JPL's Electric and Hybrid Vehicles Project—Project Activities and Preliminary Test Results

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It is clear that energy in America will become more expensive and more scarce, quite possibly to major crisis proportions in the late 1980's and in the 1990's. Petroleum fuel will certainly become the most critical element in the energy mix, largely because the United States is dependent on dwindling and interdictable foreign sources for an increasingly large share of its oil.

Since roadway vehicle operation accounts for 25 percent of the country's total petroleum use, there is obvious value in reducing gasoline use by cars and light trucks, even if this brings about no reduction in total U.S. energy consumption. However, a realistic assessment suggests that the private automobile is too deeply entrenched in the National culture and transportation scheme to be readily eliminated as a primary means of transportation for the average citizen, even as gasoline prices continue to rise dramatically.

A partial but important solution seems to be the development of light vehicles powered by energy sources other than petroleum. Electric and hybrid electric-gasoline vehicles are prime candidates for this task, largely because electricity is a source now conveniently available for the average American.

In 1976, the Department of Energy (DOE) began implementing its electric and hybrid vehicle program at Caltech's Jet Propulsion Laboratory. The structure and goals of the Electric and Hybrid Vehicle System Research and Development project are given in figure 1.

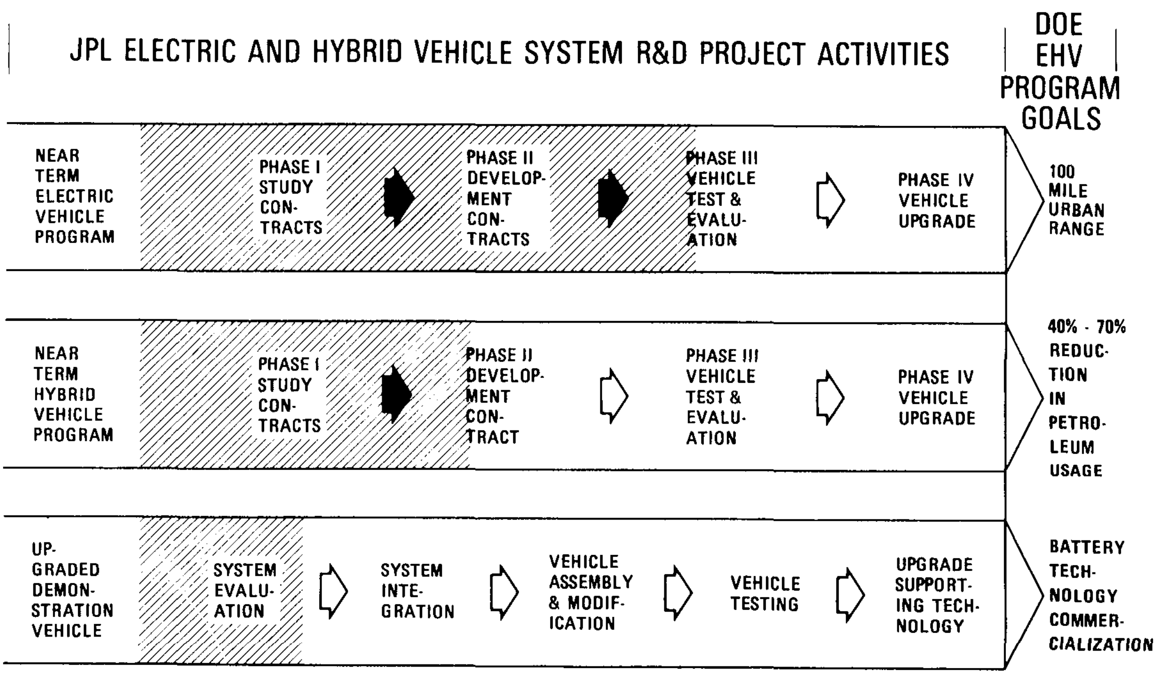

Figure 1

Hardware

Near-Term Electric Vehicles

Table I shows the state of the electric vehicle art in 1976 and the DOE goals for 1980. They are stringent, particularly the requirement for a 75-mile range. Two contractors have developed vehicles intended to meet these goals: Garrett AiResearch and General Electric Corp. The results of their efforts so far are set forth below.

Garrett AiResearch.—Garrett's vehicle is a four-passenger car that is flywheel assisted and battery powered and uses an all-plastic body. It incorporates some highly innovative approaches, as shown in figure 2. The corrugated structure in the front of the car is designed to allow a controlled, noninjury frontal barrier crash from 30 mph (fig. 3).

The batteries are housed in a central tunnel extending into the passenger compartment much like the drive shaft tunnel in today's gasoline-driven cars. Figure 4 shows the battery tunnel open and the batteries being rolled out. The batteries can be disconnected and removed from their carriage in approximately 30 minutes.

Figure 5 shows the Garrett vehicle flywheel, highlighting its construction. It is composed of nine layers of ribbon: a single inner layer of S2 fiberglass, four layers of Kevlar 29, and four outer layers

TABLE I.—STATE OF THE ART AND OBJECTIVES OF THE NEAR-TERM ELECTRIC VEHICLE PROGRAM

	Presently available	Near-term (1980 objectives)
Range, miles	30	75
Top speed, mph	40	60
Acceleration (0 to 30 mph), sec	25	9
Safety standards	Essentially none	All FMVSS
Cost, dollars	Variable (3000 to 12 000)	5000 (FY 1975 dollars)
Recharge time, hr	Up to 12	6 or less

OVERALL VIEW OF GARRETT ELECTRIC VEHICLE

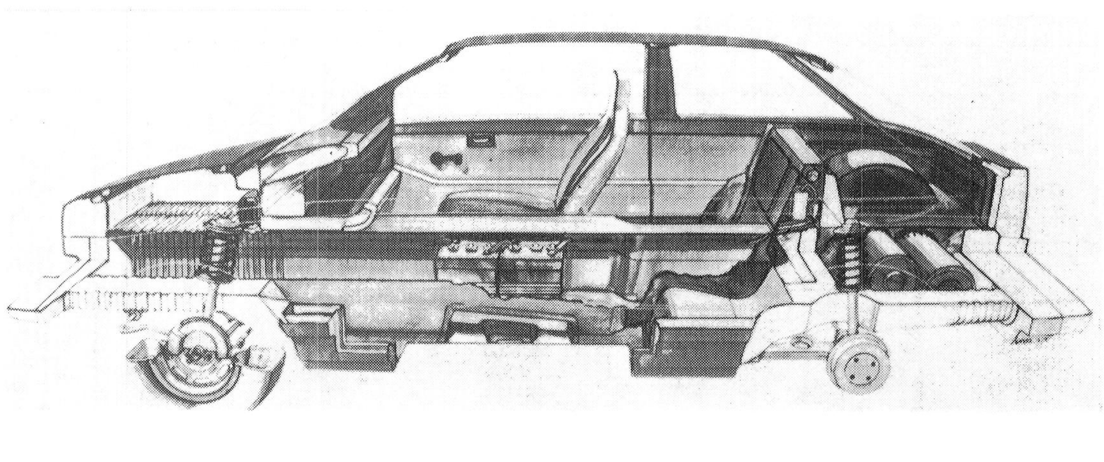

Figure 2

CONTROLLED COLLAPSE OF GARRETT ELECTRIC VEHICLE

FRONT END AT 30 mph

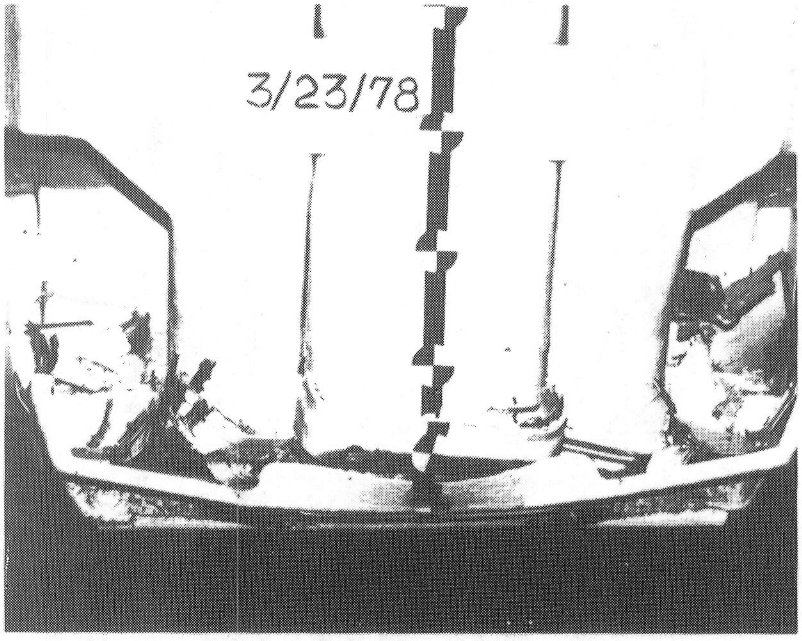

Figure 3

BATTERY CARRIAGE EXTENDING FROM

GARRETT ELECTRIC VEHICLE

Figure 4

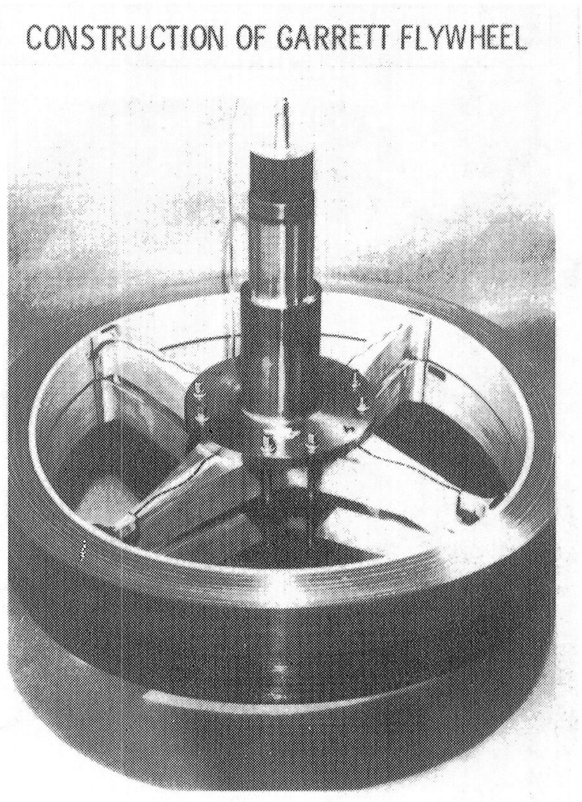

Figure 5

of Kevlar 49. Because of its layered fiber design, a high-speed failure of the flywheel causes the fibers to disintegrate into a "cotton candy" type of material (fig. 6), eliminating the danger of chunk fragmentation present in more conventional flywheels. The Garrett vehicle is now fully assembled (fig. 7) and is being tested on a dynamometer.

General Electric Corp.—The GE-designed vehicle, shown in figure 8, is a more conventional car than the Garrett vehicle. It is a four-passenger, all-metal car and uses significantly less innovative design and materials than the Garrett vehicle. It has front-wheel drive and a front motor, much like conventional compact cars. The batteries, as in the Garrett vehicle, are housed in a center tunnel.

Figure 9 shows the GE car in construction. It uses unit body construction, very similar to today's compact cars and therefore easily adaptable to current assembly-line construction. Figure 10 shows the underside of the GE car with the batteries and battery tray on the floor below the car. It is more difficult to install and remove the batteries from the GE car than from the Garrett car, largely because the GE car must be elevated on a lift to allow removal of the batteries. However, the GE car employs a central watering system so that batteries do not have to be removed from the car to add water. The GE car's shell is very stylish, as evident in figure 11. It is also quite functional: Its aerodynamic design gives it a drag product of 5.8 ft^2 (vs 10 ft^2 for the equivalent Volkswagen Rabbit). Other test results are as follows:

(1) Range with 300-lb payload
- (a) J227a schedule D, 74 miles
- (b) Constant 45 mph, 92 miles
- (c) Constant 35 mph, 123 miles

(2) Top speed, 71.4 mph

(3) Acceleration
- (a) 0 to 30 mph, 8.7 sec

GARRETT FLYWHEEL TESTED TO DESTRUCTION

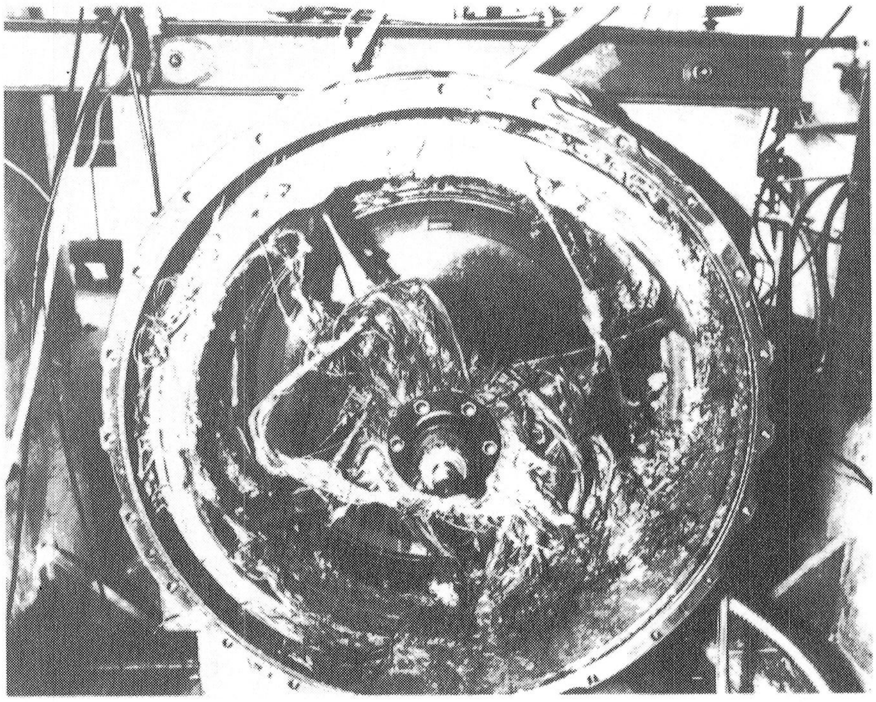

Figure 6

BODY STYLING OF GARRETT ELECTRIC VEHICLE

Figure 7

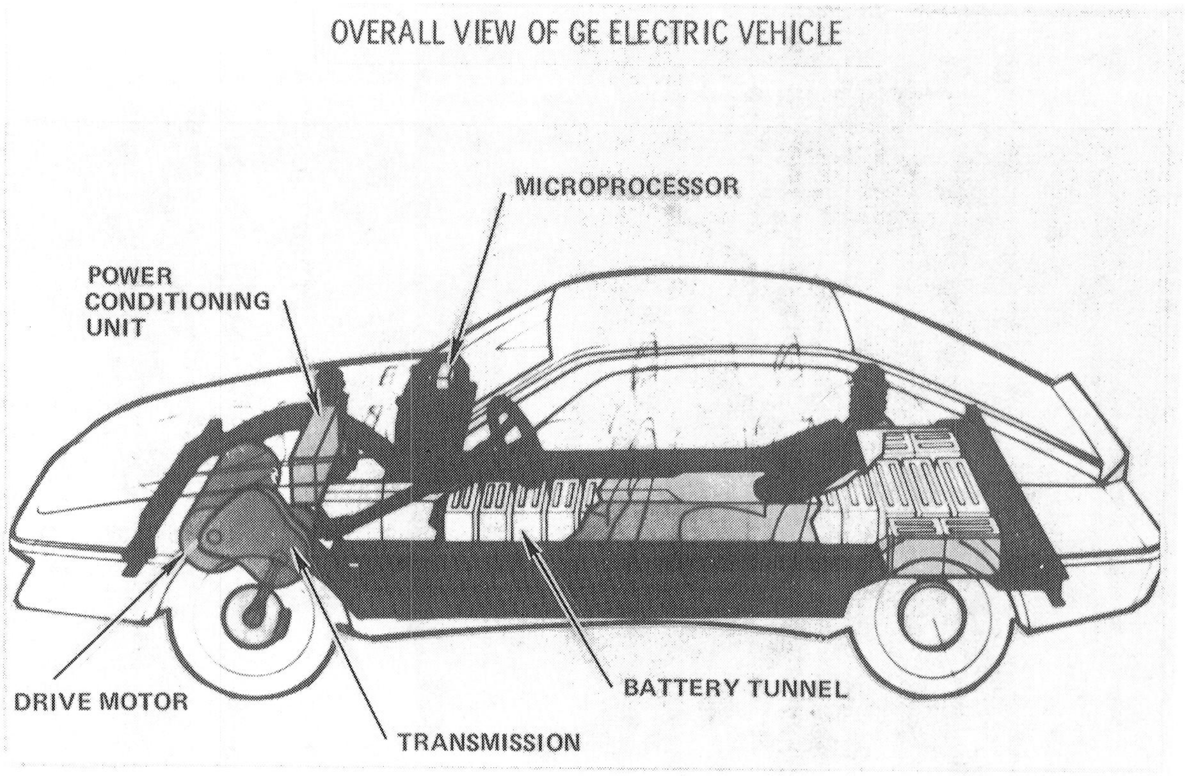

Figure 8

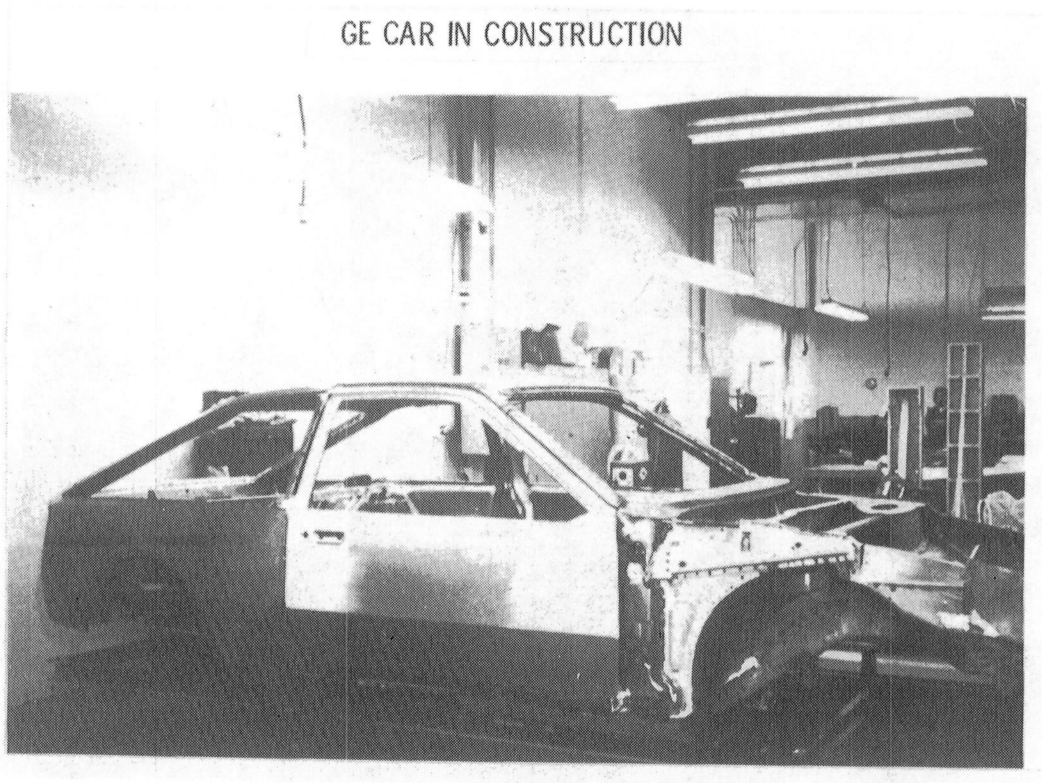

Figure 9

GE CAR WITH BATTERY TRAY REMOVED

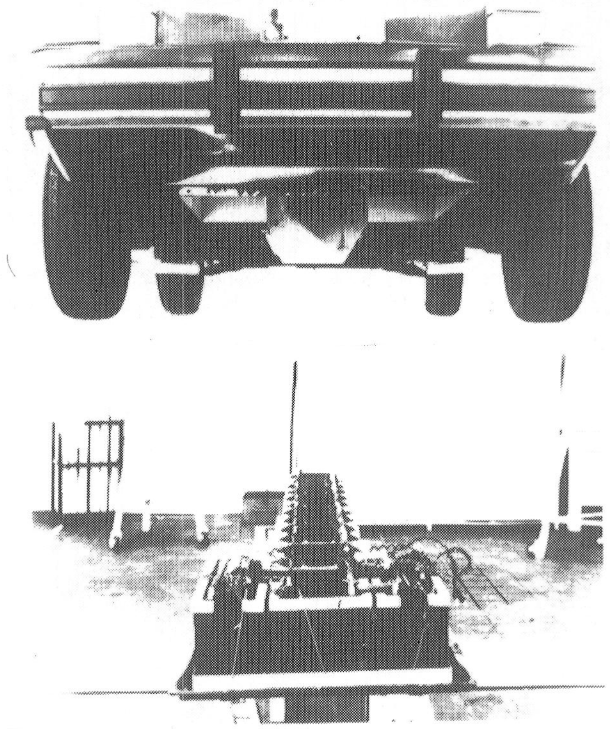

Figure 10

BODY STYLING OF GE ELECTRIC VEHICLE

Figure 11

(b) 25 to 55 mph, 21 sec
(4) Gradeability, 18% grade for 45 sec

Near-Term Hybrid Vehicles

Phase II of this program, the detailed design and fabrication phase, has just begun. Phase I, the study phase, was conducted largely by General Electric, South Coast Technology, MiniCars, and CR Fiat. Results of Phase I from all four contractors indicate that a parallel hybrid is a better choice for implementation than a series design. Parallel refers to a design in which both the electric motor and the internal combustion engine may directly power the drive wheels. In a series arrangement, only the electric motor directly powers the wheels, the heat engine's function being only to energize the motor. Table II shows the specifications for the near-term hybrid vehicle.

TABLE II.—NEAR-TERM HYBRID VEHICLE SPECIFICATIONS

Speed capability, km/h	
Cruise	90
Maximum	(a)
Acceleration time, sec:	
0 to 50 km/h	6
40 to 90 km/h	12
Gradeability:	
Speed on 3-percent grade, km/h	90
Minimum duration, km	1.0
Payload:	
Number of passengers	5
Cargo capacity, m^3	0.5
Total payload, kg	520

[a]Not specified.

In the GE vehicle shown in figure 12, the electric motor and the internal combustion engine both feed into the same transmission, which drives the two front wheels. The GE car is relatively large at 5-passenger capacity; its size illustrates a fundamental difference between electric and hybrid vehicles. An electric vehicle cannot accommodate more than 4 passengers because of limitations imposed by energy storage. The GE car is approximately the size of today's "A-body" cars such as the GM Malibu.

Upgraded Demonstration Vehicles

Each experimental vehicle being tested by the EHV project will be tested with the batteries installed in it as delivered. When that testing is completed, each car will be tested with nickel-iron, nickel-zinc, lead-acid, and zinc-chlorine batteries.

Figure 13 shows the South Coast Technology VW Rabbit being tested with Westinghouse nickel-iron batteries. Note that the tests are being conducted with the batteries adjacent to the car rather than in it. Figure 14 shows the SCT Rabbit being tested with ESB advanced lead-acid batteries. A summary of the test results appears in table III.

GE PARALLEL HYBRID VEHICLE

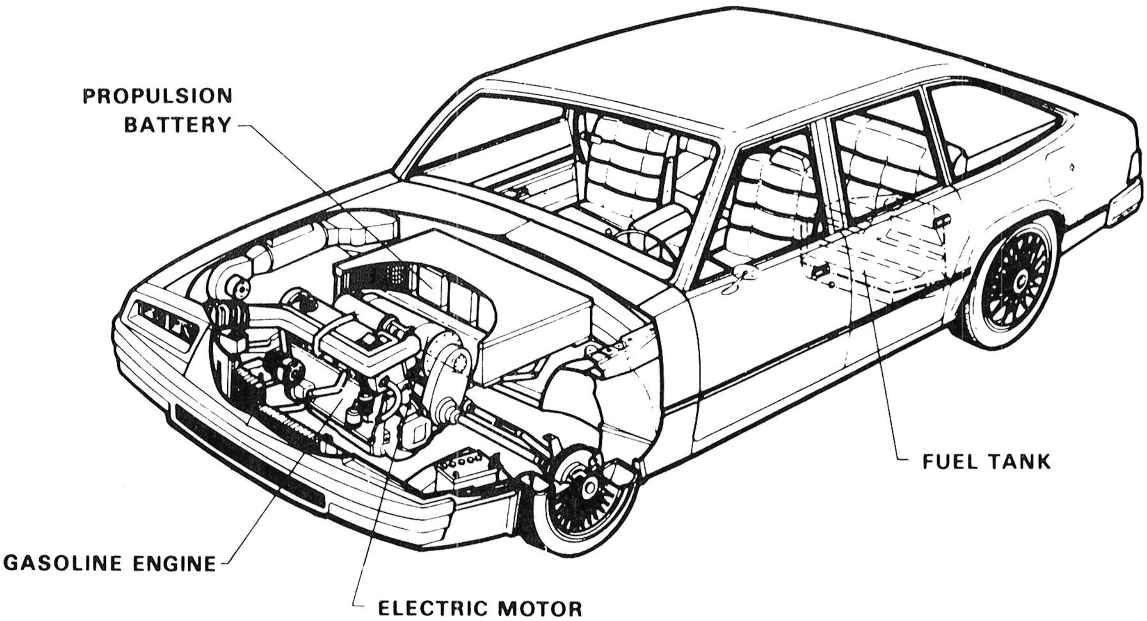

Figure 12

TESTING OF SOUTH COAST TECHNOLOGY VW RABBIT WITH WESTINGHOUSE Ni-Fe BATTERIES

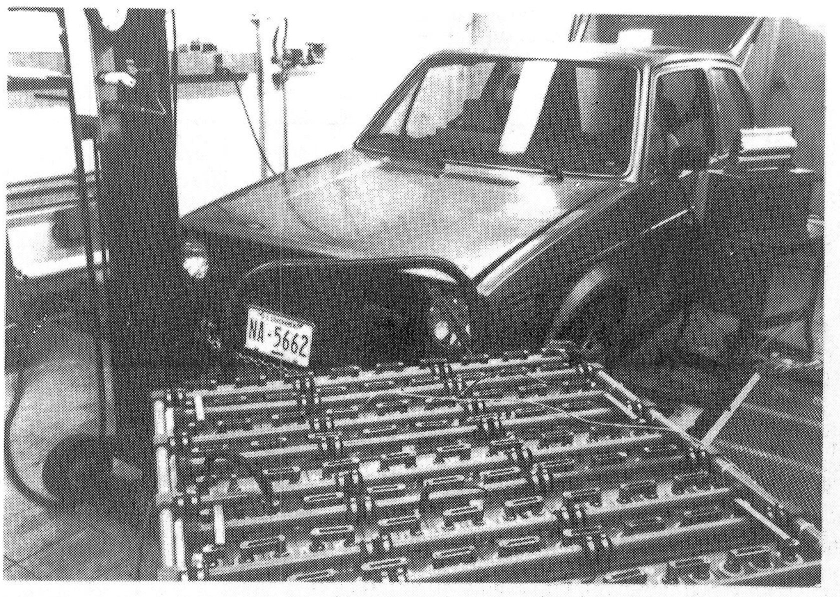

Figure 13

Figure 14

TABLE III.—COMPARISON OF BATTERY PERFORMANCE

Battery type	Power, kWh	Cycle life	Vehicle range (D-cycle)[a], miles	Recharge time, hr
Lead-acid	18	40	36	10-12
Nickel-zinc	26	8-10	49	(110 V, 30 A)
Nickel-iron	24	(b)	48	5-6
Zinc-chlorine	[c]36	1000	[c]105	(220 V, 30 A)

[a] D-cycle = Stop-and-go driving test.
[b] Unknown.
[c] Estimated.

Battery Test Results

The SCT vehicle near-term battery tests on the JPL dynamometer have been completed, and the results are presented here. However, at the time of this paper, the other 2 × 4 vehicles (two wheels in front, four in the rear to support the battery pack) had not completed the testing program for various reasons, and only limited baseline test data were available.

The SCT vehicle was fairly reliable in over 6500 km (4000 miles) of testing at JPL. Yet the motor required replacement, and intermittent problems with the controller hampered normal operation early in the test program. The SCT vehicle has exhibited substantial reduction in energy consumption over the testing period, attributed to vehicle break-in (i.e., reduction in rolling resistance and drivetrain losses). The break-in period is continuing after 9000 total driven kilometers though the drop in energy consumption in identical tests appears to be leveling off. Because of this new vehicle break-in characteristic, the range of the SCT vehicle should not be viewed as the ultimate comparator of the near-term batteries. The apparent energy density exhibited by the batteries in each of the tests, which is less directly affected by the differences in vehicle energy consumption, would be a fairer comparison.

Results obtained from testing the SCT vehicle with both the baseline and near-term batteries are presented in the following sections.

Maximum Acceleration

The results of the maximum-effort acceleration tests, which were conducted at Edwards Air Force Base, California, are

(1) 0 to 48 km/h (30 mph) in 9.8 to 11.4 sec

(2) 0 to 72 km/h (45 mph) in 21.1 to 24.9 sec

These results show that the acceleration capability of the SCT satisfies the 2×4 program requirement of 0 to 48 km/h in 11 seconds and the J227a "D" cycle acceleration requirement of 0 to 45 mph in 25 seconds.

Constant-Speed Results

The baseline lead-acid battery supplied with the SCT vehicle (ESB XPV-23) performed consistently throughout the testing period. The 35-mph test produced a range of approximately 80 miles. The range dropped to about 44 miles at 55 mph, reflecting the higher road load and lower net energy output of the battery at higher power levels (i.e., "soft" discharge capability). The battery supplied approximately 15 kWh in the 35-mph range test, with a constant power demand of about 6 kW. However, the energy capacity was reduced by almost 25 percent to approximately 12 kWh when tested at the higher power requirement (13 kW) of the 55-mph test. The results of testing the SCT vehicle at constant speeds with the baseline lead-acid battery as well as the near-term batteries are shown in table III.

The ERC nickel-zinc battery substantially increased the range of the vehicle at 35 mph to 121 miles (initially); but when tested at 55 mph, the battery produced a negligible improvement over the baseline battery. The battery was found to be quite "soft" compared to the baseline lead-acid battery, with the energy capacity reduced by 54 percent in a 55-mph test when compared to a 35-mph test (21.7 kWh at 35 mph vs 9.9 kWh at 55 mph). In the same tests the ampere-hour capacity dropped by a like amount, with the battery yielding 210 Ah in the 35-mph test versus 101 Ah at 55 mph.

The Yardney nickel-zinc battery exhibited a very "hard" discharge capability. The energy capacity dropped only 6 percent, from 21 kWh to 19.7 kWh, in 35-mph versus 55-mph tests. Hence, the Yardney battery substantially increased the 55-mph range to 84 miles (up 91 percent over baseline) as well as the 35-mph range, which was boosted to over 126 miles (up 58 percent).

The nickel-iron battery developed by Westinghouse was also relatively "hard," with the energy capacity reduced by 14 percent in the 55-mph test (17 kWh) when compared to the 35-mph test (19.8 kWh). The SCT vehicle with the nickel-iron battery went over 121 miles at 35 mph and approximately 76 miles in the 55-mph range test.

The lead-acid battery supplied by Globe-Union (the EV2-13) produced a noticeable improvement over the baseline lead-acid battery but suffered from a comparatively "soft" discharge capability. The range at 35 mph was 117 miles, with 18.6 kWh discharged. The range dropped to 58 miles at 55 mph, and 27 pecent less energy (13.5 kWh) was obtained from the battery.

Because of the early state of development of the near-term nickel batteries, the manufacturers had not optimized the details of recharging and in some cases varied the procedure during the course of the test program based on interpretation of test results. In the case of the ERC nickel-zinc battery, the range in ampere-hour capacity was also a result of cell degradation.

Battery Behavior

The baseline lead-acid battery pack was found to be quite consistent in terms of repeatability and efficiency as evidenced by the data presented previously. There were no obvious signs of self-discharge. However, three of the original 18 batteries appear to have degraded to failure (battery voltage below 3 V when battery pack is fully charged) after approximately 50 charge-discharge cycles. The fact that the batteries were subjected to an equalization charge after each deep discharge to obtain repeatability could have been a factor in the failures.

The ERC nickel-zinc battery exhibited poor cycle life, experiencing significant performance degradation after a limited number of charge-discharge cycles. Over the 2-month testing period the battery was subjected to 10 charge-discharge cycles at JPL. The energy capacity dropped 28 percent in 35-mph range tests and 41 percent in the J227a "D" cycles.

The Yardney nickel-zinc battery has performed quite well to date; however, in life cycle testing under the Technology Demonstration program at Argonne National Laboratory, Yardney modules experienced a cycle life of less than 30 cycles.

The Westinghouse nickel-iron battery has experienced no performance degradation; however, several problems were encountered during the test period. The state of development of the electrolyte circulation system made it impossible for the battery to be installed in the vehicle. A large volume of hydrogen is generated during charging, compared to other battery types, and requires special venting. Six of 90 cells have failed. Five failures were due to faulty assembly, and the sixth is under investigation.

The Globe-Union EV2–13 has performed consistently throughout the testing period with no obvious signs of degradation.

Conclusions

The near-term batteries demonstrated significant range improvement relative to current lead-acid batteries. The increases in range were due to improved energy density and ampere-hour capacity, with relatively small weight and volume differences. The effect of charging procedure on battery efficiency, performance, and lifetime remains unclear at this time. The nickel-iron battery requires a substantial development effort in packaging the circulating electrolyte system and handling of the generated hydrogen volume before the battery can be successfully integrated into demonstration vehicles. The nickel-zinc batteries tested suffer from short cycle life.

The 2 × 4 vehicles also require further refinement in the efficiency and reliability of the propulsion systems in order to operate successfully in the Department of Energy's Electric and Hybrid Vehicle Technology Demonstration program.