rochester carburetor damage.

Fig. 16. Damaged turbocharger blades (scale is cm).

Fig. 17. Head, rocker arm, and rocker-arm cover with white, cream-like substance inside the rocker-arm cover.

Fig. 18. Left head, rocker arm, and rocker-arm cover at the end of the project.

automated system with it only necessary for the operator to connect the transfer lines and an electrical connector, to push a "start" button, and to disconnect the transfer lines and electrical connector when the refueling process is completed. The refueling system should incorporate the latest cryogenic engineering technology to minimize losses during refueling. Some of the remaining refueling problems include the lack of a suitable mass flowmeter for determining quantity of hydrogen transferred to the VLH, a system that will minimize liquid hydrogen loss from cooling warm transfer lines, and a system that will prevent contamination and ice buildup in the transfer lines because of the lines being open to the atmosphere while still cold.

- o The very latest in cryogenic engineering technology should be applied in the fabrication of an onboard liquid-hydrogen storage tank to produce a tank that is rugged, has a low heat leak, is lightweight, and can be mass produced at a cost which is not prohibitive.
- o A method for safely disposing of any vented hydrogen must be developed. During this project hydrogen was vented to the atmosphere (through a vent-stack whenever possible), but this was not always satisfactory, and definitely would not be a satisfactory method of hydrogen disposal for a hydrogen-fueled vehicle in public use. A catalytic converter (or some such device) is needed to eliminate the release of hydrogen to the atmosphere when a tank is vented either deliberately or after it has reached its maximum operating pressure.

The three most frequently made comments regarding the experimental vehicle were: (1) "where do you carry the luggage?"; (2) "is this safe?"; and (3) "it doesn't have much power." Consequently, three additional recommendations are made.

- o A vehicle incorporating a liquid-hydrogen tank be designed with the tank packaged as safely and unobtrusively as possible.
- o A safety assessment and testing program (including crash tests of hydrogen storage tanks) be conducted to ascertain that liquid-hydrogen can be safely transferred and stored onboard a vehicle.
- o An engine development program be pursued to eliminate backfiring and provide an output power equivalent to that achieved with gasoline fuel. Although engine development was not part of this program, the lackluster performance of the engine was a negative influence on how hydrogen as a fuel was perceived by those who drove the vehicle.

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(A) MAN. AIR VALVE	(C) PRESSURE GAUGE
(B) SAFETY RELIEF VALVE	(D) THERM. VALVE
(E) SOL. (SOL) VALVE	(F) PRESSURE TRANSDUCER