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Hydrogen-Fueled Postal Vehicle Performance Evaluation

R.A. Hall

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Prepared for
U.S. Department of Energy
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U.S. Postal Service
Through an agreement with
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The work described in this report was done by the Jet Propulsion Laboratory, California Institute of Technology, for the U.S. Department of Energy and the U.S. Postal Service through an agreement with the National Aeronautics and Space Administration.

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The evaluation of the hydrogen-fueled postal vehicle involved the participation of several individuals. Ed Davis and Vaughn Anderson of the Billings Energy Corporation provided technical information on the vehicle, and inspected it at JPL prior to the tests to verify that it was operating as designed. At JPL, L.E. (Gene) Baughman provided Project Management, and T. W. Price, the Task Leader, assisted in the initial planning phase and in preparation of this report. Operation of the dynamometer laboratory, and gathering the data were accomplished by J. A. Bryant, R. E. Burleson, L. Johnson, and J. Allison. The analysis of exhaust oxygen content as a function of equivalence ratio was provided by M. D. Crouch.

ABSTRACT

A hydrogen-fueled postal delivery vehicle has been evaluated by the Jet Propulsion Laboratory for the U. S. Department of Energy and the U. S. Postal Service (USPS). The vehicle was modified for USPS by the Billings Energy Corporation. This report describes the test vehicle, the tests performed, the fueling technique, the test results, and discusses observed vehicle limitations. The evaluation was based on the vehicle's fuel consumption, range, and emissions. These data were obtained while operating the vehicle over a defined Postal Service Driving Cycle and the 1975 Urban Driving Cycle. The vehicle's fuel consumption was 0.366 pounds of hydrogen per mile over the postal driving cycle and 0.22 pounds of hydrogen per mile over the Urban Driving Cycle. These data correspond to 6.2 and 10.6 mpg equivalent gasoline mileage for the two driving cycles, respectively. The vehicle's range was 24.2 miles while being operated on the postal driving cycle. Vehicle emissions were measured over the Urban Driving Cycle. HC and CO emissions were quite low, as would be expected. The oxides of nitrogen were found to be 4.86 gm/mi, a value which is well above the current Federal and California standards.

The discussion of vehicle limitations includes comments about the excessive engine flashbacks, inadequate acceleration capability, the engine air/fuel ratio, the water injection system, and the cab temperature. Some of the other concerns discussed are safety considerations, iron-titanium hydride observed in the fuel system, evidence of water in the engine rocker cover, and the vehicle maintenance required during the evaluation.

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SECTION I

INTRODUCTION

The performance of a U. S. Postal Service Jeep delivery vehicle, modified to operate on hydrogen, has been evaluated by the Jet Propulsion Laboratory (JPL) under the joint sponsorship and funding of the U. S. Postal Service and the U. S. Department of Energy. Preparation of this vehicle is part of an ongoing program within the U. S. Postal Service to evaluate alternative vehicle systems for U. S. mail delivery. Modification of the vehicle was performed by the Billings Energy Corporation of Provo, Utah.

The objectives of this evaluation were to measure the vehicle fuel consumption and range over a defined Postal Service Driving Cycle (PSDC), and to measure vehicle fuel consumption and emissions over the EPA 1975 Urban Driving Cycle. The fueling technique and driver comfort were also evaluated.

The performance tests at JPL were conducted under controlled laboratory conditions on a chassis dynamometer. Some changes to both the PSDC and the 1975 Urban Driving Cycles were necessary to be able to perform these tests with this particular vehicle.

This report presents the results of the range and emissions tests and, in addition, provides results from secondary objectives and general observations. These include a discussion of the technique used to measure the fuel consumed by the vehicle, the vehicle equivalence ratio as determined from exhaust oxygen measurements, some safety considerations, the method of determining the test dynamometer inertia weight and load settings, measured vehicle speedometer readings compared to actual speeds, vehicle cab temperatures, and vehicle maintenance during the evaluation program.

SECTION II

VEHICLE DESCRIPTION*

The vehicle (Figure 1) is basically a 1977 Jeep model DJ-5F Dispatcher 100 with an AMC 232 CID six cylinder engine and automatic three-speed transmission. The rear axle and suspension system have been modified: (1) The rear axle is equipped with a Trac-lok differential and 4.89 gears. The 4.89:1 axle ratio was installed in place of the original 3.07:1 ratio to allow the engine to operate in an adequate power-producing region at normal vehicle speeds. The transmission shift program appears to have been altered to allow the vehicle to shift at normal speeds, compensating for the 4.89 gears installed in the differential. (2) The suspension system has been modified to support the added fuel tank weight. The original shock absorbers have been replaced with air shocks, and additional leaves added to the rear springs to provide a 900-pound increase in the vehicle load capacity.

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*Many of the details of the vehicle configuration were not independently verified at JPL. They were obtained from the Billings Energy Corporation.

Figure 1. USPS Hydrogen-Fueled Jeep Delivery Vehicle on JPL Chassis Dynamometer

The air injection reactor pump has been replumbed so as to create a positive crankcase ventilation and thereby purge the crankcase of water vapor, the prime combustion product.

The fuel system has been modified to accomodate hydrogen operation of the vehicle. Six fuel storage tanks, containing iron-titanium hydride, developed by the Billings Energy Corporation, have been added. Four are mounted on the rear cargo floor inside the cab (with a new cargo shelf above the tanks) and two are mounted as saddle tanks on each side of the vehicle beneath the floor. Each aluminum fuel tank is water-jacketed and insulated to facilitate heating and cooling during fuel usage and vehicle fueling. When the vehicle is operating, the engine coolant circulates through the fuel tank water jackets to warm the hydride. This helps to drive the hydrogen out of the metal hydride. During fueling, the reverse process occurs: An external cooling system is connected to the vehicle and cooled water is circulated through the water jackets to help the hydride absorb hydrogen. The external cooling system was provided with the vehicle. During fueling, it is connected to the vehicle via two quick-disconnect fittings. It cools and circulates water through the vehicle tank water jackets. It is operated by external power (110-120 volts, 15 amperes). During vehicle operation the flow of coolant through the fuel tank water jackets is verified by monitoring the temperature of the water jacket return line with a thermocouple.

An Impco model CA 125 carburetor, modified from propane to hydrogen operation, is installed on the engine. Dual Impco PEV low pressure regulators are used to lower the vehicle tank hydrogen pressure to near atmospheric. The regulators are plumbed in parallel to provide adequate flow for maximum demand conditions. The low-pressure hydrogen is plumbed through a solenoid-operated valve before it reaches the carburetor. As a safety feature, the solenoid valve will not open unless power exists through the stock ignition switch, through a separate toggle switch on the dash, and finally, through an engine vacuum-operated switch. The three switches are wired in series and must all be closed to power the solenoid valve.

The engine ignition system has been modified for hydrogen operation. A Mallory ignition transformer has been installed in place of the original coil, and the spark timing is fixed at 10 degrees BTDC. The vacuum and centrifugal advance devices have been disabled. The spark plug heat range and gap were selected by Billings for operation on hydrogen.

A water injection system has been added to suppress engine flashbacks. Spray nozzles have been installed in each of the six engine inlet ports upstream of the intake valves. A water storage tank of approximately 6 gallons capacity has been installed on the floor, beneath the front cargo tray. Air is used to pressurize the storage tank and force the water through the nozzle network. An engine vacuum-powered pump is used to pressurize the water storage tank to 15 psig. A water flow regulator senses engine intake manifold pressure and controls the amount of water injection.

SECTION III

TESTS PERFORMED

The purpose of the evaluation program was to measure fuel consumption of the vehicle, and to determine the vehicle range at fuel depletion while operating the vehicle over the Postal Service Driving Cycle (PSDC). The vehicle emissions data were determined by using the standard EPA Federal Test Procedure. In order to measure fuel consumption, refueling parameters were measured, and the hydrogen consumed was calculated from the temperatures, pressures, and known volume of the fuel source.

A. POSTAL DRIVING CYCLE TESTS

The objective of these tests was to measure the fuel consumption of the vehicle over the PSDC. A secondary objective was to determine the vehicle range to fuel depletion by repeating the delivery portion of the PSDC.

The Postal Service Driving Cycle was designed by the U.S. Postal Service to be representative of a postal service curbside delivery route. In the PSDC the vehicle is driven around a closed-loop, relatively level track (0.4% grades) with 45 stakes located 150 feet apart. The vehicle is driven in such a manner as to simulate the drive-out, stop and go, and drive-in of a mail delivery truck. A full lap, by definition, starts at stake 45 and ends at stake 45. Each lap is performed in a prescribed manner: Laps 1-3 are at steady speeds simulating drive-out; laps 4-22 consist of moving to and stopping at each of the stakes to simulate mail delivery; laps 23-25 simulate the return. All accelerations are at a rate of 3.25 ft/sec/sec and all decelerations are at 4.03 ft/sec/sec.

The estimated time to drive the 25 controlled laps is approximately 5 hours. In order to eliminate the closed-loop track (and hence allow more elaborate and sophisticated instrumentation), the PSDC was modified and adapted by JPL for testing on a chassis dynamometer. The incline grades of 0.4% and simulation of mail loading and unloading were deleted and a constant increment was added to the dynamometer inertia weight for these tests to simulate the weight of the driver and load. The drive-out and drive-in sequences of the cycle are driven first, simulating laps 1-3, and 23-25. Then the delivery sequence is driven, simulating laps 4-22. The total accumulated distance of the PSDC is nominally 31.96 miles, consisting of 7.67 drive-out/in miles, and 24.29 delivery miles.

For the PSDC, the dynamometer test inertia weight was selected based upon the curb weight (3910 pounds) plus a 150-pound driver, plus the average cargo load. Since the cargo load varies from 500 pounds at the start of a test, to zero at the end of the test, a constant 250 pounds was used. Then the test weight was computed as 3910 pounds plus 150 pounds plus 250 pounds, or a total of 4310 pounds. The nearest test inertia weight available, and the one used, was 4250 pounds.

The chassis dynamometer 50 mph load setting was 15.5 hp. This setting was provided by the EPA for this test vehicle. It is based upon the aerodynamic load calculations which appear in the Federal Register.

Since fuel depletion was expected to be somewhat gradual, the end of the test was defined as the point in time when the vehicle was unable to accomplish three consecutive 0-11 mph accelerations which occur in the delivery portion of the test. (Note that these particular accelerations did not suffer the limitations from flashback discussed in Section IV-A). This definition turns out to be unambiguous since, when an acceleration ramp was missed, the two immediately following were always missed.

Some compromises in the normal test procedure were made in order to accommodate the peculiarities of the vehicle being tested. These are as follows:

(1) Normally, the test vehicle is started <u>after</u> the test instrumentation is started. In particular, the strip-chart recorder which provides the drivers prerecorded speed-time trace is started before the vehicle, and when the instruction "start engine" passes the recording pen, the vehicle is started. Since this particular test vehicle did not start easily, the starting procedure was modified. The stripchart recorder was set to the "start engine" position but the chart drive left "off". The vehicle was then started. The engine starting process was allowed as much time as required. As the vehicle engine started, the strip-chart drive was then immediately turned on and the test begun.

(2) During the driving cycle (either the PSDC or the EPA Urban) most of the "idle" periods are supposed to be with the transmission in gear. It was found that long "in gear" idles caused the engine to die. Before the engine died, and also during the attempted restart, the engine acted as if it were "loading up", i.e. operating as a gasoline engine does when it runs too rich. However, after several occurrences, it became apparent the problem was not the result of excess fuel since there were no flashbacks on restarting and the engine appeared to be starved for fuel. The engine misfired and ran very erratically after it was restarted. It is assumed, although not verified, that the problem originated with the water injection system. There may have been an excess of water during idling which led to the idling difficulties. All of the in-gear idles were deleted in favor of in-neutral idles, and the driver was instructed to operate the throttle as required, to keep the engine running.

(3) It was found that, when the driver attempted to match the vehicle speed to the prerecorded speed/time trace (as he was instructed to do), the vehicle operated at wide open throttle a large fraction of the time. However, sustained wide open throttle, or rapid accelerations resulted in what are referred to as "flashbacks". The vehicle stumbled and ignition occurred in the intake manifold (i.e. flashback). As a means of partially avoiding this flashback problem, the driver was instructed to avoid wide-open-throttle operation, and to avoid forcing the vehicle to downshift on severe acceleration ramps. This resulted in the vehicle lagging behind the prerecorded speed/time trace. Thus, fewer total miles were accumulated over a fixed period of time than would have been accumulated by a vehicle which is capable of following the prerecorded speed/time trace.

B. 1975 URBAN DRIVING CYCLE TESTS

Federal Test Procedure (FTP) Urban Driving Cycle tests were performed to measure the vehicle emissions, and to provide fuel consumption data that would allow a direct comparison with gasoline-fueled vehicles. The 1975 Urban Driving Cycle is the current standard for measuring fuel economy and emissions. The procedure for this test is fully described in the Federal Register. The test consists of a mix of urban driving adapted to a chassis dynamometer. A prerecorded speed/time trace defined in the Federal Register is followed by the vehicle being tested. The vehicle exhaust products are collected and diluted by a Constant Volume Sampler (CVS) in a manner prescribed in the Federal Register and stored in plastic bags. At the conclusion of the driving cycle, the contents of the bags are measured to detect NO_x, hydrocarbons, CO, and CO_2. The total distance for an Urban Driving Cycle is nominally 7.5 miles performed in 31.25 minutes or actual driving time. An additional 10 minutes of test time are required for a "hot soak" of the vehicle 22.83 minutes into the test.

Five Urban Driving Cycles were performed. In three of the tests only the tailpipe emissions were recorded; in the other two total vehicle emissions were recorded, i.e. both the tailpipe and crankcase emissions. The compromises to the normal Urban Driving Cycle procedure were the same as those reported for the PSDC tests (Section III-A) with one new addition: The vehicle was not operated above 45 mph. All of the portions of the 1975 Urban Driving Cycle which are above 45 mph were reduced to a level 45 mph. This caused the total mileage accumulated for the Urban Driving Cycle to be slightly less than that recorded for a typical vehicle which follows the speed/time trace. This compromise was adopted to reduce flashbacks which were observed each time it was attempted to operate the vehicle over 45 mph, i.e. when nearly wide open throttle was required.

Test weights for the two driving cycles are calculated differently, although for this particular vehicle the results were the same. For the Urban Driving Cycle, the EPA specifies curb weight plus

300 pounds for the test weight. The test inertia weight is then set to the nearest 125-pound increment. The 4250 pound test inertia weight is nearest to 3910 plus 300 pounds.

Since the principal product of combustion from hydrogen and air is water, there is a considerable amount of water in the vehicle exhaust. For complete combustion, it can be shown that up to 9 pounds of water can be produced from the combustion of 1 pound of hydrogen. It was determined that for a complete Urban Driving Cycle, the total amount of water in the exhaust would be excessive for the capabilities of the Constant Volume Sampler (CVS) and other exhaust instruments. Therefore, the vehicle exhaust was cooled and sufficient water condensed such that the remaining exhaust stream, when at room temperature, was above its dew point. The postal vehicle, installed on the chassis dynamometer with its exhaust connected to two coolers, is shown in Figure 2. The first heat exchanger is a liquid-to-gas heat exchanger. Tap water was used for the liquid, and the gas (vehicle exhaust) temperature was reduced to approximately 225-250°F. Minimal condensation occurred in the first heat exchanger and in the plumbing between it and the second heat exchanger. The second heat exchanger shown in Figure 2 consists of a pressure vessel surrounded by a closed outer cylinder. Liquid nitrogen was used to fill the outer cylinder, and the majority of the vehicle exhaust water was allowed to condense in the inner vessel. The vehicle exhaust leaving the second heat exchanger ranged from 80-125°F. The side effects of this technique are discussed in Section IV.

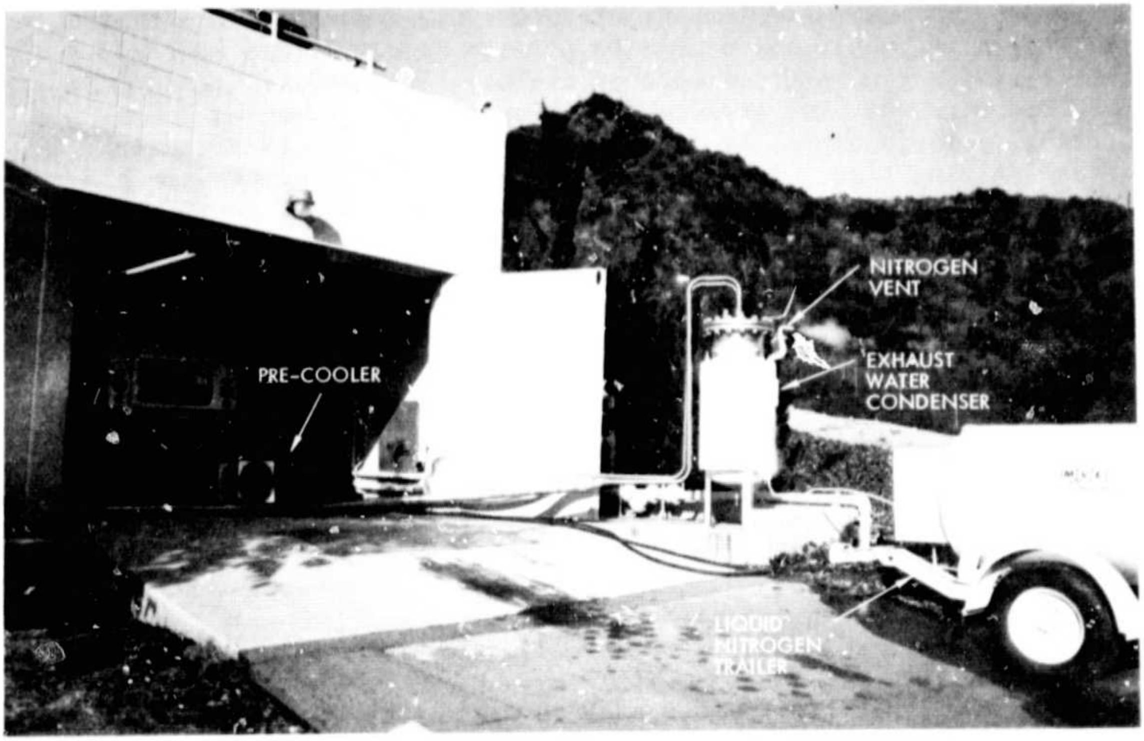

Figure 2. Exhaust Cooling System for Hydrogen USPS Jeep Tests

C. FUELING

The approach used to determine how much hydrogen was used for any particular test was straightforward: Each test was started with the vehicle storage tanks completely filled (how they were known to be full is discussed below). Then, after the test, the quantity of hydrogen required to refill the tanks was measured (again, see below). No attempt was made to measure hydrogen flowrates during a test.

Vehicle fueling was accomplished by transferring hydrogen from a storage bank of 38 cylinders. Since the cylinders had individual valves, only the number of cylinders actually required for a particular fueling operation were selected. Before and after the hydrogen was transferred to the vehicle, the temperature and pressure of the source tanks were measured. These values, along with the known cylinder volume, were used to calculate the mass of hydrogen transferred to the vehicle. The transfer of fuel to the vehicle occurred over a period of 16 hours; however, at the recommended vehicle tank pressure, most of the hydrogen was absorbed by the hydride in the first few hours. This procedure was repeated for each fueling operation so that the vehicle contained the maximum amount of hydrogen possible, and hence the same amount of fuel at the start of each test.

The ratio of hydrogen mass to hydride mass is nearly constant when the vehicle tank pressure is near 500 psig (a constant temperature is also assumed). This is illustrated in Figure 3 (by one isotherm) by the nearly vertical hydrogen/hydride ratio at 34 atm (500 psig). Small variations in the final vehicle tank pressure following refueling do not appreciably change the mass of hydrogen contained in the vehicle.

In determining the length of time required for fueling, a trial fueling, lasting nearly 22 hours, was made. The temperature and pressure of the storage bank and the vehicle tank pressure were recorded. It was observed that, after 16 hours, the system was stable and no additional hydrogen was being transferred from the source tank to the vehicle. All fueling operations took place outdoors and were planned so that fueling ended in the early morning when the system temperature had stabilized, and before the sun had begun to warm up the system. These techniques were followed because of the way in which the hydrogen temperature was measured. It was not practical to measure the gas temperature directly; therefore, the storage tank wall temperature was measured. The above procedures insured that the tank wall and the hydrogen were in thermal equilibrium.

A cooling system for use during fueling was supplied with the vehicle. It is an external heat exchanger which removes the excess heat resulting from the exothermic reaction of refueling. When connected to the vehicle, it pumps cooled water through the fuel tank water jackets. Its purpose is to cool the hydride for rapid fueling, as heat must be removed from the hydride to enable it to absorb hydrogen. For the purposes of this evaluation, the cooling system was

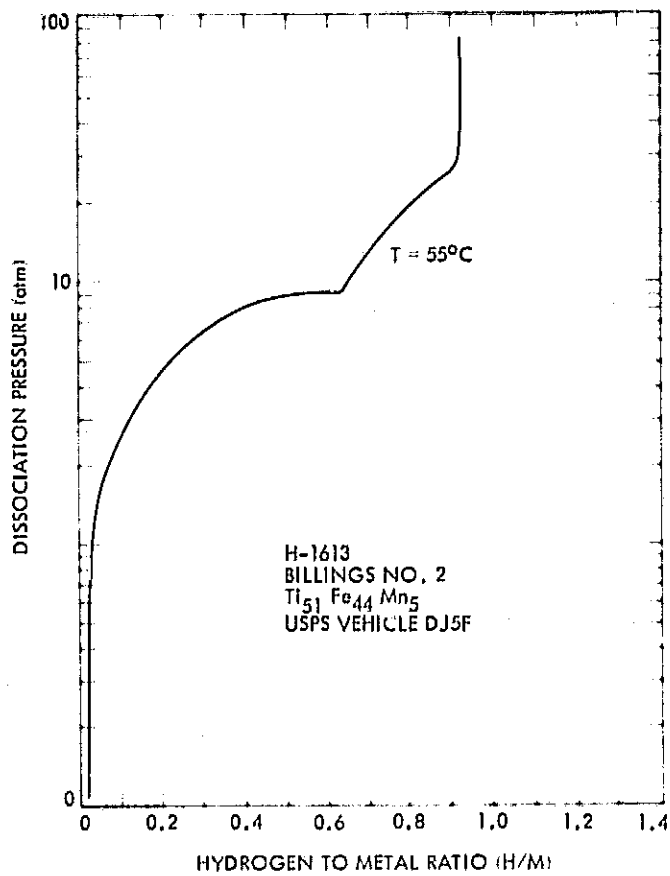

Figure 3. Hydride Dissociation Pressure Equilibrium Curve (reproduced from Hydrogen Fueled Vehicle-Hydride Storage System, Project 6120, final report to the U. S. Postal Service, by V. Anderson, Billings Energy Corp., July 31, 1978)

connected to the vehicle and operated for the first hour of each fueling. This procedure was recommended by the Billings personnel. The remainder of each fueling was accomplished with the cooling system disconnected from the vehicle.

The volume of each individual cylinder in the storage bank is stamped on it. The variation in individual cylinder volumes is only about 1%. This was judged to be a small variation, and a single value of supply tank volume (9.071 cubic feet) was used for all hydrogen mass transfer calculations.

A summary of fueling data for each JPL test appears in Table 1. The method of calculating the hydrogen mass is straightforward, and takes into account the initial and final temperatures, pressures, compressibility, cylinder volume, number of cylinders used, and the gas constant. The calculation is discussed further in the Billings final report, Hydrogen Fueled Vehicle-Hydride Storage System, Project 6120, submitted to the U.S. Postal Service, July 31, 1978.

Table 1. USPS Hydrogen Jeep - Fueling Summary

Test No.	Date (1978)	Hydrogen Consumed, lb	Test Distance, mi	Fuel Consumption, lb/mi	Vehicle Mileage, mi/lb	Vehicle Tank Press. at End of Fueling, psig	Source Tank Press., psig/Temp. °F: Start of Fueling	Source Tank Press., psig/Temp. °F: End of Fueling	Number of Cylinders (Vol=9.071 ft^3/cyl)
POSTAL SERVICE DRIVING CYCLE TESTS									
1	10-20	8.50	24.778	0.342	2.92	525.4	1959/64.7	968/61.7	3
2	10-25	8.43	24.153	0.350	2.86	525.1	1971/61.8	990/58.6	3
3	10-26	8.12	23.693	0.342	2.92	526.2	1906/59.3	976/59.6	3
3, contd.	10-27	3.48	7.957	0.366*	2.73*	489.2	1913/59.8	1232/50.2	2
URBAN DRIVING CYCLE TESTS									
1	11-27	2.23	10.450	0.213	4.69	504.3	2043/62.6	1223/49.7	1
2	11-28	2.24	10.516	0.213	4.69	511.2	2052/63.1	1229/50.2	1
3	11-29	2.15	10.15	0.212	4.72	505.9	2054/63.7	1265/52.7	1
4	11-30	2.23	10.544	0.212	4.73	503.0	2073/68.6	1232/50.4	1
5	12-1	2.40	10.543	0.228	4.39	514.8	2051/63.6	1162/45.7	1

*Total for test

SECTION IV

RESULTS AND DISCUSSION

A. POSTAL SERVICE DRIVING CYCLE TESTS

It was found that not enough fuel is carried aboard the Jeep to allow it to complete the entire Postal Service Driving Cycle. Three partial PSDC's were performed, and the average vehicle range was 24.21 miles. Each of these three tests terminated near the beginning of the third delivery sequence. The measured fuel consumption for these tests averaged 0.345 pound of hydrogen per mile.

Since none of these PSDC's could be carried to completion with the fuel available aboard the vehicle, and since the fuel consumption cited is biased slightly in the optimistic direction because the ratio of delivery cycle miles to drive-out/drive-in cycle miles was low, one PSDC was carried to completion by refueling the jeep and continuing the delivery phase from the point at which it was previously stopped. For this one test, 7.96 additional miles were completed for a total of 31.65 miles over the complete PSDC. An additional 3.48 pounds of hydrogen were used, for a total of 11.60 pounds of hydrogen over the complete postal cycle. Thus, the fuel consumption for the complete PSDC was 0.366 pound per mile. A summary of the fueling data for each of the PSDC tests appears in Table 1.

B. URBAN DRIVING CYCLE TESTS

The tailpipe-plus-crankcase vehicle emissions (Table 2) resulting from Urban Driving Cycle Tests 4 and 5, are 0.022 gm/mi HC, 0.17 gm/mi CO, and 4.86 gm/mi NO_x. The 1979 Federal standards for light trucks are 1.7/18/2.3 gm/mi, respectively. The measured HC and CO emissions were quite low, as would be expected. The measured NO_x emissions were above the Federal standard by a factor of 2.1.

The average fuel consumption for all five Urban Driving Cycle tests was 0.216 pound of hydrogen per mile. The hydrogen fuel consumption can be converted to an equivalent gasoline consumption by using the ratios of the heating values for hydrogen and gasoline. Although not exact, this gives an indication of the gasoline equivalent fuel consumption. The 0.216 pound of hydrogen per mile is equivalent to a gasoline fuel consumption of 0.578 pound per mile or approximately 10.6 mpg. The EPA-reported fuel economy data for a stock 1977 and 1979 jeep of the same type are 19.0 mpg and 15.0 mpg, respectively. If the vehicle mass is included in the energy consumption values, the test vehicle obtains 0.383 pound-mile/Btu, the stock 1977 vehicle obtains 0.484 pound-mile/Btu, and the stock 1979 vehicle obtains 0.382 pound-mile/Btu. The stock vehicles are tested with a higher (3.07) axle ratio, and a lower (3000 pound) dynamometer inertia weight. If the additional weight is taken into account, the test vehicle is less efficient than a stock 1977 vehicle, but it compares favorably with a stock 1979 vehicle.

Table 2. USPS Hydrogen Jeep – Urban Driving Cycle Emissions Data: Emissions/Phase

PHASE	DISTANCE, mi	TOTAL EMISSIONS, gm				EMISSIONS RATE, gm/mi			
		CO_2	NO_x	CO	HC	CO_2	NO_x	CO	HC
URBAN DRIVING CYCLE TEST 1									
1	3.281	0.000	12.593	0.205	0.008	0.000	3.838	0.063	0.002
2	3.883	0.000	16.249	0.457	0.037	0.000	4.185	0.118	0.010
3	3.286	4.986	15.378	0.384	0.045	1.517	4.680	0.117	0.014
Total:	10.450	4.986	44.220	1.046	0.091				
						Overall Average for 10.450 mi): 0.477	4.232	0.100	0.009
						Weighted Average* for 7.167 mi): 0.396	4.246	0.107	0.009
URBAN DRIVING CYCLE TEST 2									
1	3.343	5.721	14.600	0.232	0.021	1.711	4.367	0.069	0.006
2	3.859	2.422	16.125	0.496	0.059	0.627	4.179	0.128	0.015
3	3.314	7.733	16.672	0.306	0.061	2.334	5.031	0.092	0.018
Total:	10.516	15.876	47.397	1.034	0.141				
						Overall Average for 10.516 mi): 1.510	4.507	0.098	0.013
						Weighted Average* (for 7.185 mi): 1.293	4.441	0.107	0.014

*As defined in Federal Register

Table 2. USPS Hydrogen Jeep - Urban Driving Cycle Emissions Data: Emissions/Phase (Continuation 1)

PHASE	DISTANCE, mi	TOTAL EMISSIONS, gm CO_2	TOTAL EMISSIONS, gm NO_X	TOTAL EMISSIONS, gm CO	TOTAL EMISSIONS, gm HC	EMISSIONS RATE, gm/mi CO_2	EMISSIONS RATE, gm/mi NO_X	EMISSIONS RATE, gm/mi CO	EMISSIONS RATE, gm/mi HC
URBAN DRIVING CYCLE TEST 3									
1	2.922	7.069	19.381	0.262	0.030	2.419	6.633	0.099	0.010
2	3.893	11.800	17.112	0.630	0.073	3.031	4.396	0.162	0.019
3	3.335	10.478	17.933	0.524	0.075	3.142	5.377	0.157	0.022
Total:	10.150	29.347	54.426	1.416	0.177				
						Overall Average (for 10.150 mi): 2.891	5.362	0.139	0.017
						Weighted Average* (for 7.050 mi): 2.947	5.066	0.147	0.018
URBAN DRIVING CYCLE TEST 4									
1	3.341	0.328	17.936	0.299	0.033	0.098	5.368	0.090	0.010
2	3.886	13.258	18.460	0.877	0.127	3.412	4.750	0.226	0.033
3	3.317	7.846	17.856	0.562	0.092	2.365	5.383	0.169	0.028
Total:	10.544	21.432	54.252	1.738	0.253				
						Overall Average (for 10.544 mi): 2.033	5.145	0.165	0.024
						Weighted Average* (for 7.213 mi): 2.478	5.039	0.184	0.027

*As defined in Federal Register

Table 2. USPS Hydrogen Jeep – Urban Driving Cycle Emissions Data: Emissions/Phase (Continuation 2)

PHASE	DISTANCE, mi	TOTAL EMISSIONS, gm				EMISSIONS RATE, gm/mi			
		CO_2	NO_X	CO	HC	CO_2	NO_X	CO	HC
URBAN DRIVING CYCLE TEST 5									
1	3.303	0.000	18.490	0.246	0.024	0.000	5.598	0.074	0.007
2	3.898	20.523	16.020	0.742	0.079	5.265	4.110	[illegible]	0.020
3	3.342	4.244	17.251	0.497	0.059	1.270	[illegible]	[illegible]	0.018
Total:	10.543	24.767	51.761	1.485	0.162				
						Overall Average (for 10.543 mi): 2.349	[illegible]	[illegible]	[illegible]
						Weighted Average* (for 7.223 mi): 3.175	[illegible]	[illegible]	[illegible]

*As defined in Federal Register

A summary of the fueling data for each of the Urban Driving Cycle tests appears in Table 1. The emissions data are summarized in Table 2. Urban Driving Cycle Tests 1, 2, and 3 were performed while collecting only the vehicle tailpipe emissions. Tests 4 and 5 were performed while collecting the total vehicle emissions, including both those from the tailpipe and the crankcase.

For Urban Driving Cycle Test 3, the vehicle experienced an excessive number of flashbacks during the first 490 seconds of the test. The test was stopped and an inspection showed that the water injection source tank was not pressurized. It was found that the vacuum hose from the engine to the pressurization pump had come off the pump. The hose was reconnected, and the test was resumed. The data from this test appears to be consistent with data from the other tests, and it has been included for completeness of the data record.

C. FLASHBACK COMMENTS

Test logs were maintained during all of the PSDC and Urban Driving Cycle tests. They contain the informal comments of the vehicle and data recording operators. The large number of flashbacks experienced during the tests was mentioned frequently. Approximately 94 flashbacks were recorded during the PSDC tests, and 68 were recorded during the Urban Driving Cycle tests (in addition to the many observed during the first 490 seconds of Urban Driving Cycle Test 3, discussed above). It appears that flashbacks suppression has not been adequately implemented.

D. ACCELERATION CAPABILITY

The vehicle's acceleration capability was inadequate to achieve the accelerations required in the driving cycle tests. In addition, the avoidance of wide-open-throttle accelerations to minimize flashbacks (as indicated in Section III-A) caused the vehicle to lag even further behind the driving cycle time-velocity profile. This is not considered a serious problem, since the available acceleration capability should be adequate for the intended use of the vehicle for mail delivery.

E. EXHAUST CONDENSATE AND EMISSIONS

The condensed exhaust water from Urban Driving Cycle Tests 1 and 2 was collected and weighed. Samples of the collected water were analyzed for oxides of nitrogen and total carbon. Approximately 7800 mg/l of oxides of nitrogen were observed in 8330 gm of condensed water. This corresponds to 65 gm of condensed oxides of nitrogen for Urban Driving Cycle Test 1. This is of the same order of magnitude as the NO_x measured in the exhaust gas (44 gm/test, from Table 2). The hydrocarbons were the same order of magnitude as what remains in the exhaust gas but the total was negligible as expected.

The procedure defined for the EPA emissions measurements requires that a dry vehicle exhaust sample be analyzed. The oxides of nitrogen and carbon condensed in the water are not normally of concern when testing gasoline-fueled vehicles. Since water is the prime combustion product for hydrogen-fueled vehicles, and oxides of nitrogen and carbon are known to condense in water, the water was analyzed. These results are provided to show that considerable additional oxides of nitrogen are being formed by the test vehicle, and they are being condensed in the exhaust water. These results should not be arbitrarily added to the reported emission results since the technique employed to obtain the dry sample for analysis is not in conflict with the EPA procedure. However, it is recommended that for future emissions tests of hydrogen-fueled vehicles, the procedure for obtaining the emissions data be carefully considered. Condensed emissions are a small portion of the total from a gasoline-fueled vehicle, but a much larger portion of the total from a hydrogen-fueled vehicle.

F. OPERATING AIR/FUEL RATIO

Since the test vehicle experienced a considerable number of flashbacks, and the Urban Driving Cycle NO_x emissions were high, it was suspected that the vehicle was operating at an equivalence ratio* which would aggravate these conditions. An investigation of the approximate equivalence ratio at typical steady-state level-road load (LRL) conditions was performed. The approximate equivalence ratio was determined from measurements of the vehicle exhaust oxygen content. The relationship of theoretical exhaust oxygen content to combustion equivalence ratio is illustrated in Figure 4. The measured

*Equivalence ratio (ϕ) is the stoichiometric air/fuel ratio divided by the actual operating air/fuel ratio. Thus, ϕ less than 1.0 indicates leaner than stoichiometric combustion.

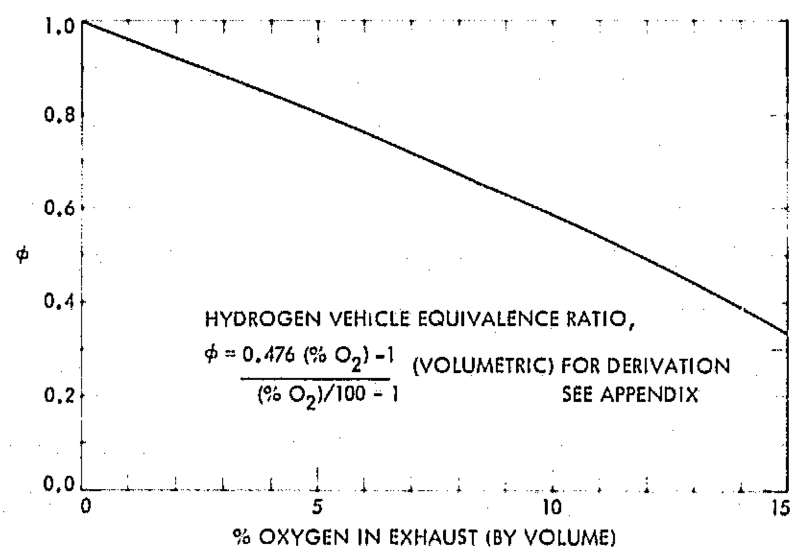

Figure 4. Equivalence Ratio vs. Exhaust Oxygen Volume for Hydrogen and Air Combustion

oxygen by volume in the exhaust was 3.6% at 15 mph LRL, 3.8% at 30 mph LRL, and 4.9% at 40 mph LRL. These correspond to equivalence ratios of 0.85, 0.86, and 0.81, respectively. Indeed, the vehicle was operating in the equivalence ratio region near maximum NO_x production, and flashback susceptibility. Further investigation of the trade-offs between emissions, flashback susceptibility, efficiency, and performance is recommended. Previous JPL experience with hydrogen-fueled vehicles has demonstrated more satisfacotry results where the engine operates in the equivalence ratio region of 0.60 to 0.70.

G. WATER INJECTION SYSTEM

The water injection system was observed to consume 4 gallons for 5 Urban Driving Cycles. This corresponds to 0.077 gallons per mile or 8 gallons per 100 miles over the Urban Driving Cycle. (By comparison, to give a single example, it may be noted that the UCLA Postal Jeep consumes 0.11 gallons of water for 100 miles of highway driving. This was reported in paper 6C-97, Crash Test of a Liquid Hydrogen Automobile, presented at the First World Hydrogen Energy Conference, March 1-3, 1976). The water injection schedule as a function of vehicle operating condition was not measured, but it is believed that an excessive water flowrate exists at idle. This was evidenced by the engine's "drowning out" at idle. The high frequency of flashbacks at higher RPMs and loads suggests that there may be too little water injection at these conditions. The implementation of the water injection should be further investigated.

H. SAFETY CONSIDERATIONS

The iron-titanium hydride tanks have been tested by the Billings Energy Corporation. Evaluations of the tanks, the pressure relief valve, the systems pressure rating, and the hydrogen valves are discussed in the Billings final report, Hydrogen Fueled Vehicle-Hydride Storage System, 104231-B-0073, 4VS-770502-300, Project 6120, submitted to the U.S. Postal Service, July 31, 1978. The additional vehicle hydrogen system comments offered here regard the selection of materials for the vehicle plumbing, the location of the tanks within the vehicle, and operator cautions.

Copper tubing has been used to plumb the hydrogen system. The automobile industry typically avoids copper tubing out of cost considerations, and also because it tends to work-harden and eventually crack when subjected to use in a vehicle. If this vehicle is placed in service, it is suggested that the complete plumbing system be frequently monitored for leaks. During this evaluation program, one small leak was detected at a pipe plug near the front of the right saddle tank. The pipe plug was tightened a small amount and the leak disappeared. A commercial soapy-solution leak detector, Snoop, was used to monitor leaks.

The main hand-operated hydrogen shutoff valve was suspected of having an internal hydrogen leak at the conclusion of the evaluation program. It was noted that the hydrogen tank pressure sometimes remained on the dashboard gauge more frequently towards the end of the program. More and more operator force was required to close the hand shutoff valve.

The hydrogen tank locations suggest that some type of "caution" notices to the operator might be advisable. It is suggested that the outside of the driver's door have a caution notice to the effect that the door should be opened and the vehicle allowed to ventilate for a few minutes after it has been closed for long periods of time. It is also suggested that an operator caution be displayed on the dash which advises no smoking within the vehicle, and that the vehicle is hydrogen-fueled.

I. DRIVER COMFORT

Warm engine water is circulated in the jackets around each of the fuel tanks. Since four of the fuel tanks are in the cab, the driver's comfort operating the vehicle in warm ambient areas is a matter of concern. It was found during the test program that operating the vehicle in a partially closed test cell on a chassis dynamometer did not provide adequate driver comfort with the vehicle doors closed. The vehicle cab temperature, determined from a thermocouple located near the driver's left ear, was recorded during the driving cycles. The temperature was also recorded from a thermocouple tucked under the insulation on the water system plumbing of the fuel tank water jackets next to the drivers left side. At the completion of one of the tests, the vehicle doors were shut, and the vehicle and test cell were allowed to soak. The temperature recorded provided an indication of the higher temperatures that might be experienced in the cab. The vehicle cab air temperature reached 98°F. This occurred while the fuel tank water jacket was cooling from 150°F to 140°F, after having been as high as 180°F during the previous operation. The ambient air temperature in the test cell remained at 75°F to 78°F during this study, and was never higher than 85°F during the previous vehicle operation.

J. VEHICLE WEIGHT

The vehicle was weighed when it was initially received at JPL and the following weights were recorded:

Left front wheel	780 lb
Right front wheel	760 lb
Left rear wheel	1230 lb
Right rear wheel	1140 lb
Front axle	1570 lb
Rear axle	2325 lb
Total vehicle	3910 lb

The above record was made without operator or cargo. It was performed on a truck-type Webb scale, surface mounted, 30-ton capacity, Serial #7033. It carries an American Scale Company inspection certification. The total vehicle weight was used to calculate the dynamometer inertia weight as discussed in the driving cycle test section of this report.

K. SPEEDOMETER CALIBRATION

The vehicle rear axle ratio was changed by the Billings Corporation without making a compensating change in the speedometer drive gear. The following table correlates actual vehicle speeds with readings of the vehicle speedometer:

ACTUAL MPH	VEHICLE SPEEDOMETER MPH
15	25
30	50
40	70

L. CARBURETOR, PRESSURE REGULATORS, AND VEHICLE MAINTENANCE

During the initial portion of the evaluation, while attempts were being made to rigorously follow the PSDC and Urban Driving Cycle velocity-time traces, the vehicle experienced a considerable number of flashbacks. These most frequently occurred during wide-open throttle (WOT) accelerations, or when the vehicle automatically down-shifted (which is also a near WOT condition). They also occurred at vehicle speeds above 45 mph. Following severe flashbacks, the vehicle usually would not idle properly, and on two occasions, would no longer develop power above idle. In each case the cause of this condition was a broken diaphragm-operated valve in the carburetor. This is illustrated in Figure 5. The smaller section shown in the figure is a portion of the fuel metering system. It is part of a metal casting and is supposed to be located in the center of the larger section below it in the figure. This failure of the casting, caused by severe flashbacks, is typical of seven diaphragm failures which occurred during the evaluation. Six of these failures occurred prior to the performance of the first PSDC.

While being prepared for the Urban Driving Cycle tests, the vehicle was exposed to some 45 to 57 mph conditions during practice runs. Severe flashbacks were experienced followed by an audible leaking of hydrogen to the atmosphere from one or both of the hydrogen pressure regulators. A leak test revealed that the leak was in the area where the regulator diaphragm is secured by the two halves of the body. Regulator repair kits were provided by Billings (Impco Kits) and were installed by JPL personnel. The carburetor diaphragm was also replaced at this time because of prior experience, but the removed diaphragm did not have a broken casting, as did all the other replaced carburetor diaphragms.

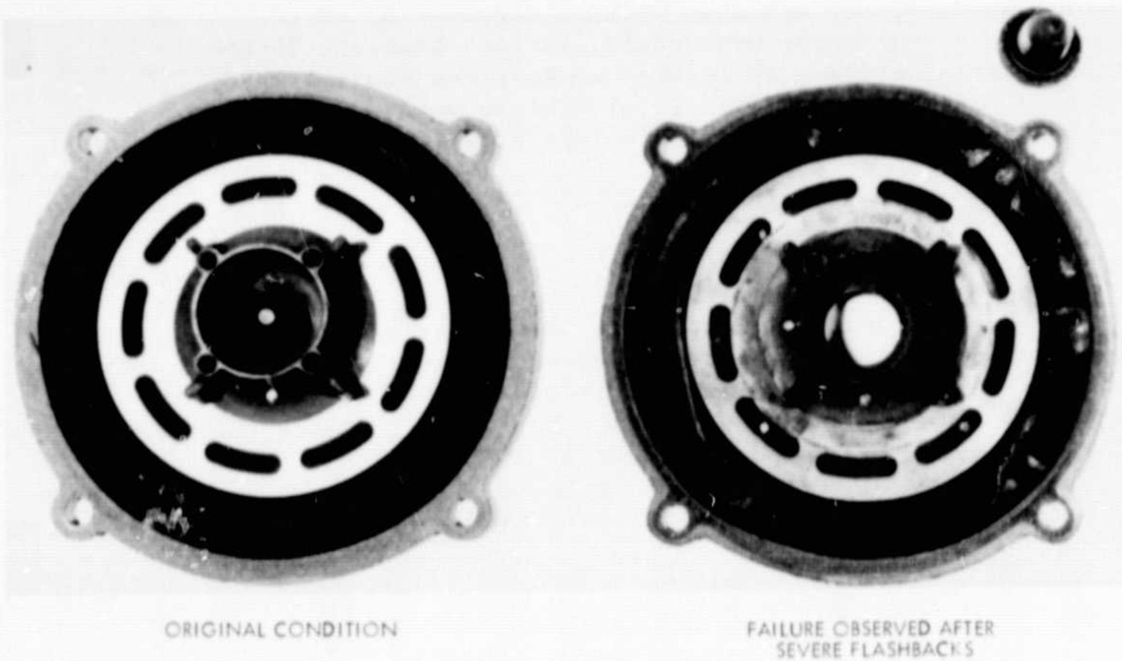

Figure 5. USPS Hydrogen Jeep - Carburetor Diaphragms

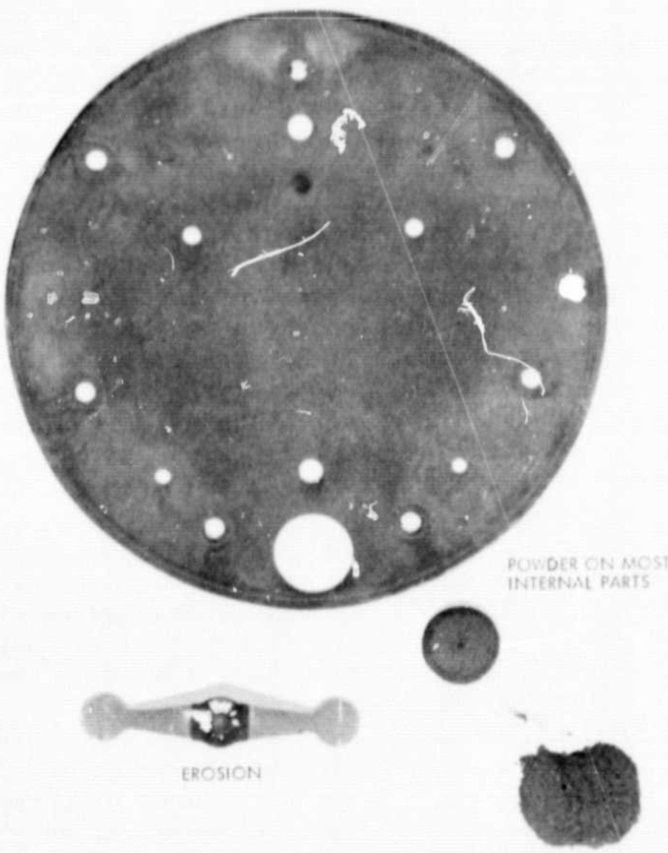

Figure 6. USPS Hydrogen Jeep - Fuel Regulator Internal Parts

During the repair of the regulators, it was noted that the inside regulator surfaces were covered with a fine, dark-gray powder. A flow valve in one of the regulators was severely eroded such that it could no longer seal. These conditions are illustrated in Figure 6. A portion of the powder recovered from the regulators was sent to Billings and they concluded that the powder was iron-titanium hydride. The hydride is evidently not being held in the tanks. This should be noted as a potentially serious problem. Premature engine wear may result from relatively small amounts of the iron-titanium.

Aside from the above-mentioned carburetor/diaphragm repair work, little maintenance was performed during the evaluation. During the checkout and preparation phase of the evaluation and prior to any of the PSDC or Urban Driving Cycles, a Billings representative twice verified proper vehicle performance. The first time that the JPL operation was inspected by the Billings representative, the problem with the carburetor diaphragm was discussed and JPL personnel were shown how to change the diaphragm. The first broken carburetor diaphragm was replaced at this time.

The second time the Billings representative visited JPL, four carburetor diaphrams had been broken and the Billings representative installed new spark plugs, adjusted the water injection system, arranged the spark plug wires (to avoid potential cross-firing), checked the ignition spark timing, and checked the vehicle coolant and crankcase levels. The Billings representative monitored a practice PSDC test, during which the fifth carburetor diaphragm was changed. Following this practice test, the vehicle was declared by Billings to be operating as designed and ready for evaluation. The tune-up parameters were not adjusted again during the evaluation.

During another practice PSDC test, the vehicle appeared to be fuel starved, and it was noted that the fuel tank water jackets were cold. The problem was discussed with Billings personnel, and they suggested bleeding the fuel tank water jacket plumbing. This was done and air was found in the system. Air had probably been admitted to the coolant system during a prior fueling operation. Bleeding of vapor from the tank water jacket plumbing is a routine maintenance item, and a valve is included on the vehicle for this purpose.

As indicated previously, in Section II, the air injection reactor pump has been replumbed to provide positive crankcase ventilation. One reason for this is to minimize water accumulation in the crankcase. No evidence of water was observed on the engine crankcase dipstick, but emulsified oil could be observed in the rocker area through the oil-fill port on the rocker cover. This evidence of water remained visible throughout the evaluation program.

SECTION V

SUMMARY AND RECOMMENDATIONS

The performance of a U. S. Postal Service Jeep delivery vehicle, modified by the Billings Corporation to operate on hydrogen, has been evaluated by the Jet Propulsion Laboratory. Prior to the start of the evaluation, proper vehicle operation was verified at JPL by a representative from the Billings Energy Corporation.

The objectives of this evaluation were to measure vehicle fuel consumption and range over a defined Postal Service Driving Cycle (PSDC), and to measure vehicle emissions and fuel consumption over the EPA 1975 Urban Driving Cycle. The fueling technique and driver comfort were also evaluated.

The vehicle energy consumption was 0.366 pounds of hydrogen per mile over the PSDC, and 0.22 pounds of hydrogen per mile over the Urban Driving Cycle. These data correspond to 6.2 and 10.6 mpg equivalent gasoline mileage for the two driving cycles, respectively. The EPA measured 19.0 mpg in 1977 and 15.0 mpg in 1979 for equivalent stock models tested with their higher axle ratio and lower test weight. If the weight of the vehicle is included, the energy consumption values are 0.383 pound-mile/Btu for the test vehicle, 0.484 pound-mile/Btu for a stock 1977 vehicle, and 0.382 pound-mile/Btu for a stock 1979 vehicle. If the additional weight is taken into account, the test vehicle is less efficient than a stock 1977 vehicle, but compares favorably with the 1979 stock vehicle.

The vehicle range was found to be inadequate to complete a PSDC. The measured vehicle range was 24.2 miles, while the complete PSDC is 32 miles. One PSDC test was carried to completion by refueling the vehicle and continuing the test. The results of this test are presented above.

The measured HC and CO emissions, over the Urban Driving Cycle, are quite low, as would be expected. The oxides of nitrogen were found to be 4.86 gm/mi, a value which is significantly above the Federal (2.3 gm/mi) and California (2.0 gm/mi) standards.

Flashbacks (ignitions in the intake manifold) were found to be a frequent problem with the test vehicle when it was operated near wide-open throttle (WOT). Approximately 94 flashbacks were recorded during the PSDC tests, and 68 during the Urban Driving Cycle tests. Numerous other flashbacks were observed during practice tests.

The vehicle's acceleration capability was inadequate to achieve the accelerations required in the driving cycle tests. In addition, the avoidance of wide-open-throttle accelerations to minimize flashbacks (as indicated in Section III-A) caused the vehicle to lag even further behind the driving cycle time-velocity profile. This is not considered a serious problem, since the available acceleration capability should be adequate for the intended use of the vehicle for mail delivery.

Operation of the vehicle's water injection system does not appear to be optimal. There appears to be excess water injection at idle, and neither the oxides of nitrogen emissions nor flashbacks were adequately suppressed. Water injection should be more effective in controlling both oxides of nitrogen and preventing flashbacks. It is recommended that the water injection schedule be further evaluated.

The equivalence ratio at which the test vehicle operates was determined by measuring the oxygen content of its exhaust. The steady-state equivalence ratio was determined to be approximately 0.81 to 0.86. This is the region of maximum oxides of nitrogen production, and possibly in the region of maximum susceptibility of flashbacks. It is recommended that operation of the vehicle be investigated at lower equivalence ratios. Lower oxides of nitrogen and less susceptibility to flashbacks should be experienced if the equivalence ratio is changed to be in the region of 0.6 to 0.7.

The vehicle cab temperature was found to be uncomfortably high. This was due to the close proximity of the heated fuel tanks to the cab. Moving the tanks, providing better insulation, or operating the vehicle with the windows or doors open should minimize the problem in warm climates.

Iron-titanium hydride was found in the fuel system. The source of this should be found and corrected. Wear in the engine should be measured to determine if the iron-titanium hydride has caused any engine damage.

The cause of the emulsified oil observed in the rocker arm cover should be investigated. It should be determined if the emulsified oil is a result of the combustion products entering the crankcase past the rings (which is more or less normal) or is a result of a mechanical defect within the engine.

APPENDIX

DERIVATION OF THE EQUIVALENCE RATIO FOR A HYDROGEN-POWERED VEHICLE

The idealized chemical equation of combustion is

$$H_2 + X(O_2 + 3.76N_2) \rightarrow H_2O + (X - 1/2)O_2 + 3.76X(N_2)$$

where the volumetric air/fuel ratio = X/1

If V equals the fraction of oxygen in the gaseous combustion products (after drying), then

$$V = (X - 1/2)/\left[(3.76X) + (X - 1/2)\right] = (X - 1/2)/(4.76X - 1/2)$$

Since the equivalence ratio, ϕ , is defined as the stoichiometric air/fuel ratio divided by the operating air/fuel ratio, and X = 1/2 for stoichiometric operation, then

$$\phi = 0.5/(X/1) = 0.5/X$$

By solving for X as a function of V, then

$$X = \left[(V - 1)/2\right]/(4.76V - 1)$$

$$\phi = (4.76V - 1)/(V - 1) \qquad \text{(volumetric)}$$