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LIQUID-HYDROGEN-FUELED-VEHICLE TESTS

Executive Summary

by

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for

U. S. Department of Energy

Division of Transportation Energy Conservation

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ABSTRACT

A program for the development of a baseline liquid-hydrogen fueled vehicle and a liquid-hydrogen-refueling system was completed at the Los Alamos National Laboratory on September 30, 1981. This program involved the cooperative efforts of the Laboratory (funded by the U.S. Department of Energy), 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 results of the program provide a reference point from which future progress and improvements in liquid-hydrogen on-board storage and refueling capabilities may be measured.

The NMEI provided the program a 1979 Buick Century 4-door sedan with 3.8-L (231-in.^3) displacement turbocharged V6 engine and automatic transmission. The DFVLR provided an on-board liquid-hydrogen storage tank and a refueling station. The DFVLR tank, and the engine modifications for operation on hydrogen rather than gasoline, represented readily available, state-of-the-art capabilities when the program began in March 1979. The original tank provided by the DFVLR was replaced with a larger capacity tank, which was fabricated using more advanced cryogenic engineering technology.

The vehicle was refueled at least 60 times with liquid hydrogen using various liquid-hydrogen storage Dewars at Los Alamos and the semiautomatic refueling station designed and built by the DFVLR.

At the end of the program, the engine had been operated for 133 h and the car driven for 3540 km (2200 miles) on hydrogen without any major difficulties. The vehicle obtained 2.4 km/L (5.7 miles/gal.) of liquid hydrogen or 8.9 km/L (21 miles/gal.) of gasoline on an equivalent energy basis for driving in the high-altitude Los Alamos, Santa Fe, and Albuquerque areas. Without refueling, the car had a range of about 274 km (170 miles) with the first liquid-hydrogen tank and about 362 km (225 miles) with the second tank.

OBJECTIVES

The major objectives of the program include:

- 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;

- investigate the problems involved in the on-board storage of liquid-hydrogen;

- investigate the problems involved in fueling vehicles with liquid hydrogen;

- develop a liquid-hydrogen refueling system that can be operated by personnel with minimal special training; and,

- develop an automobile of conventional appearance and performance operating on liquid hydrogen.

These objectives were accomplished with the exception that the vehicle performance was not equivalent to the normal performance when operating on gasoline.

OBJECTIVES

- provide a baseline vehicle using state-of-the-art LH_2 storage, refueling, and engine conversion capabilities

- investigate the problems involved in the on-board storage of LH_2

- investigate the problems involved in fueling vehicles with LH_2

- develop a LH_2 refueling system that can be operated by personnel with minimal special training

- develop an automobile of conventional appearance and performance operating on LH_2

Los Alamos

PROGRAM PARTICIPANTS

The program involved the cooperative efforts of the New Mexico Energy Institute (NMEI) for the State of New Mexico, the Deutsche Forschungs- und Versuchsanstalt für Luft- und Raumfahrt (DFVLR) of the Federal Republic of Germany, and the Los Alamos National Laboratory with funding from the Office of Vehicle and Engine Research and Development of the U.S. Department of Energy. The DFVLR is an organization similar to the National Aeronautics and Space Admininstration (NASA) although it is not a government organization.

The NMEI provided a 1979 Buick Century sedan for the program.

The DFVLR provided the initial liquid-hydrogen tank and a semiautomatic refueling station for the program.

The DFVLR and the Los Alamos National Laboratory jointly designed and fabricated the second liquid-hydrogen storage tank used in the program.

Program management and coordination was provided by the Los Alamos National Laboratory. The Laboratory also installed the liquid-hydrogen tanks and ancillary equipment into the car and made road tests of the vehicle. The initial engine modifications for operation on hydrogen rather than gasoline were subcontracted by the Laboratory to the Billings Energy Corporation (BEC).

HCAR PROJECT

NMEI — vehicle

DFVLR — hydrogen tank
refueling station

LASL — liquid hydrogen
engine modification
tank installation
instrumentation
operation

VEHICLE MODIFICATIONS

Modifications to the vehicle by BEC and the Laboratory include:

- Removal of the gasoline tank, the exhaust catalytic converter, and some of the sheet metal to make room in the trunk compartment for the liquid-hydrogen tank.

- Vapor sealing between the trunk space and the passenger compartment to prevent hydrogen from entering the passenger compartment in the event of a hydrogen leak in the trunk space.

- Installation of louvers in the trunk lid for ventilation of the trunk compartment to avoid an accumulation of hydrogen in the event of a hydrogen leak in the trunk space.

- Installation of hydrogen detectors in the trunk and the passenger compartment to provide a warning in the event of a hydrogen leak.

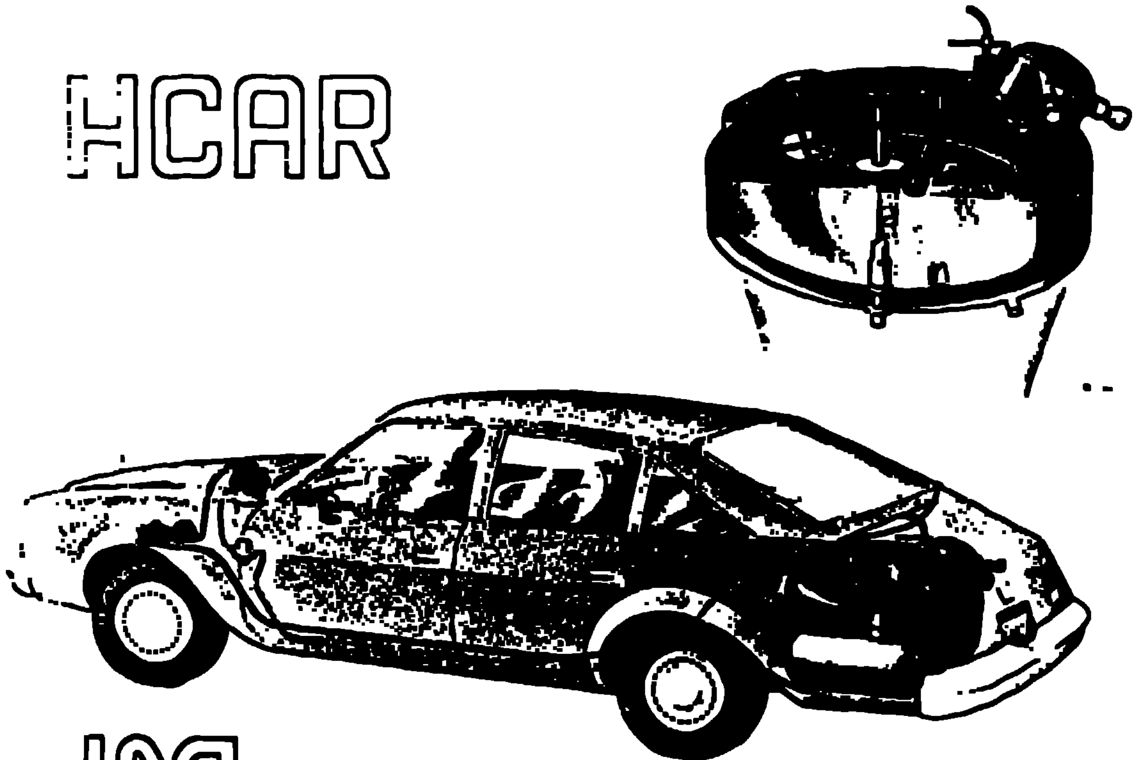
- Installation of a 25.7 L (6.8 gal.) water tank in the trunk for a water induction system that uses the vehicle's original equipment gasoline pump and carburetor to deliver water to the intake manifold. Water induction is used to reduce backfiring in the intake manifold and to lower NO_x emissions, especially during operation at high power.

- Installation of a hydrogen feed system, including controls, to deliver hydrogen from the liquid-hydrogen tank to the engine.

- Installation of a hydrogen tank liquid-level gauge and pressure indicator/controller to permit the driver to monitor and control the hydrogen fuel system.

- Installation of instrumentation such as a tachometer, intake manifold pressure gauge, and a hydrogen pressure gauge at the inlet to the Impco gas mixer.

HCAR



ENGINE MODIFICATIONS

The engine modifications that were made by the BEC and the Laboratory for operating the engine on hydrogen rather than gasoline include:

- Removal of all stock emission-control equipment because it was not needed.

- Installation of an Impco CA-300 gas mixer on the standard Rochester gasoline carburetor (original equipment which was left in place). The Impco carburetor controls the hydrogen/air mixture and the Rochester carburetor controls the water induction rate. The engine is operated in a throttled mode at a constant fuel/air equivalence ratio of about 0.9 (slightly lean).

- Plugging the idle jets in the Rochester carburetor to prevent water use at idle.

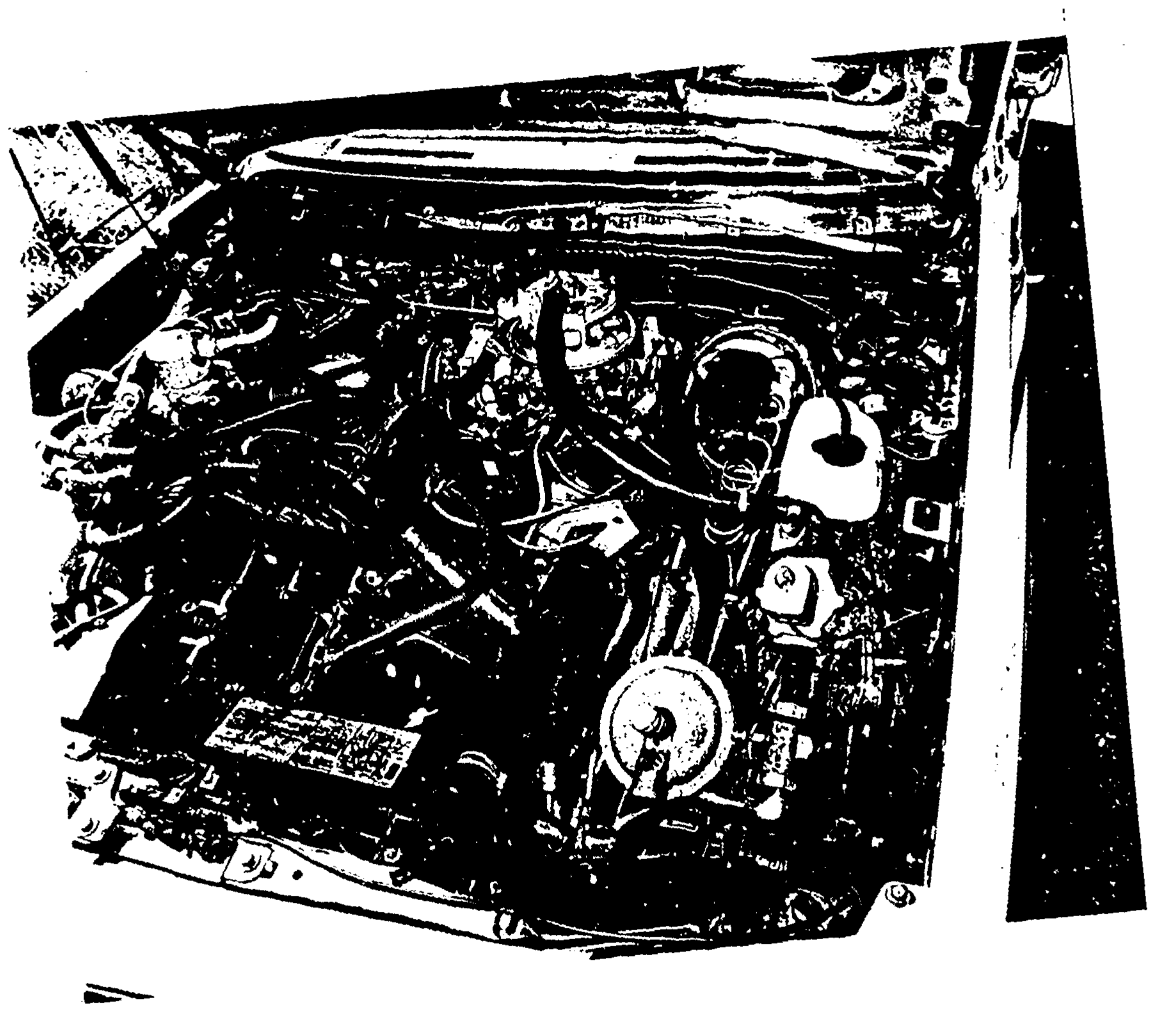
- Installation of a positive crankcase ventilation system to prevent a hydrogen/air mixture from accumulaing within the crankcase.

- Replacement of the standard spark-plug wires with heavy-duty solid wires to reduce crossfiring and misfiring.

- Removal of the vacuum advance and centrifugal advance and setting the ignition timing at a fixed 20° before top center (BTC) to reduce backfiring as much as possible. Later, a modified centrifugal advance system was installed to allow the engine to be started at one timing and operated at another.

- Installation of an oxygen sensor in the exhaust to provide an indication of the fuel/air mixture.

- Changing the radiator thermostat to one with a setting of 70°C (158°F) to operate the engine cooler than normal to reduce the backfiring, yet still provide heated water for the hydrogen heat exchanger on tank #1.

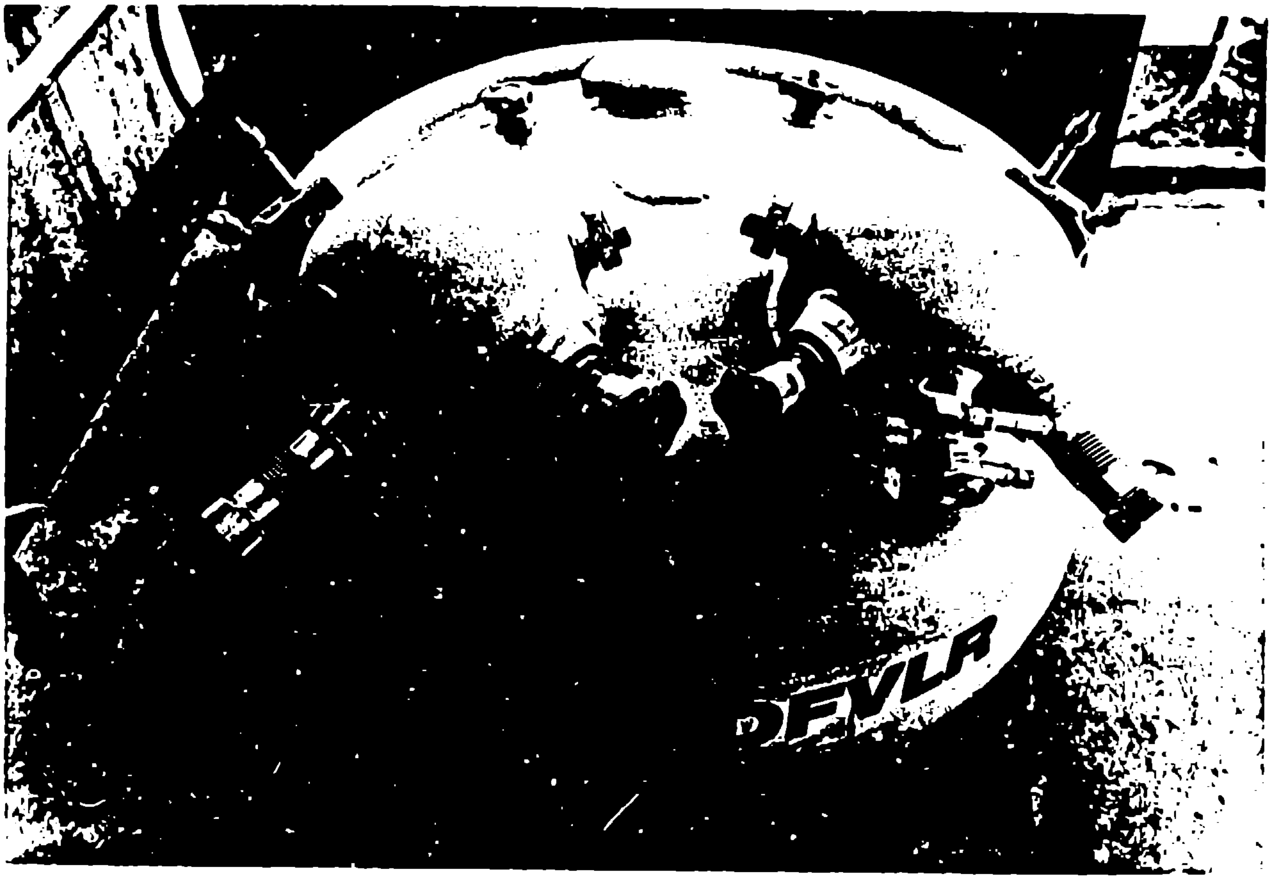


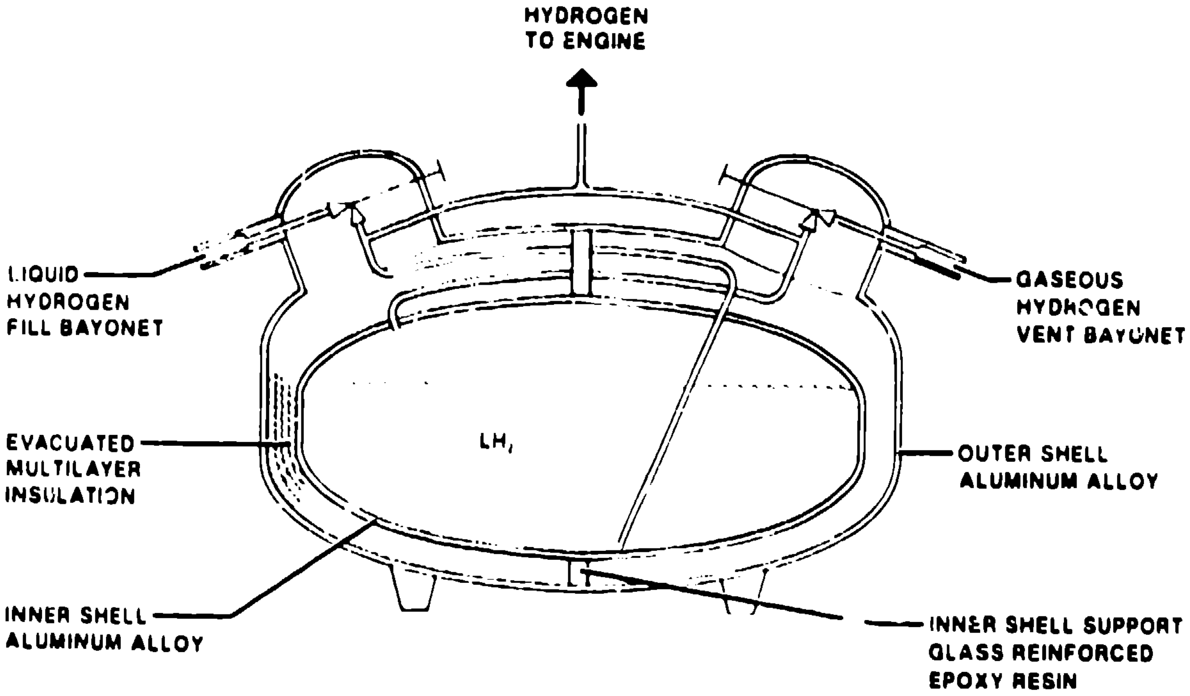
LIQUID-HYDROGEN ON-BOARD STORAGE TANK #1 DESCRIPTION

The first liquid-hydrogen on-board storage tank used in the program was a dual-shell vessel with 60 mm (2.4 in.) of evaucated multilayer insulation between the aluminum alloy inner and outer shells. This particular tank configuration was chosen for use on a bus (but was never used for that application) and thus its design was not necessarily optimum for this vehicle. Both the inner and outer shells were fabricated from commercially available 4-mm- (0.157-in.-) thick aluminum alloy end caps, or pressure vessel heads.

A liquid-level indication was provided by 10 carbon resistors mounted within the inner vessel.

The manually operated refueling valves, tubing connections between the inner and outer vessels, and the connections to the heat exchanger are located in the two domes shown on top of the tank. The vacuum spaces of the two domes are separate from the vacuum space between the inner and outer shells. The inner shell has three 12.7-mm-(0.5-in.-) o.d. stainless steel connecting tubes: one to add or withdraw liquid hydrogen, one to withdraw gaseous hydrogen, and one to attach safety relief valves. The gaseous-hydrogen vent line is used for routing the electrical leads for the liquid-level sensor into the inner vessel.


DFVLR


HYDROGEN TO ENGINE
LIQUID HYDROGEN FILL BAYONET
GASEOUS HYDROGEN VENT BAYONET
LH_2
EVACUATED MULTILAYER INSULATION
OUTER SHELL ALUMINUM ALLOY
INNER SHELL ALUMINUM ALLOY
INNER SHELL SUPPORT GLASS REINFORCED EPOXY RESIN

LIQUID-HYDROGEN ON-BOARD STORAGE TANK #1 DESCRIPTION

The inner shell of the first liquid-hydrogen on-board storage tank used in the program had a volume of about 150 L (39.6 gal.): 110-L (29-gal.) liquid volume and 40-L (10.6-gal.) ullage space. The actual amount of liquid hydrogen within the tank varies from 97.7 to 112.8 L (25.8 to 29.8 gal.) depending upon the refueling procedure.

The empty weight of the tank is 83.8 kg (184.4 lb) and the maximum filled weight is 91.8 kg (202.3 lb).

The tank has a maximum operating pressure of 447 kPa (65 psia) and is designed to withstand a 10 g acceleration load in any direction with a safety factor of two.

When the vehicle is not in operation and the tank is closed (unvented), the pressure in the tank gradually increases at about 21 kPa/h (3 psi/h) for a nearly full tank, or about 45 kPa/h (6.6 psi/h) for a nearly empty tank, until the relief valve is activated or until hydrogen is intentionally vented from the tank. Thus, the time that the tank may be left closed (the lock-up time) varies from 10 to 21 h depending on the liquid level in the tank. After the relief valve opens, or if the tank is left in a vented condition, liquid hydrogen will be lost at the rate of 11 L/day (2.9 gal./day). At this rate, a full tank of liquid hydrogen would require 10 days to evaporate.

SUMMARY OF LIQUID-HYDROGEN ON-BOARD STORAGE TANK #1 PARAMETERS

	Hydrogen Goal	Hydrogen Achieved	Original Gasoline Tank
Outside diameter, m (in.)	---	0.9 (35.4)	---
Overall height, m (in.)	---	0.66(26.0)	---
Empty weight, kg (lb)	43.2(95.0)	83.8(184.4)	13.6(30.0)
Filled weight, kg (lb)	54.1(119.0)	91.8(202.3)	63.0(138.6)
Maximum working pressure, kPa (psia)	447.(65.0)	447.0(65.0)	---
Liquid volume, L (gal.)	150.0(39.6)	110.0(29.1)[a]	68.5 (18.1)
Heat leak, W	2.0	4.0	---
Boiloff rate, %/day	3.5	10.0[b]	---
Loss rate for vented tank, L/day (gal./day)	5.0(1.3)	11.0(2.9)	---
Pressure build-up rate, kPa/h (psi/h)	10.0(1.4)	21.0-45.5 (3-6.6)[c]	---
Lock-up time, minimum, h	48	10-21[c]	---

[a] Original volume estimates were not achieved because available pressed-tank-head domes were used which "not to specifications."

[b] Based on the total liquid volume of 110 L.

[c] Depends upon the liquid-level in the tank.

LIQUID-HYDROGEN ON-BOARD STORAGE TANK #2 DESCRIPTION

The second liquid-hydrogen on-board storage tank used in the program is a cylindrical, dual-shell vessel with two copper thermal radiation shields. The inner vessel is fabricated from stainless steel and the outer vessel is made of 5083 aluminum alloy. The two copper shields and the inner vessel are wrapped with aluminized mylar superinsulation and the space between the inner and outer vessels is evacuated. This Dewar was built jointly by Los Alamos and the DFVLR to overcome some of the disadvantages such as the high heat leak into the liquid hydrogen in the first Dewar, and to incorporate more advanced cryogenic engineering techniques into a tank that would represent an improvement over the first tank.

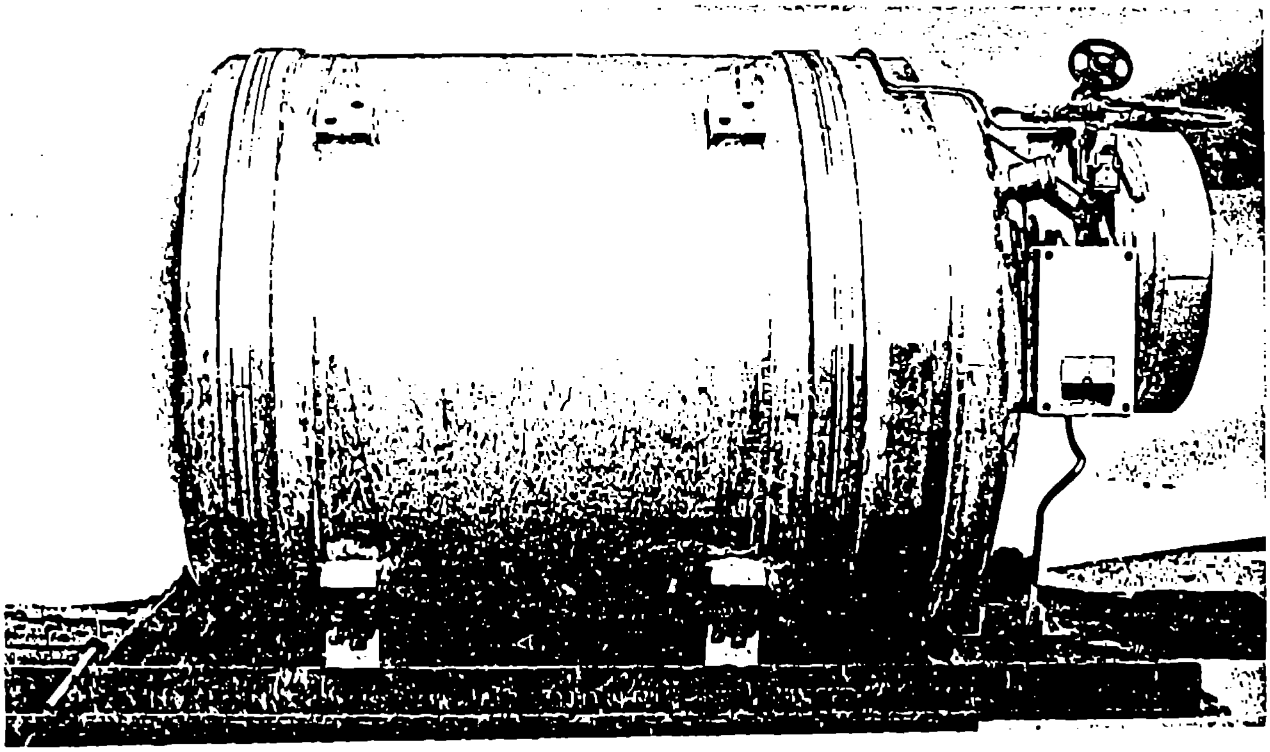
The inner vessel and the two radiation shields are supported within the outer vessel by three fiberglass-epoxy support rods on each end of the tank. This support system is designed to sustain an acceleration load of 10 g's in any direction. Heat leak through the supports is reduced by a thermal connection between the two radiaton shields and the six support rods.

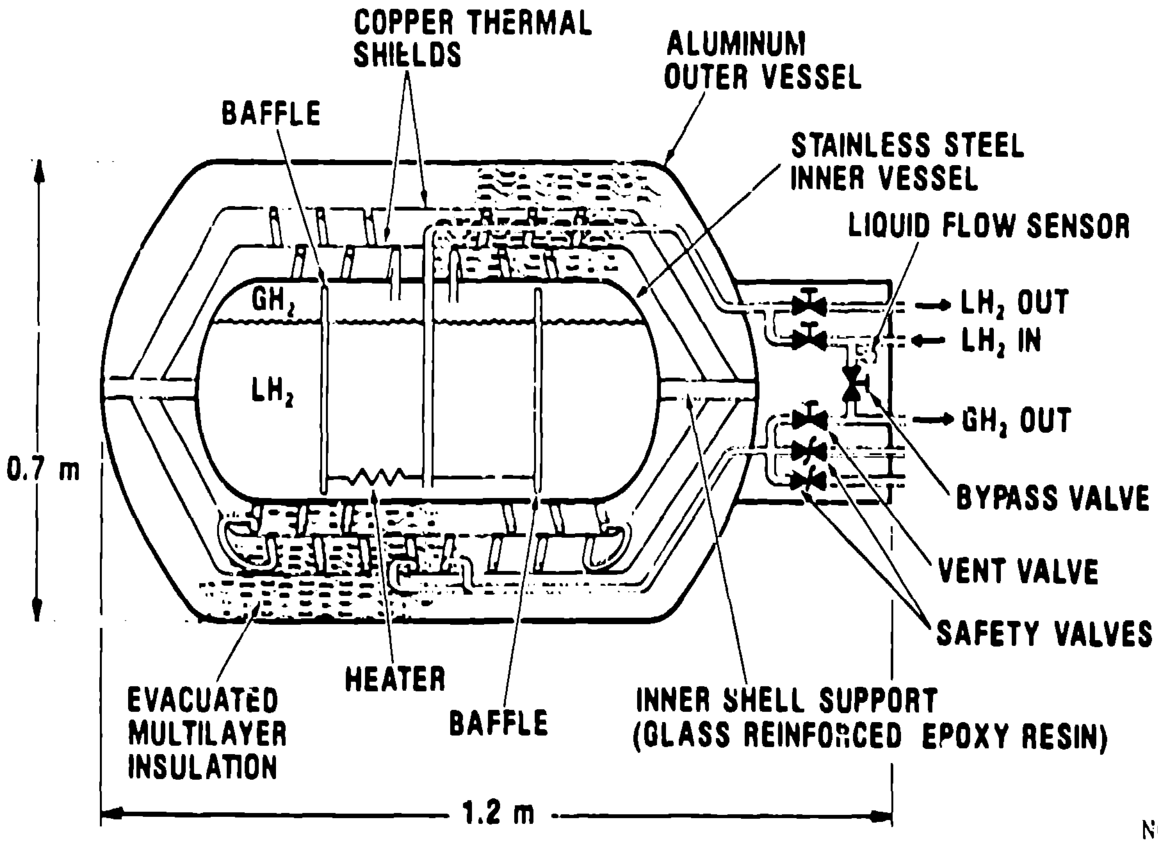
The heat leak into the inner vessel casues the liquid-hydrogen to boil; the cold gaseous hydrogen generated by this boiling is used to cool the two copper shields which reduces the heat leak into the inner vessel. This requires that a small quantity of hydrogen be continuously vented from the tank whenever the vehicle is not in use.

The inner vessel contains a capacitance type liquid-level sensor, two electrical heaters to assist in pressure build-up, and two perforated aluminum alloy baffle plates to reduce sloshing and thermal stratification.

The manually operated valves (for control of liquid hydrogen fill or withdrawal and gaseous hydrogen venting), the refueling bayonets, and the connection for the hydrogen supply to the engine are enclosed within a vacuum space which is separated from the main vacuum space by a flange and vacuum-feedthroughs. This arrangement provides additional safety because the main vacuum space of the tank is not affected in the event of leaks caused by material defects or by crash damage in the valve section.

For ease of access during testing, the outer vessel closure flanges are clamped together and sealed by O-rings. A permanent closure could be made by welding the ring flanges together, with access to the valve section still possible through a valve section closure flange.





COPPER THERMAL SHIELDS
ALUMINUM OUTER VESSEL
BAFFLE
STAINLESS STEEL INNER VESSEL
LIQUID FLOW SENSOR
GH_2
LH_2
LH_2 OUT
LH_2 IN
GH_2 OUT
0.7 m
BYPASS VALVE
VENT VALVE
SAFETY VALVES
HEATER
EVACUATED MULTILAYER INSULATION
BAFFLE
INNER SHELL SUPPORT (GLASS REINFORCED EPOXY RESIN)
1.2 m

NOT TO SCALE

LIQUID HYDROGEN ON-BOARD STORAGE TANK #2 DESCRIPTION

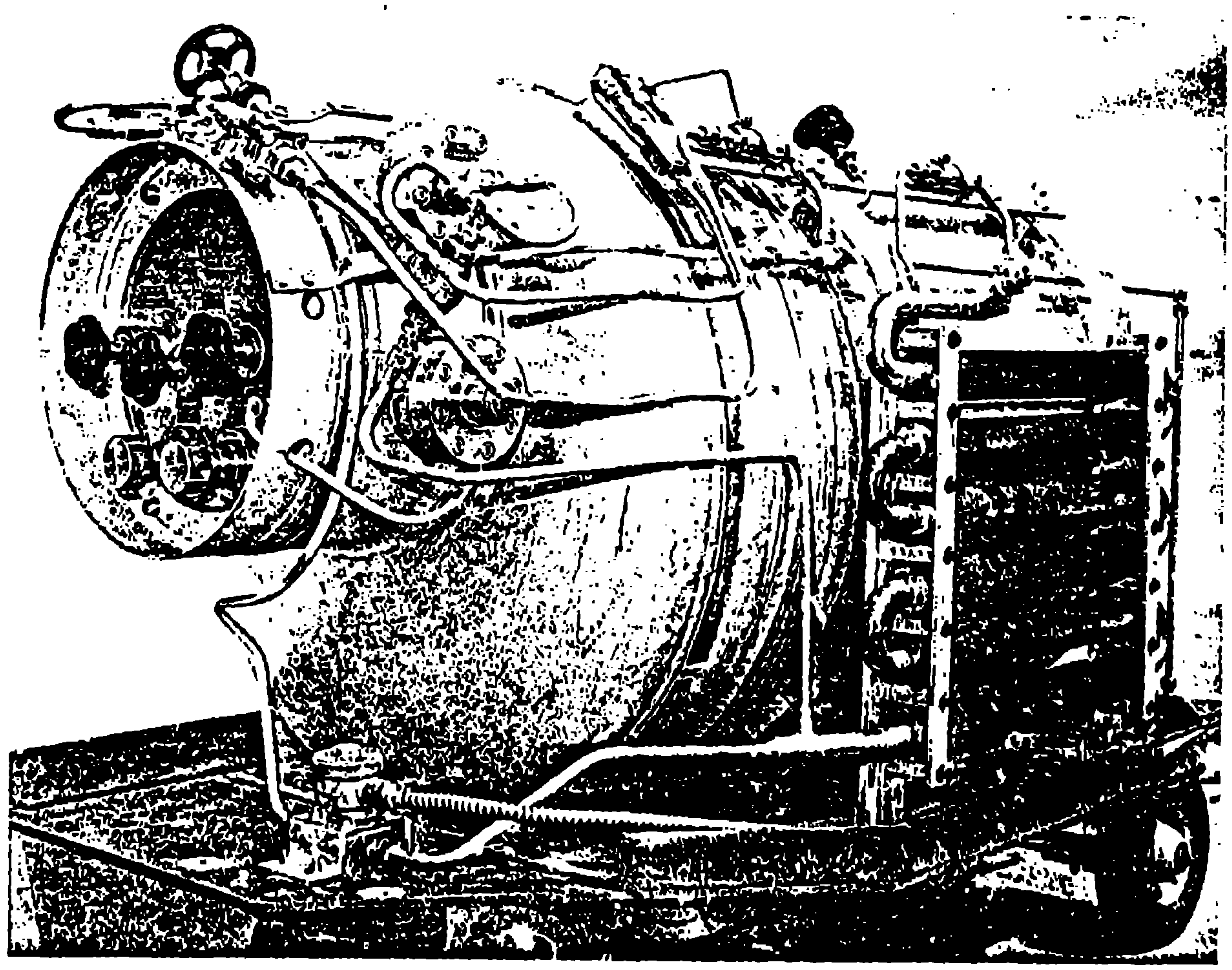
The second liquid-hydrogen on-board storage tank used in the program has a liquid-hydrogen storage capacity of 155 L (41 gal.) and an ullage space of approximately 12 L (3.2 gal.). The overall length of the tank is 1.22 m (48 in.) and its o.d. is 0.712 m (28 in.). The inside diameter of the inner tank is 0.546 m (21.5 in.).

This tank has an empty weight of 156 kg (344 lb) and a filled weight of 167 kg (368 lb). The stainless steel inner vessel weighs 35 kg (77 lb) and the copper thermal radiation shields weigh 42.2 kg (92.8 lb). Thus, the weight of a tank such as this could be reduced by using aluminum for the inner vessel and the thermal radiation shields.

The heat leak into the liquid hydrogen has been measured as about 2 W, about twice the expected amount. Therefore, the tank has a loss rate of about 6.2 L/day (1.6 gal./day) when the vehicle is not in operation. At this rate, a full tank of liquid hydrogen would require about 25 days to evaporate.

This Dewar, utilizing a principle (vapor-cooled thermal radiation shields) not previously used in a vehicle liquid-hydrogen on-board storage application, has not been optimized for vehicle use and improvements (such as reducing the weight of the Dewar) are possible.

Fabrication, and some limited testing, of the Dewar was completed about mid-September 1981, and its installation into the vehicle was completed the first part of October; consequently, testing and operating experience with the Dewar is rather limited.



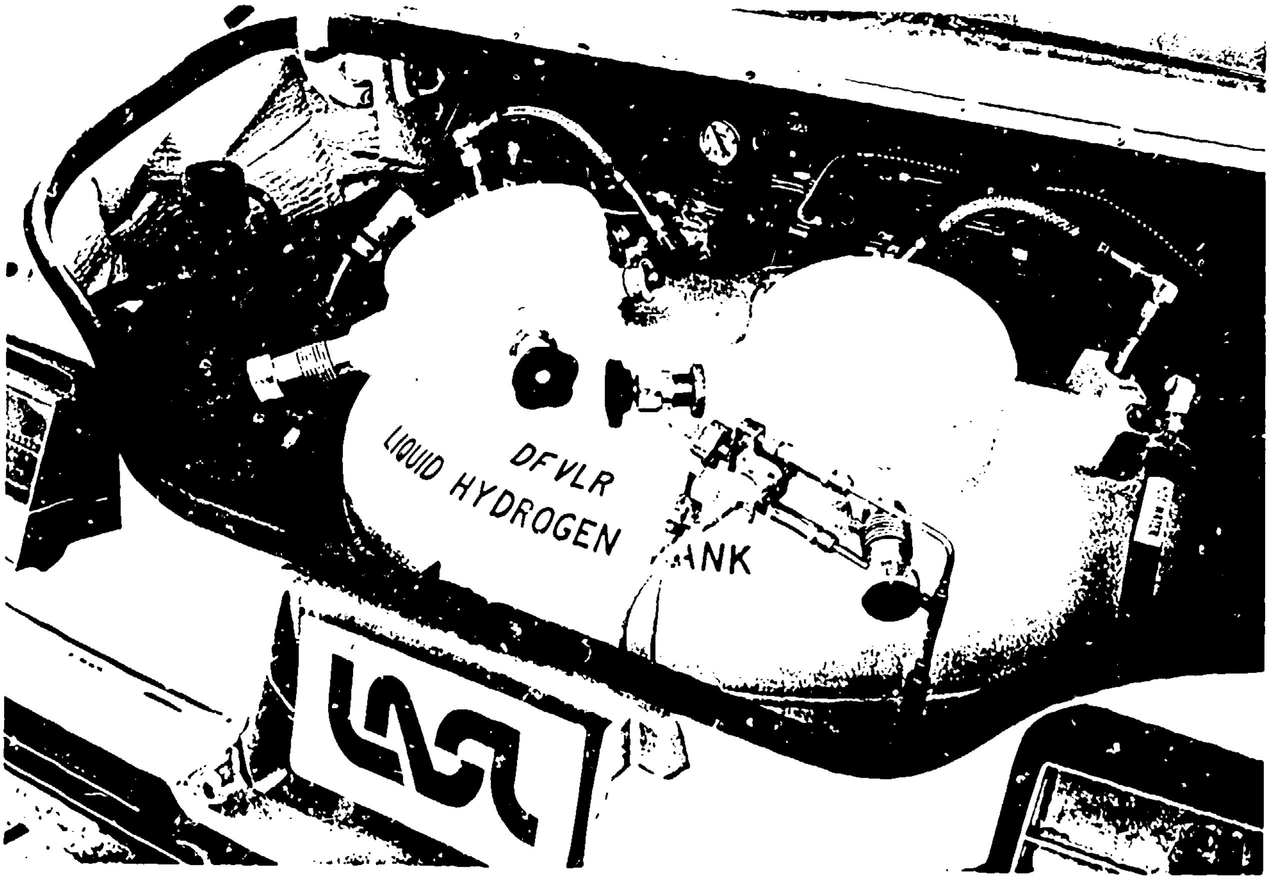
SUMMARY OF LIQUID-HYDROGEN ON-BOARD STORAGE TANK #2 PARAMETERS

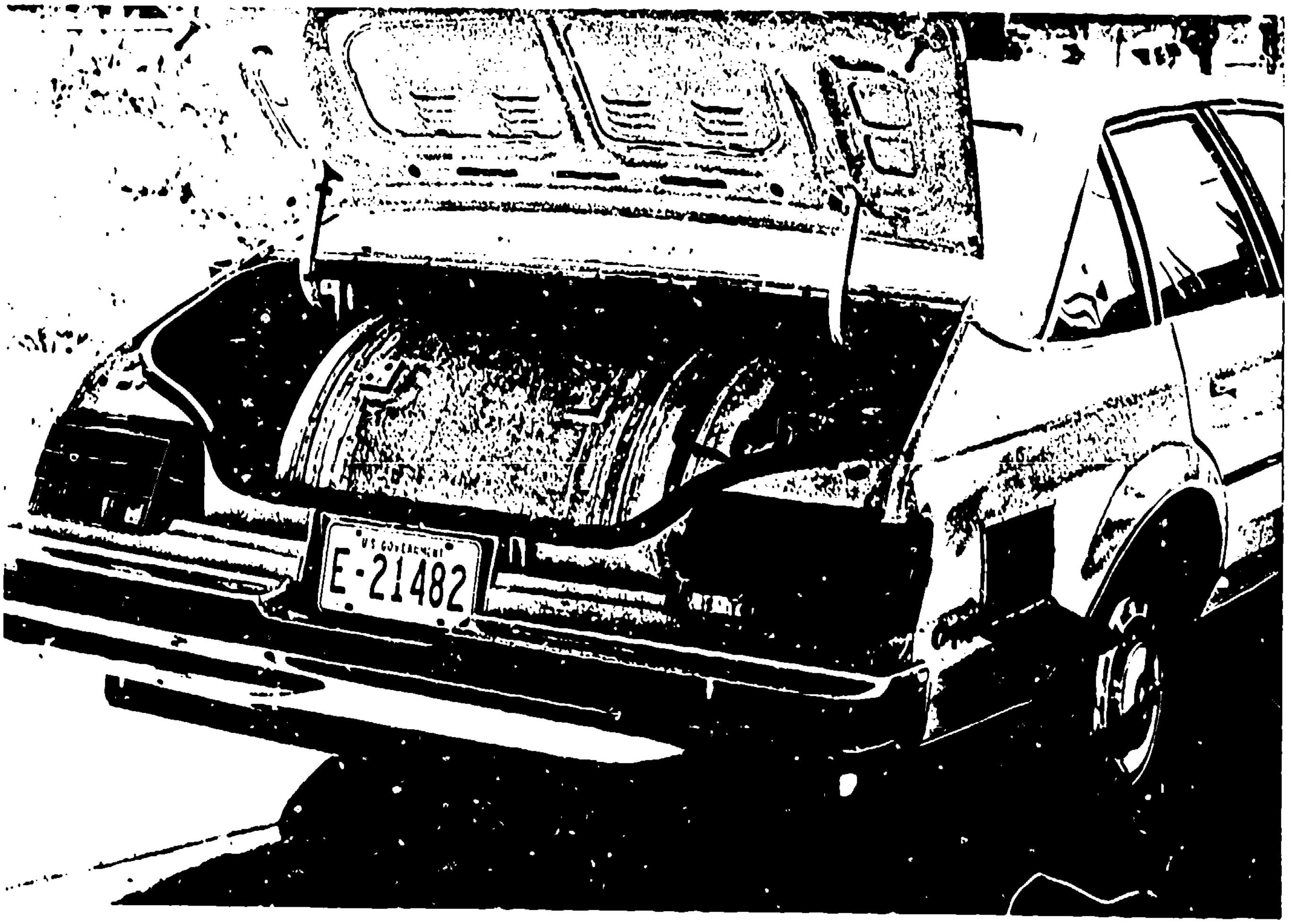
Overall Length, m (in.)	1.22 (48)
Outside Diameter, m (in.)	0.712 (28)
Empty Weight, kg (lb)	156 (344)
Filled Weight, kg (lb)	167 (368)
Maximum Working Pressure, kPa (psig)	206 (30)
Liquid Volume, L (gal.)	155 (41)
Heat Leak, W	2
Boiloff Rate, %/day	4
Loss Rate for Vented Tank, L/day (gal./day)	6.2 (1.6)

LIQUID-HYDROGEN ON-BOARD STORAGE TANK INSTALLATION

The installations of the two liquid-hydrogen on-board storage tanks in the trunk of the vehicle are shown in these figures.

Hydrogen storage will require a tank with a volume about 3.8 times larger than that of a gasoline storage tank for the storage of an equivalent amount of energy because of the difference in energy per unit volume for h rogen and gasoline.


DFVLR
LIQUID HYDROGEN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VEHICLE PERFORMANCE AND OPERATION

The vehicle has been operating at Los Alamos on hydrogen as a fuel since April 29, 1980, and as of October 1, 1981, has been driven a distance of 3563 km (2214 miles) on hydrogen without any major difficulty. An occasional backfiring does occur during its operation; this occurs most frequently when starting the engine.

The fuel economy corresponds to 2.4 km/L (5.7 miles/gal.) of liquid hydrogen (equivalent to 8.9 km/L or 21 miles/gal. of gasoline) in driving in the Los Alamos, Santa Fe, and Albuquerque areas. The US Environmental Protection Agency (EPA) estimated fuel economy for this vehicle is 7.2 km/L (17 miles/gal.) of gasoline, which is equivalent to an energy use of 4435 J/m (6765 Btu/mile). The 2.4 km/L of liquid hydrogen corresponds to an energy use of 3436 J/m (5240 Btu/mile). Thus to go a given distance, about 22% less energy is required using hydrogen instead of gasoline.

Although an increase in fuel economy has been achieved, the vehicle has less power operating on hydrogen than it did on gasoline.* Acceleration from 0 to 80.5 km/h (0 to 50 miles/h) requires 16.8 s at near sea level and 25.6 s at Los Alamos, New Mexico, which is 2225 m (7300 ft) above sea level. This car would be expected to accelerate from 0 to 80.5 km/h (0 to 50 miles/h) in about one-half this time when operating on gasoline. A gasoline-fueled Buick Regal with a similar engine accelerated from 0 to 80.5 km/h (0 to 50 miles/h) in 14.4 s at Los Alamos. The stock turbocharger on the engine has not been changed, and as a result of its not being properly sized for hydrogen, a maximum boost pressure of 13.8 kPa (2 psi) at Los Alamos, and 34.5 kPa (5 psi) at Independence, Missouri was achieved; a maximum boost pressure of 65.5 kPa (9.5 psi) is possible when gasoline is used as the fuel.

The water consumption in the engine is equivalent to 9.1 km/L (21.4 miles/gal.).

A range of 236.5 to 273.5 km (147 to 170 miles) has been obtained driving in the Los Alamos, Santa Fe, and Albuquerque areas with tank #1; tank #2 gives the vehicle a range of about 362 km (225 miles) because of its greater liquid-hydrogen capacity. With its 68.1-L (18-gal.) gasoline tank, the car would have a range of about 483 km (300 miles).

The NO_x emissions as measured in only one test on a chassis dynamometer ranged from 25 ppm at idle to 1000 ppm at full load; this has been estimated to be equivalent to about 0.037 and 3.7 g/km (0.06 and 6.0 g/mile) for idle and full load. According to General Motors the Buick produces an average of 0.4 to 0.5 g/km (0.6 to 0.8 g/mile) operating on gasoline over the standard driving cycle. Unfortunately, we do not have a similar average value for the vehicle to make a direct comparison with the GM data. The NO_x emissions from using hydrogen as a fuel could be reduced considerably by operating at a lower fuel/air equivalence ratio.

*An 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 program since we were not attempting to advance the state-of-the-art in engine conversion.

SUMMARY OF VEHICLE PERFORMANCE AND OPERATION ON LIQUID HYDROGEN

	Hydrogen		Gasoline
	Goal	Achieved	
Acceleration, 0 to 50 miles/h (s)	13	16.8[a], 24.8[b]	14.4[c]
Fuel economy (miles/gal.)	5.6	5.7[d]	17[f]
gasoline equivalent (miles/gal.)		21[e]	..
NO_x production (g/mile)	< 1.0	0.06, 6.0[g]	0.6-0.8[h]
Range, maximum (miles)	224	170, 225[d,i]	300
Curb weight (lb)	3400	3550, 3780[i]	3350
Distance driven on hydrogen (miles)	--	2214	--
Water use (miles/gal.)	20	21.4	--

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[a] In Independence, Missouri.

[b] In Los Alamos, New Mexico, elevation 7300 ft.

[c] At Los Alamos in a similarly equipped Buick Regal.

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

[e] On an equivalent energy per mile basis.

[f] EPA estimate.

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

[h] Data provided by GM for the average achieved in operation over a standard driving cycle.

[i] Tank #1 and tank #2 respectively.

HYDROGEN DELIVERY SYSTEM FROM THE STORAGE TANK TO THE ENGINE

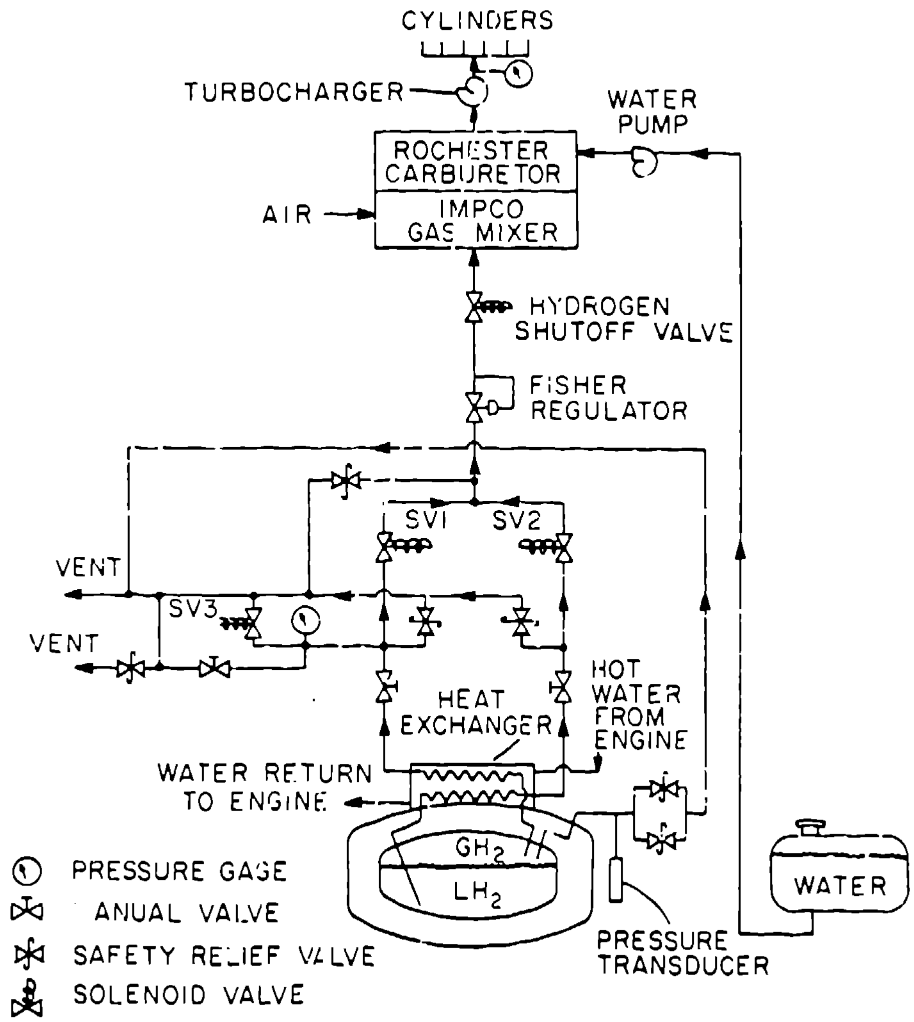
The hydrogen delivery system contains such components as solenoid valves, relief valves, manual valves, regulators, and instrumentation as needed for the transfer of hydrogen from the storage tank to the engine and for other needs such as hydrogen venting.

Hydrogen for the engine is withdrawn from tank #1 from either the liquid or the gaseous phase depending on the pressure within the tank. If the tank pressure is above a selected value, solenoid valve SV1 will open and solenoid valve SV2 will close and hydrogen is taken from the gaseous phase to reduce the pressure to a selected minimum operating pressure. When the tank pressure is below a selected value, solenoid valve SV2 is opened and solenoid valve SV1 is closed and hydrogen is taken from the liquid phase. The Dewar pressure (and thus, the Fisher regulator inlet pressure) can be increased during driving by adjusting the controls for solenoid valves SV1 and SV2. With tank #2, hydrogen is normally taken from the liquid phase because the tank is usually left in a vented condition.

The cold (20 K) hydrogen (gas or liquid) removed from either of the two tanks is warmed in a heat exchanger (using hot water from the engine cooling system for tank #1, or ambient air for tank #2) before it is delivered to the engine.

The purpose of the Fisher regulator is to maintain a constant hydrogen gage pressure of about 10 torr (5.4 inches of water) at the input to the Impco gas mixer.

The fuel system schematic shown in this figure is for tank #1; the fuel system schematic for tank #2 is slightly diffeient.


CYLINDERS
TURBOCHARGER
WATER PUMP
ROCHESTER CARBURETOR
AIR
IMPCO GAS MIXER
HYDROGEN SHUTOFF VALVE
FISHER REGULATOR
SV1
SV2
VENT
SV3
VENT
HOT WATER FROM ENGINE
HEAT EXCHANGER
WATER RETURN TO ENGINE
GH_2
LH_2
WATER
PRESSURE TRANSDUCER
PRESSURE GAGE
ANUAL VALVE
SAFETY RELIEF VALVE
SOLENOID VALVE

ROAD TESTS

Hydrogen flow and pressure data were taken for three modes of operation: (1) driving at constant speeds from 20 to 50 miles/h over several roads in Los Alamos; (2) acceleration from 0 to 50 miles/h; and, (3) 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 liquid-hydrogen Dewar.

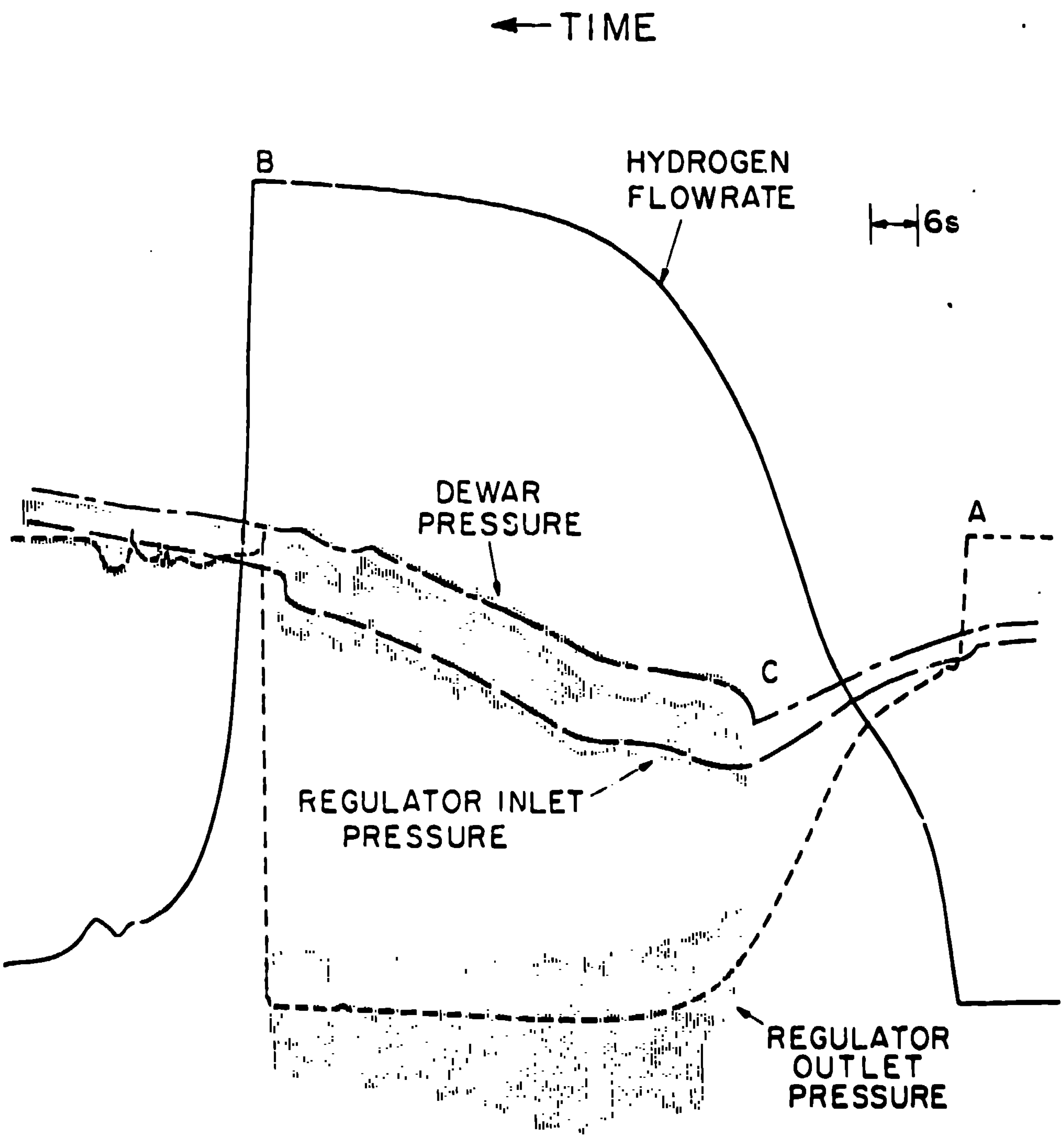
A typical chart recording of the data for a hill climb test is shown in this figure. The test begins at Point A with the vehicle accelerating from a standing start and climbing the hill in low gear; the test is terminated at Point B when the vehicle reaches the top of the hill. The automatic switching of solenoid valves SV1 and SV2 to remove hydrogen from the liquid phase to maintain the desired Dewar pressure is shown at Point C. There is a considerable oscillation in the Fisher regulator inlet and outlet pressures when liquid hydrogen is being taken from the Dewar (i.e., when solenoid valve SV2 is open and SV1 is closed). Hydrogen flow and pressure data for Points A, B, and C of this figure are given in the following table.

	Hydrogen Flowrate (cfm)	Dewar Pressure (psig)	Regulator Pressure Inlet (psig)	Regulator Pressure Outlet (torr)
Point A	7.3	18.0	17.6	11.1
Point B	43.5	22.2	20.4	2.9
Point C	30.0	15.3	13.6	3.5

The pressure drop from the Dewar to the regulator inlet (less than 3 psi) is not significant except at low Dewar pressures (less than about 10 psig).

The drop in the regulator outlet pressure during high hydrogen flowrates results in a drop in hydrogen pressure at the Impco gas mixer which causes the fuel/air mixture to become lean which reduces the maximum power output.

The test data indicate that a high regulator inlet pressure, would be required to maintain a constant regulator outlet pressure. Consequently, the Fisher regulator was replaced with a larger one with a higher flow capacity but no significant difference in operation was observed with the larger regulator.


TIME
B
HYDROGEN
FLOWRATE
6s
DEWAR
PRESSURE
A
C
REGULATOR INLET
PRESSURE
REGULATOR
OUTLET
PRESSURE

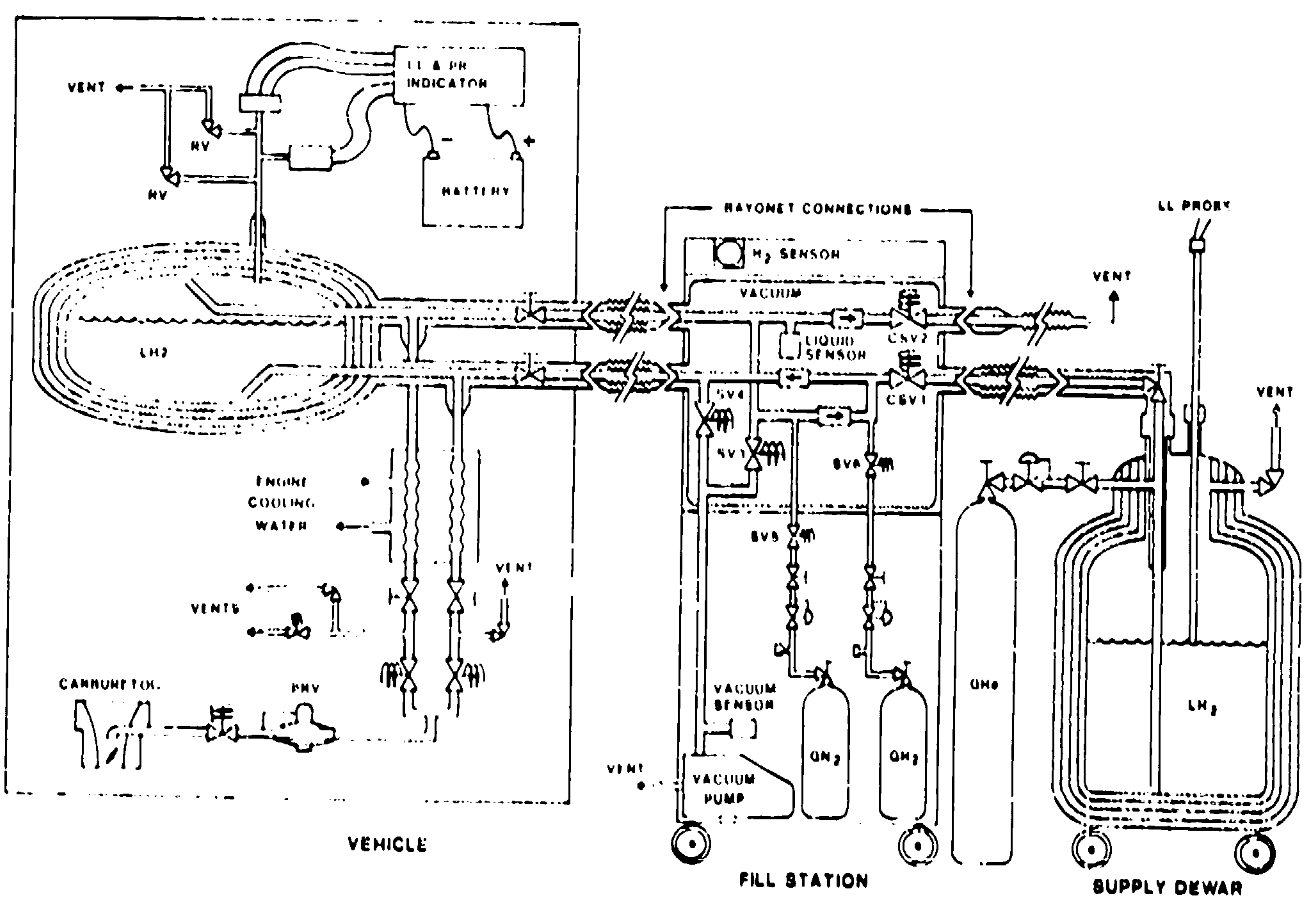
LIQUID-HYDROGEN REFUELING

The vehicle was refueled numerous times with liquid hydrogen using various liquid-hydrogen storage Dewars available at Los Alamos and the semiautomatic refueling station designed and built by the DFVLR. The refueling station permits the transfer of liquid-hydrogen from a storage Dewar to the on-board liquid-hydrogen storage tank. The semiautomatic operation of the refueling stations makes it possible for personnel with little or no special training to refuel a vehicle with liquid hydrogen.

A refueling operation with a 500-L (132-gal.) storage tank is shown with a schematic of the system in these figures. The refueling operation is described below.

The vehicle is driven to the liquid-hydrogen-refueling station. The operator mates two bayonet connections and an electrical ground connection and then initiates the following semiautomatic sequence of events. The hydrogen fill and vent lines are evacuated by the vacuum pump. This provides a leak check of the connections and removes impurities such as air from the lines. If the leak check is satisfactory (as determined by the evacuation rate in the two lines) the hydrogen fill and vent valves in the refueling station will open. The operator must then open the manual fill and vent valves on the vehicle tank. When the fill and vent valves are open, the tank will fill until the transfer is terminated manually or until the liquid sensor detects liquid in the vent line. The fill and vent valves in the refueling station will then close. Liquid hydrogen remaining in the fill line is blown into the tank by gaseous hydrogen from a small compressed gas storage tank. The operator must now close the manual fill and vent valves on the vehicle tank. After the fill and vent lines are evacuated to remove the remaining hydrogen, the vacuum will be broken and the lines filled with nitrogen gas. The operator may then disconnect the fill and vent lines, thus completing the refueling operation.

In summary, only the pressing of two buttons and four manual steps are necessary: connect the fill and vent lines, open the fill and vent valves, close the fill and vent valves, disconnect the fill and vent lines.


VENT
RV
RV
INDICATOR
BATTERY
BAYONET CONNECTIONS
LL PROBE
H_2 SENSOR
VENT
VACUUM
LIQUID SENSOR
CSV2
CSV1
LH2
VENT
SV4
SV3
SV5
SV6
ENGINE
COOLING
WATER
VENT
VENTS
CARBURETOR
VACUUM SENSOR
VENT
VACUUM PUMP
GN_2
GH_2
GHe
LH_2
VEHICLE
FILL STATION
SUPPLY DEWAR

LIQUID-HYDROGEN REFUELING

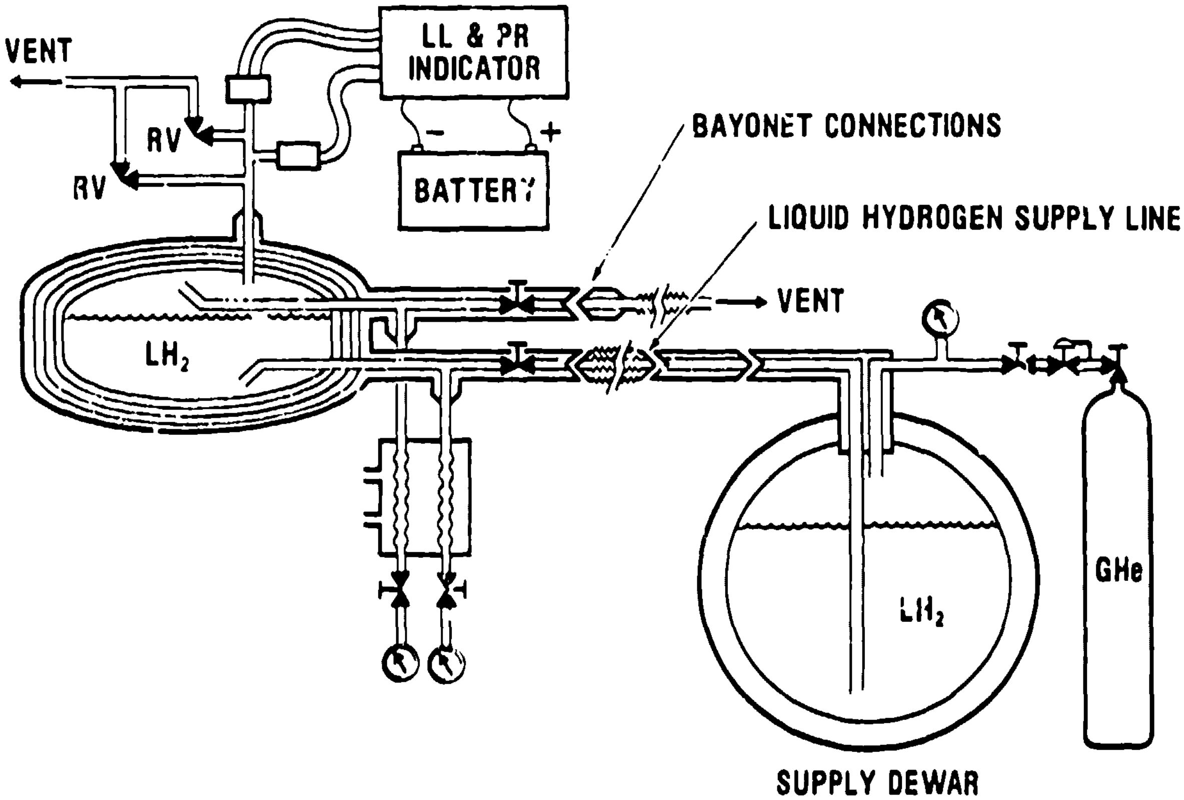
Although the refueling system may be rather simple as shown in the previous figure (and thus could be portable), a liquid-hydrogen service station comparable to today's gasoline service station would be more complex and have a greater liquid-hydrogen storage capacity than the 500-L Dewar shown. A refueling operation at the Laboratory's liquid-hydrogen storage facility with a 52990-L (14000-gal.) tank (which might be an appropriate size for a service station) is shown in this figure.

LIQUID-HYDROGEN REFUELING TESTS

During a liquid-hydrogen transfer using a pressure differential between a supply tank and a receiving tank to effect the transfer (as shown in this figure), some amount of liquid hydrogen is vaporized or lost as a result of:

- flashing of the saturated liquid in the supply tank to the lower pressure of the receiving (automobile storage) tank;
- cooldown of the supply tank pressurization gas (hydrogen or helium);
- cooldown of the transfer lines, refueling station, and receiving tank (if previously warm);
- heat leak into the storage tank, the receiving tank, the refueling station, and the transfer lines;
- liquid entrainment in the vent gas.

Tests were conducted to determine the extent of liquid hydrogen lost during a transfer and to determine optimum conditions and transfer procedures using various arrangements of the refueling station, the on-board storage tank, and the 500-L (132-gal.) and 190-L (50-gal.) supply tanks as shown in a previous figure and this one. In these transfer tests the pressure in the supply tank (190-L or 500-L Dewar) was varied from 22.7 to 172.4 kPa gauge (3.3 to 25 psig). The corresponding transfer times ranged from 45 to 9 min to fill the on-board storage tank, with corresponding liquid-hydrogen transfer rates from 1.8 to 14.5 g/s (0.004 to 0.032 lb/s). The liquid-hydrogen loss for the test setup shown in a previous figure was about 2.9 kg (6.4 lb) for a warm on-board storage tank and about 1.1 kg (2.4 lb) for a cold tank. The liquid-hydrogen loss for the test setup shown in this figure was about 0.64 kg (1.4 lb) for a cold storage tank. These losses did not change significantly as a function of the various transfer pressures and flow rates.



LIQUID-HYDROGEN TANK #1 REFUELING SUMMARY

	Goal	Achieved
Minimum Refueling Time (minutes)		
Cold Tank	5	9
Warm Tank	30	33
Liquid Hydrogen Loss (lb)		
Cold Tank	--	1.4[a], 2.4[b]
Warm Tank	--	4.6[b]

[a]Without refueling station.
[b]With refueling station and an additional transfer line.

PROGRAM SUMMARY

A baseline experimental liquid-hydrogen fueled mid-size sedan and a liquid-hydrogen semiautomatic refueling station have been operated for about 17 months. During this time the vehicle was driven for 2200 miles on hydrogen and was refueled over 60 times with liquid hydrogen. Also, two different types of on-board liquid-hydrogen storage tanks were tested under actual, on-the-road, operating conditions. A final report is being prepared to document the technical information base established during this program to provide data which has not previously existed, or was not readily available. The experience gained during this program will provide for improved and more efficient liquid-hydrogen on-board storage and refueling systems in future programs.

Although the program was completed on September 30, 1981, the disposition and future plans for the vehicle have not yet been determined. We have been requested to display the car and refueling system at the World Hydrogen Energy Conference IV, June 13-17, 1982 in Pasadena, California. We plan to maintain contact with others who are involved in developing the use of hydrogen as a fuel, and to seek other opportunities for the application of the experience gained during this program.

PROGRAM SUMMARY

ACCOMPLISHMENTS

- A documented (with technical data) baseline vehicle was established.
- A liquid-hydrogen-fueled vehicle was operated for 17 months and was driven for 2200 miles.
- Liquid-hydrogen refueling accomplished more than 60 times.
- Two different types of liquid-hydrogen on-board storage tanks were tested.
- Data on refueling time and efficiency (or losses) were obtained.
- Data on vehicle performance and efficiency were obtained.

STATUS

- The program was completed on September 30, 1981.
- The final report is being prepared.

FUTURE PLANS

- Possibly display the car and refueling system at the WHEC IV.
- Maintain contact with other efforts involved in the development of hydrogen as a fuel.
- Pursue the possibility of the application of the experienced gained during this program in a follow-up program.

RECOMMENDATIONS

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

- A fully integrated liquid-hydrogen bulk storage, refueling, and on-board storage system should be fabricated and tested. This should be a completely automated system with it 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.
- The very latest in cryogenic engineering technology should be applied in the fabrication of an on-board 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.
- A method for safely disposing of any vented hydrogen must be developed. During this program hydrogen was vented through a vent-stack, but this would not be a satisfactory method of hydrogen disposal for a hydrogen-fueled vehicle in public use.

The three most frequently made comments regarding the vehicle are: (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.

- An assessment and design of a vehicle incorporating a liquid-hydrogen tank be made so that the tank can be packaged as safely and unobtrusively as possible.
- A safety assessment and testing program be conducted to ascertain that liquid-hydrogen can be safely transfered and stored on-board a vehicle.
- 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.

RECOMMENDATIONS

- Develop a fully integrated, automatic liquid-hydrogen bulk storage, refueling, and on-board storage system.
- Develop an on-board liquid-hydrogen storage tank utilizing the latest cryogenic engineering technology.
- Develop a method for safely disposing of any vented hydrogen.
- Develop a vehicle design incorporating a liquid-hydrogen tank.
- Conduct a safety assessment and testing program for liquid-hydrogen on-board storage and refueling systems.
- Pursue an engine development program.