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VEHICLE TEST REPORT: SOUTH COAST TECHNOLOGY ELECTRIC VOLKSWAGEN RABBIT WITH DEVELOPMENTAL LOW-POWER ARMATURE CHOPPER

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June 1983

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Electric & Hybrid Vehicle System
Research & Development Project

Vehicle Test Report: South Coast Technology Electric Volkswagen Rabbit with Developmental Low-Power Armature Chopper

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June 1983

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ABSTRACT

Dynamometer performance of a South Coast Technology electric conversion of a Volkswagen (VW) Rabbit designated SCT-8 was tested. The SCT-8 vehicle was fitted with a transistorized chopper in the motor armature circuit to supplement the standard motor speed control via field weakening. The armature chopper allowed speed control below the motor base speed. This low speed control was intended to reduce energy loss at idle during stop-and-go traffic; to eliminate the need for using the clutch below base motor speed; and to improve the drivability.

Test results indicate an improvement of about 3.5% in battery energy economy for the SAE J227a-D driving cycle and 6% for the C-cycle with only a minor reduction in acceleration performance. A further reduction of about 6% would be possible if provision were made for shutting down field power during the idle phases of the driving cycles. Drivability of the vehicle equipped with the armature chopper was significantly improved compared with the standard SCT Electric Rabbit.

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SECTION I

INTRODUCTION

Public Law 94-413, passed by Congress on September 17, 1976, authorized funds to the Energy Research and Development Administration, now the U.S. Department of Energy (DOE), to promote increased research and development of electric and hybrid vehicles. In consonance with the act of Congress, DOE awarded contracts in June 1978 to four small business firms for purchasing improved electric vehicles. These contracts called for the delivery of two identical models from each of the four manufacturers; hence, the name "2 x 4" vehicles.

One of these firms, South Coast Technology (SCT) of Detroit, Michigan, converted a 1978 Volkswagen Rabbit chassis to a two-passenger electric car. (See Reference 1 for a complete description.) This front-wheel drive vehicle was propelled by a Siemens' motor (model IGVI 161-Z). The shunt-wound motor is nominally rated at 17 kW, peak 33 kW, and is controlled by a separately excited field. The vehicle is powered by eighteen 6-volt ESB-XPV-23 lead-acid batteries connected in series and uses the conventional Volkswagen four-speed manual transmission. Regenerative braking has been incorporated into the design of the vehicle.

In the original "2 x 4" vehicles, SCT employed only field weakening to control motor speed. The field weakening is achieved by a transistorized, pulse-width-modulated chopper operating at a 20-Hz rate. The on time of the transistor is continually modified by accelerator position and motor speed. Armature current assumes whatever value is required to satisfy the torque needs (up to the 300-A limit) until the motor (vehicle) achieves the speed commanded by the weakened field. No means of control of the motor speed below the base speed of 1800 rev/min existed in this control system. If the motor goes below base speed, excess current could be demanded by the motor. As field control of armature current is functional only above base speed, the motor is protected by a 350-A limit, which opens the main contactor. This would occur if the clutch is engaged too quickly or if the clutch is engaged with the transmission in the wrong gear. During normal operation (above base speed), the controller logic limits current to a nominal maximum of 300 A.

To improve the drivability of the vehicle and to increase the operating range and durability, DOE gave SCT an additional contract to develop a version of the electric Rabbit that incorporates an armature chopper for the motor. SCT then subcontracted with EHV Systems Corp. to develop a transistorized chopper. This improved vehicle (designated SCT-8) has been tested on the chassis dynamometer in the Automotive Research Facility of the California Institute of Technology (Caltech), Jet Propulsion Laboratory (JPL), in Pasadena, California.

In developing and incorporating the armature chopper into their electric Rabbit design, it was the objective of SCT and EHV Systems Corp. to:

(1) Reduce or eliminate the energy loss associated with idling the motor at base speed in stop-and-go traffic.

(2) Eliminate the necessity to use the clutch to get the vehicle underway and modulate its speed below 12 km/h (7.5 m/h).

(3) Reduce or eliminate the tendency of some drivers to "stall" the motor (i.e., cause an automatic shutdown because of excessive current draw) as a result of engaging the clutch too rapidly, failing to downshift or release the clutch when decelerating, or failing to shift down when ascending a steep grade.

The first of these items was intended to improve the operating range of the vehicle, especially in certain commercial applications like meter reading, in which a large portion of the operating time is at idle. The last two items would enhance the drivability and the durability of the clutch and drive train in the hands of the average driver.

In this report, the degree of success in achieving these objectives is discussed quantitatively in the first instance and qualitatively for the items related to drivability. Tests in which the armature chopper was disconnected from the controller and some of the tests on the original vehicle (see Reference 1), which had only the field-weakening motor speed control, are the basis for comparison.

SECTION II

TEST OBJECTIVE

The objective of the test program described here was to characterize the performance of a special SCT Volkswagen Rabbit that had been fitted with an armature chopper as a means of motor control below base speed. In particular, the performance in terms of battery energy economy, acceleration, and drivability was compared to that of the standard (without armature chopper) SCT electric Rabbit. The tests performed were best-effort acceleration; constant speed runs at 56, 72 and 89 km/h (35, 45 and 55 mi/h); the SAE J227a "C" and "D" driving schedules; and a qualitative evaluation of drivability.

SECTION III

VEHICLE DESCRIPTION AND OPERATION

A. DESCRIPTION

The design and vehicle modifications of the electric Rabbit are the products of South Coast Technology (SCT), Detroit, Michigan. The developmental "low-power armature chopper" is the product of EHV Systems Corp., Centereach, New York, under contract to SCT. The vehicle used is a 1981 Volkswagen Rabbit (Figure 3-1). The curb weight of the Volkswagen Rabbit is 880 kg (1940 lb), with a manufacturer's gross vehicle weight (GVW) of 1309 kg (2887 lb). As a result of the electric conversion by SCT, the curb weight was increased to 1424 kg (3140 lb) with a maximum gross vehicle weight of 1633 kg (3600 lb). The gross vehicle weight is also the vehicle test weight. The vehicle load distribution, as received from SCT, was rear axle 754 kg (1663 lb) and front axle 670 kg (1477 lb). The presence of the armature chopper did not significantly increase the vehicle weight over that given for the basic electric conversion. The vehicle is equipped with 175/70-SR 13 size steel-belted radial tires inflated to a pressure (cold) of 220 kPa (32 psi) in the front and 248 kPa (36 psi) in the rear. The vehicle is 3.94 m (155.3 in.) long, 1.61 m (63.4 in.) wide, 1.41 m (55.5 in.) high, and has a wheel base of 2.40 m (94.5 in.). The body is a standard two-door model with a hinged rear hatch.

Figure 3-1. View of SCT Rabbit

1. Body and Suspension

The vehicle's suspension was modified to support the additional weight of conversion to electric propulsion. The front shock absorbers were replaced with heavy-duty Koni shocks. The existing rear suspension was redesigned to become a heavy-duty, fully independent suspension by replacing the stock bushing and springs with heavy-duty units. Gussets were added in the trailing arms of the rear suspension for additional strength. The rear shock absorbers were also replaced with the Koni heavy-duty type model. The rear drum brakes were replaced with larger Volkswagen Dasher brakes, and the entire vacuum-assisted braking system was replaced with a non-power Rabbit design.

The vehicle body is equipped with front door window vents to provide passenger ventilation in place of air-conditioning. A gasoline-fueled hot air heater is installed in place of the normal hot water heater, and a 3.8-ℓ (1-gal) fuel tank for use with the heater is located in the front motor compartment. The propulsion batteries were accommodated by removing the rear seat and cutting out a section of the floor. A metal box, welded into the floor and fitted internally with a heavy-duty fiberglass container, houses the 18 propulsion batteries, as shown in Figure 3-2. The battery compartment is covered with a fiberglass lid that has three access panels to allow for convenient checking of the electrolyte level and measurement of electrolyte specific gravities. An opening in the right rear quarter panel was cut to provide an inlet for ventilation of the battery compartment. A 115-Vac centrifugal blower is installed at the inlet of the battery compartment to provide positive ventilation during battery charging. The air circulated through the battery compartment is exhausted at the rear of the vehicle. Should the airflow become restricted during battery charging, the charger automatically shuts off. During driving, ram air provides ventilation to the batteries. The batteries are secured in the compartment by strips of fiberglass "T" bars that are wedged between individual strings of batteries and then bolted through the floor of the vehicle.

2. Battery and Propulsion

Propulsion energy is provided by eighteen 6-V lead-acid batteries, manufactured by the Electric Storage Battery Company (now Exide Corporation) (Model ESB-XPV-23). These batteries are rated at 155 Ah at a 75-A rate. The total battery weight is 514 kg (1134 lb). Therefore, based on curb weight, the battery weight fraction of the Rabbit, as delivered to JPL, is 36%. The batteries were cycled extensively at SCT during the development of the low-power armature chopper. Initial checks of the batteries identified a few weak modules necessitating replacement of the entire battery pack. Prior to the start of vehicle testing at JPL, the new ESB-XPV-23 batteries were conditioned using a JPL charging procedure. The battery discharge cycle was performed by discharging the batteries through a nominally constant resistive load.

The vehicle is propelled by a separately excited, shunt wound, direct-current electric traction motor manufactured in Germany by the Siemens' Motor Company (Model No. IGVI 161-Z). The traction motor weighs 88 kg

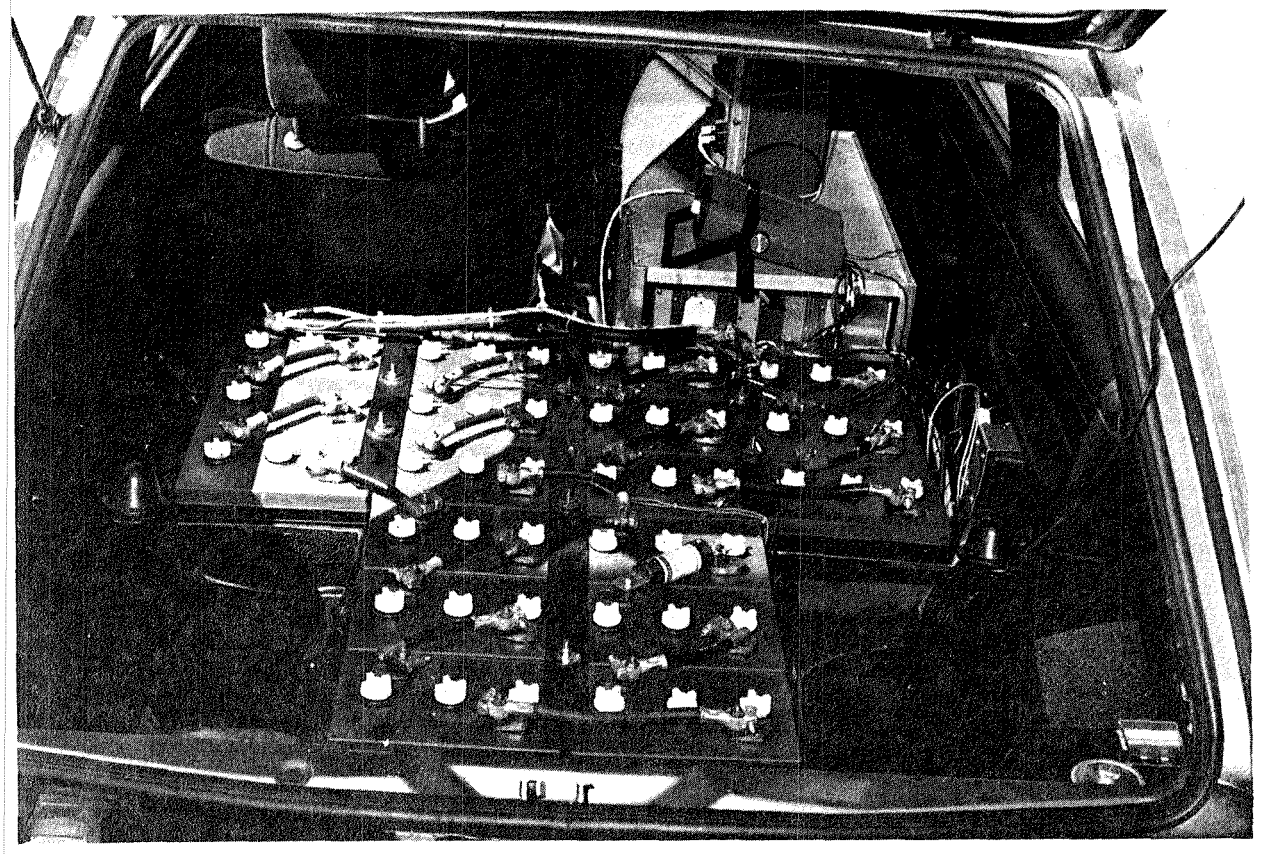


Figure 3-2. View of Battery Compartment

(195 lb), and is equipped with an internal tachometer generator. The rated continuous power of the motor is 17 kW (22.8 hp) with a peak rating of 33 kW (44 hp). The rated continuous motor voltage and current are 130 V and 150 A, respectively. An upper limit to the motor current of about 300 A is provided by the controller. As additional motor protection, a fuse rated at 200 A (time-delay, dual element) is located in the main battery electrical cables. The base (idle) speed of the motor, with a fully charged 108-V battery, is 1800 rev/min. The recommended maximum safe motor speed is 6700 rev/min. Thermal protection of the motor is provided by two Positive Temperature Coefficient (PTC) type thermistors (Model P395D201). The over-temperature sense logic is designed to limit current to 150 A at motor temperatures greater than 115°C (239°F) but less than 135°C (275°F). If the temperature rises further, a complete motor shutdown will occur. A two-speed blower provides cooling for the motor. When the vehicle electrical system is on, the blower operates continuously on low speed and switches to high speed if the motor temperature reaches 75°C (167°F).

The traction motor drives the front-wheel drive vehicle through a standard Rabbit four-speed transaxle with a differential ratio of 3.90:1. The gear ratios are: first, 3.45:1; second, 1.94:1; third, 1.37:1; and fourth, 0.97:1. A stock Rabbit clutch is used. The traction motor is connected to the transmission by means of an adapter plate and shaft coupler designed by SCT.

3. Motor Control

Both the conventional SCT vehicles and the developmental car (SCT-8) with the low-power armature chopper (LPAC) employ field weakening to control car speed. Field weakening is used to achieve motor speed control above base speed, which corresponds to 12 km/h (7.5 mi/h) in first gear. The field weakening is achieved by a transitorized, pulse-width-modulated chopper operating at a 20-Hz rate. Chopper on-time is continually modified by accelerator position and motor speed. Above base speed, armature current assumes whatever value is required to satisfy the torque needs, up to a 300-A limit, until the motor (vehicle) achieves the speed commanded by the weakened field. Below base speed, the conventional SCT cars will allow armature currents up to 350 A before overcurrent is detected, which shuts down the car.

In the LPAC vehicle, the need to idle the motor at base speed is avoided by the addition of the armature chopper. However, the 300-A current limit is reduced to 120 A during armature chopping. If driven as recommended by SCT, the 120-A limit is in effect only during first-gear operation below 12 km/h (7.5 m/h). Once above 12 km/h, the motor is above base speed and the 300-A field weakening limit is reinstated. Therefore, the low power limitation is in effect only briefly during initial acceleration.

The approach of limiting the motor power in the 0- to 12-km/h range has allowed the armature current to be controlled by means of a high-frequency chopper using recently available 10- to 15-kW peak power output transistors in place of the silicon-controlled rectifiers (SCR) used as switching elements in higher power applications. The use of transistors in place of SCRs has permitted a great deal of circuit simplification with an attendant reliability improvement as well as reductions in weight, volume, and operating noise.

In return for an expected small degradation in low-speed acceleration as discussed, the use of the transistorized armature chopper was expected to provide the following benefits:

(1) Armature current is reduced to zero when the vehicle is stopped or idling.

(2) Vehicle can be started from rest, and the speed can be modulated below motor base speed without use of the clutch.

(3) Excessive current drain and drive train abuse can be eliminated.

(4) Drivability is markedly improved.

The benefits would also occur with an SCR chopper, but there would be no degradation in the acceleration performance as is the case with the transistorized LPAC. Therefore, the benefits of armature chopping are clearly established for the SCT vehicles. Both energy economy and drivability benefit. The choice between transistors and SCRs for the chopper is less obvious. Although transistors offer greater reliability and efficiency, it is at the expense of additional cost and a slight penalty in acceleration

performance. Although SCRs offer the advantage of higher power capability and lower cost, there are penalties in efficiency and reliability. The differences in transistor- and SCR-chopper efficiencies have a negligible impact on overall system efficiency if the proper shift logic is employed because the chopper is bypassed during most of the time the vehicle is operated. Therefore, the choice between transistors and SCRs should be based on controller reliability, cost, and acceleration performance.

Figure 3-3 is a schematic of the SCT Rabbit propulsion system with the LPAC, showing the controls and the location of key electrical measurements. Details of the LPAC operation and the integrated controller are contained in Appendix A. Figure 3-4 is a view of the controller installed in the vehicle.

Regenerative braking, which is operational down to approximately 13 km/h (8 mi/h) if downshifting is used, has been included in the vehicle design. The regenerative braking occurs automatically when the accelerator pedal is released, as long as the motor speed is above 1880 rev/min; it is especially effective at motor speeds above 3000 rev/min. The implementation of the regenerative braking provides for more "motor" braking than the compression braking of a conventional engine.

A heavy-duty, 12-V auxiliary battery provides power for the electronic controller, lights, windshield wipers, and traction motor cooling fan. The auxiliary battery is charged from the main propulsion batteries by means of a dc-to-dc converter during vehicle operation. The on-board charger provides a constant 108-V input to the dc-to-dc converter during recharge of the main battery pack.

In addition to the conventional tachometer and speedometer, the vehicle instrumentation panel contains several special gauges. A brief description of each gauge follows:

(1) Motor Temperature Warning Gauge: (converted water temperature gauge)

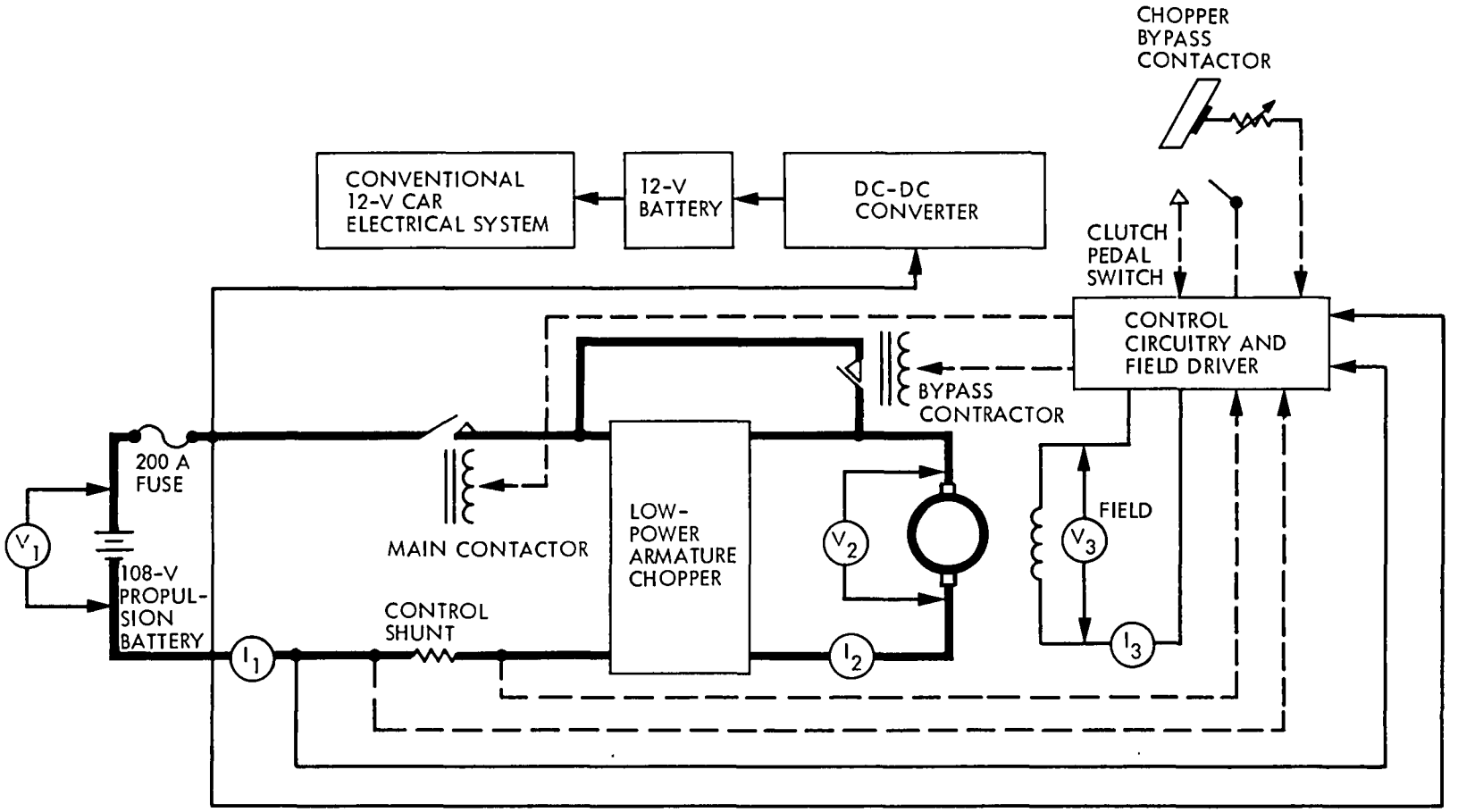
This gauge indicates the internal temperature of the motor. If the motor temperature reaches the red zone, 115°C (239°F), the motor current is automatically limited to 150 A.

(2) Motor Temperature Warning Light: (converted oil pressure light)

Light comes on if the motor temperature reaches 135°C (275°F). Motor shuts down when this occurs.

(3) Auxiliary Battery Warning Light:

Light comes on when the auxiliary battery voltage drops below 10 V. Warning only.



NOTES:

(1) ALL CURRENTS WERE SENSED WITH CALIBRATED SHUNTS INSTALLED IN THE NEGATIVE LEG OF THE CIRCUIT

(2) ALL CONTROL SIGNALS DASHED LINES ARE NOT SHOWN HERE

JPL SENSORS

V_1 = BATTERY VOLTAGE
V_2 = ARMATURE VOLTAGE
V_3 = FIELD VOLTAGE
I_1 = BATTERY CURRENT
I_2 = ARMATURE CURRENT
I_3 = FIELD CURRENT

Figure 3-3. Schematic of SCT Rabbit Propulsion System with Motor Armature Chopper

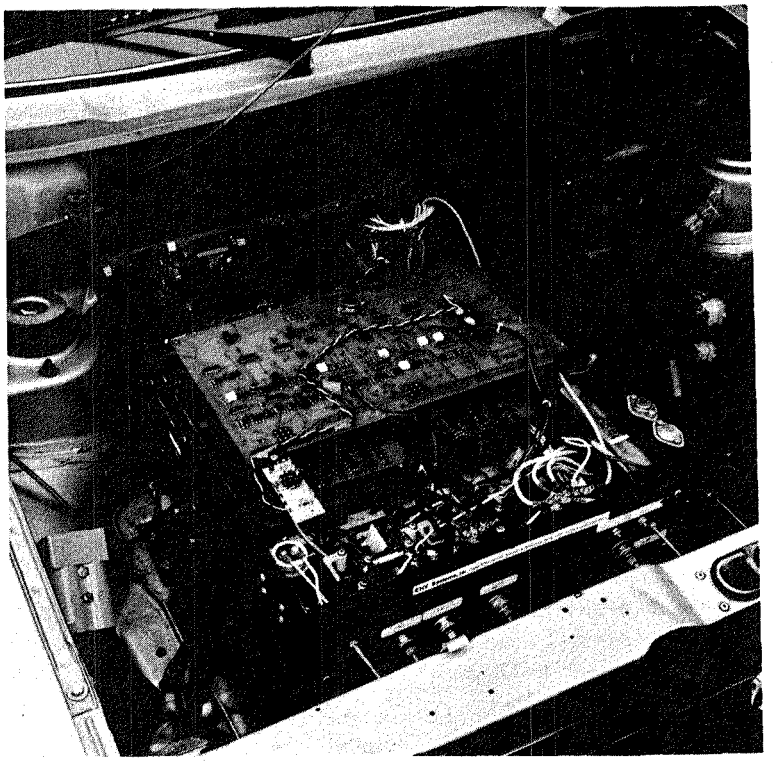


Figure 3-4. View of Integrated Controller Installed in SCT Vehicle

(4) Main Contactor Warning Light: (This light is labeled "EGR" because it is a converted exhaust gas recirculation over-temperature light for an internal combustion engine application.)

Indicates the main contactor is off. The main contactor may open and the light may come on if the motor current exceeds 350 A. This may happen as a result of attempting to accelerate or in climbing a steep hill in too high a gear, by not disengaging the clutch when the car is brought to a stop, or if the system is shut down by motor overheating.

(5) State-of-Charge Indicator: (converted fuel gauge)

Provides a coarse indication of the available battery energy. When the needle enters the red area, there is a reserve of about 10% of the maximum battery capacity. NOTE: No tests were conducted to evaluate the accuracy of this indicator.

(6) Ammeter:

Indicates the battery current being drawn by the motor (positive scale) or the current being returned to the battery by the regenerative braking system (negative scale).

B. VEHICLE OPERATION

Operation of the Low-Power Armature Chopper SCT Rabbit (SCT-8) is very straightforward and can easily be mastered in a short period of time. There are a few minor differences from a conventional IC engine vehicle in regards to starting procedure, but once started, it is driven in essentially the same manner as any conventional manually shifted vehicle. The starting procedure is as follows:

(1) Fasten seat belt. The vehicle cannot be started without the seat belt fastened.

(2) Fully depress the clutch pedal. As a safety feature, the vehicle cannot be started unless the clutch is fully depressed.

(3) Turn the ignition key to the "start" position and hold for 1s. The main contactor warning will light and then go out indicating the drive system is energized.

(4) Shift the transmission into first gear, engage the clutch, and depress the accelerator pedal with the clutch fully engaged. A noise from the armature chopper will be heard, and the vehicle will begin to accelerate.

(5) Once the motor speed reaches approximately 1600 rev/min, the bypass contactor will be heard to close, bypassing the armature chopper and putting the vehicle in field-weakening mode.

(6) When motor speed reaches approximately 3000 rev/min, disengage the clutch, shift the transmission into second gear, and re-engage the clutch.

(7) Thereafter, drive the vehicle in a conventional manner, shifting up at approximately 3000 rev/min, and down at approximately 1600 rev/min. Note that it is <u>not</u> necessary to disengage the clutch when coming to a stop.

C. BATTERY CHARGER

The on-board charger failed just before initiation of the SCT-8 test series. However, the charger was repaired promptly and has operated reliably subsequent to the testing reported here. As this charger represents a considerable improvement compared to those found in the first two SCT R-1 electric vehicles, it is described here. Actual charging methodology during evaluation of the LPAC is described in Section V. JPL plans a future report that evaluates the performance of the Lester charger, itself.

Lester Electric Corporation of Lincoln, Nebraska, was selected by SCT to provide an improved battery charger for the R-1 Electrics. This charger was tailored to physical constraints of the SCT vehicle and to the charging requirements dictated by ESB Corporation for their XPV-23 EV

battery. Each of these general characteristics is discussed in a separate paragraph.

1. Physical Characteristics

Figure 3-5 shows the charger as it is installed in the SCT vehicle. It can be seen that the controls, indicators, and fuses are all relatively accessible. Figures 3-6 and 3-7 show two views of the charger; Table 3-1 provides its physical specifications.

2. Electrical Characteristics

The input transformer is designed so that 115-Vac or 208/230-Vac power can be used. However, the charger is designed primarily for use with a 208/230-Vac circuit. The 115-Vac input circuitry is intended for emergency use only, if the higher voltage circuits are not available. Much of the

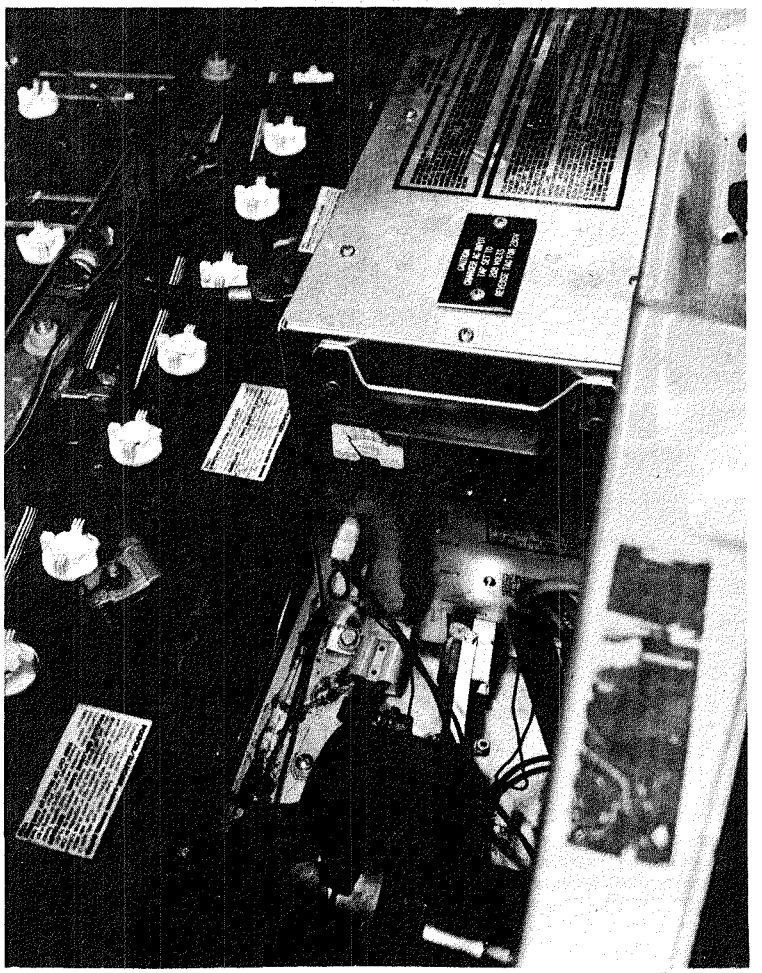


Figure 3-5. Lester Charger Installed in SCT Vehicle

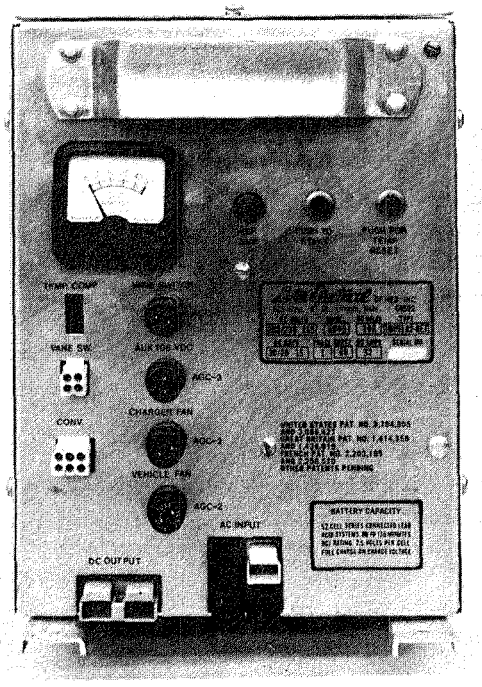


Figure 3-6. Front View of Lester Chassis

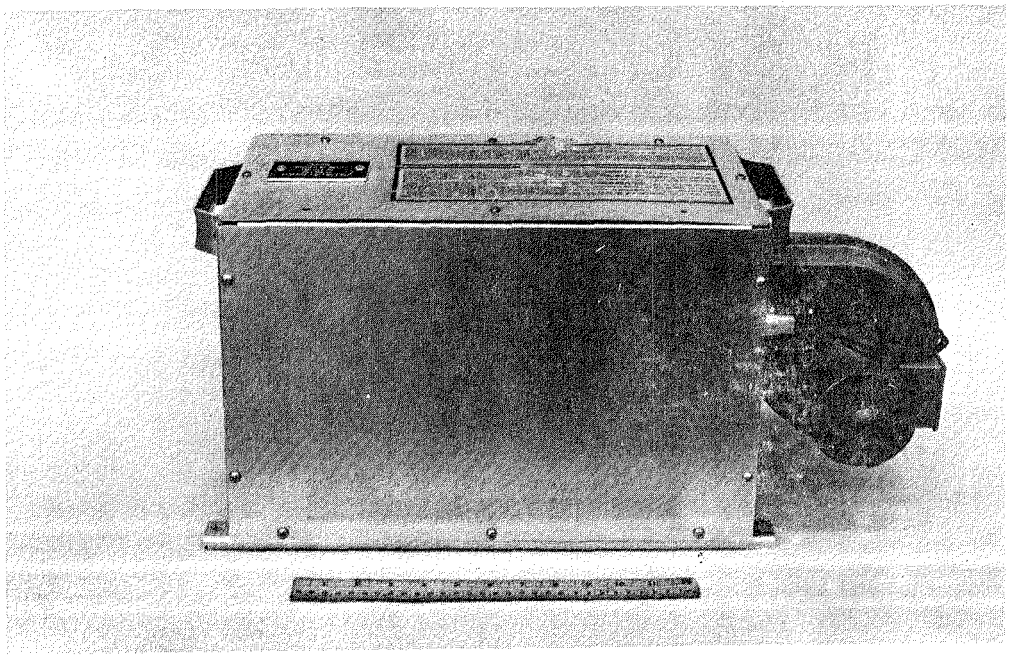


Figure 3-7. Side View of Lester Chassis

Table 3-1. Lester Electrical Charger Physical Specifications

Size	
Height	27.9 cm (11.0 in.)
Width	20.3 cm (8.0 in.)
Length (excludes fan)	41.9 cm (16.4 in.)
Weight	
Total (includes fan)	33.6 kg (74 lb)

automatic operation of the charger (namely, charger shutdown) is not functional during 115-Vac operation. Isolation between the battery pack and the input powerline is also provided by this transformer. Charger current and voltage are controlled by SCRs in response to charge control logic that is proprietary to Lester. In addition to the basic charging function, the charger also controls a purge fan for the battery compartment. The purge fan is operated for 60 min following charge termination to ensure that hazardous gaseous effluents from the battery are purged from the battery compartment. Operation of the charger is interlocked with the purge fan for the battery compartment. Charging cannot take place unless the fan is operating. Accessory battery charging is also done from the Lester charger. This is accomplished by supplying the dc-to-dc converter with power at 108 Vdc, as would be the case during vehicle operation. In this manner, the Lester charger is not required to duplicate the hardware already needed (e.g., dc-to-dc converter) for normal vehicle operation. Table 3-2 lists the charger electrical specifications.

Table 3-2. Lester Charger Electrical Specifications

115-Vac Mode	
Input Voltage	115 Vac
Input Current	15 A
Output Voltage	150 Vdc max
Output Current	8 Adc max
208/230-Vac Mode	
Input Voltage	208 or 230[a] Vac
Input Current	25 A
Output Voltage	150 Vdc max
Output Current	32 Adc max

[a]Requires selection of appropriate tap on charger's input transformer.

3. Charge Algorithm

When operated in the normal 208/230-Vac mode, and assuming the battery has been at least partially discharged, the following charge sequence occurs:

(1) Charge at a nominal fixed current of 32 A until battery voltage rises to 124 V (2.296 V/cell).

(2) Decrease charge current linearly to approximately 8 A as battery voltage rises to 127.5 V (2.36 V/cell). In other words, from 124 to 127 V, battery current (32 to 8 A) is inversely proportional to battery voltage.

(3) Maintain charge current at about 8 A until battery voltage rises less than 0.036 V (67 V/cell) in a 50-min period.

(4) Terminate charge.

Figure 3-8 shows the battery charger's voltage-current characteristic just described. From this figure it can be seen that, even when in the two current control modes (32 A or 8 A), there is a slight decrease in current as

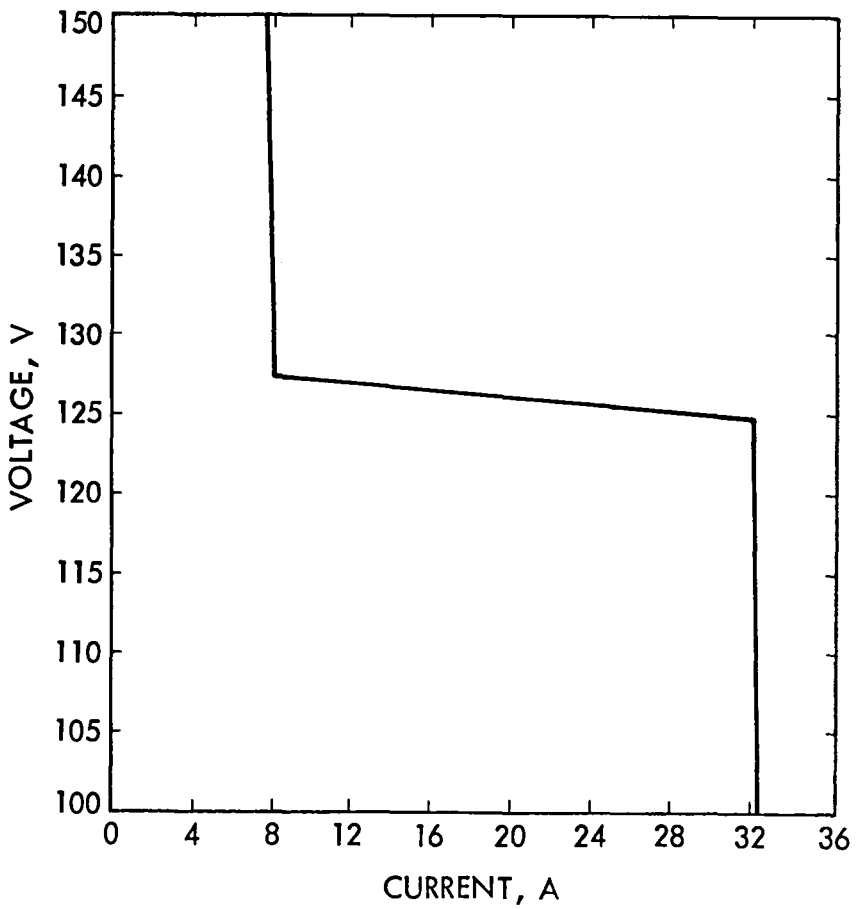


Figure 3-8. Charger Control Schedule

battery voltage increases. Lester specifically designed this current taper into the control algorithm to get more ampere hours into the battery before the onset of gassing. Lester consulted with ESB Corporation in the development of this charge algorithm. As such, some of the controlled parameters (e.g., 8-A finish current) reflect the needs of the XPV-23 battery, as defined by ESB.

D. BATTERY CONDITIONING

Before the start of vehicle testing, the newly installed Exide XPV-23A/S8[1] batteries were conditioned at JPL by being deep-discharged and recharged 12 times. The method was to discharge the battery pack through a nominally constant electrical load that consisted of a resistance load. The discharge was terminated when a voltage of 94.5 V (1.75 V per cell) was reached.

Each battery was discharged at 75 A so capacity could be compared to Exide's rated capacity (determined at 75 A). The initial 11 battery conditioning cycles were performed without regard for electrolyte temperature. Battery test conditions were tightly controlled during the twelfth, and last, conditioning cycle. Conditions were matched to those used by Exide, and the battery's capacity was determined to be 133 Ah at 75 A and 23°C. By monitoring individual module voltages, it was also determined that the battery pack consisted of well matched (±2%) modules.

E. VEHICLE MODIFICATION AND PREPARATION FOR TEST

Upon receipt of the vehicle at JPL, a safety inspection was performed. The primary purpose of the inspection was to ensure that the vehicle was safe for testing purposes. For example, it was verified that the battery terminals were covered, all points of high voltage were shielded from accidental human contact, the propulsion system was electrically isolated from the vehicle chassis, the batteries were adequately constrained, the conventional safety equipment (horn, lights, turn indicators, etc.) operated correctly, and the battery compartment ventilation system functioned properly, etc.

Before the start of the test phase, the wheel bearing and suspension system were inspected and lubricated. All wheels were balanced and aligned according to the manufacturer's specifications. The vehicle was weighed and the load distribution between the front and rear axles defined. Based on this measurement, the ballast required to bring the vehicle to the manufacturer's recommended gross vehicle weight of 1633 kg (3600 lb) was determined.

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[1]In the designation (XPV-23A/S8), the underlined characters are JPL suffixes meaning: A the first battery pack replacement for /SCT-8.

Several modifications were made to the vehicle at JPL in preparation for the performance testing. Quick-disconnect connectors were installed between the battery pack and the motor/controller. These provided a safe way to isolate the batteries from the motor and controller during maintenance and repair, and also allow a convenient place to connect and use batteries that are not physically within the vehicle. Current sensors (coaxial shunts) were installed on the negative cable side of the battery pack, the motor armature, the motor field, and the battery charger. Voltage sense points were also connected at positions to correspond with the current sensors. A schematic of the Rabbit power system, including instrumentation sense points, is presented in Figure 3-3.

SECTION IV

TEST METHODOLOGY[2]

All of the tests reported in this document were conducted in the chassis dynamometer portion of the JPL Automotive Test Facility. A twin-roll Clayton dynamometer with 218-mm (8.6-in.)-diameter rollers and direct-drive inertia weights was used in the dynamometer tests. This dynamometer is the type recommended by the Environmental Protection Agency (EPA) for exhaust emission certification testing, and has inertia weight increments of 57 kg (125 lb).

The Clayton twin-roll type of dynamometer used at JPL has only a single adjustment for the simulation of aerodynamic load. That is, the aerodynamic load can be set at a single value which corresponds to one vehicle speed. The loads at other speeds are fixed by the nominally cubic variation of load as a function of roller velocity that is inherent in the dynamometer. The tire pressure and/or the tire loading (vehicle weight on the drive wheels) was manipulated, within limits, to vary the tire/roller losses to match road-load data obtained from coast-down tests of a different SCT electric Volkswagen at Edwards Air Force Base.

The fact that the specific road-load for SCT-8 was not used during the testing does not compromise the validity of the test results presented here. Of importance were the relative differences in performance caused by the addition of the LPAC. These differences were determined by operating the same vehicle (SCT-8) with and without the armature chopper. Because SCT-8 is the same basic construction (from a road-load viewpoint) as SCT-2, the SCT-2 road-load characteristics were used for SCT-8 in the interest of cost effectiveness.[3]

The chassis dynamometer tests consisted of range tests at steady speeds of 56, 72 and 89 km/h (35, 45 and 55 m/h), SAE J227a "C" and "D" driving schedules, and best-effort accelerations with the armature chopper active and inactive. Results are discussed in a subsequent section of this report.

A. ENVIRONMENTAL CONDITIONS - DYNAMOMETER

An important advantage of dynamometer testing is the ability to eliminate winds and provide a relatively stable set of environmental conditions, thereby significantly reducing the effect of the environment on the test results. This is especially true when looking for small differences in performance

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[2]Additional information on this subject is given in Reference 2.

[3]Dynamometer road load settings were based on coast-down data from a "standard" SCT electric Rabbit (designated by JPL as SCT-2). The presence of the armature chopper in the vehicle reported on here did not affect the road load in any way. Energy economy data from SCT-2 tests are also used for comparison with SCT-8 LPAC data in steady 35- and 55-mi/h tests because no SCT-8 data with disabled LPAC were available for steady-speed tests.

attributable to component changes as in the case of the LPAC. The chassis dynamometer room is maintained at a relatively constant 21 $\pm 2^{o}C$ (70 $\pm 4^{o}F$) during all testing; and the effects of winds are non-existent.

Although precise measurements of relative humidity and atmospheric pressure are routinely recorded in the JPL Automotive Research Facility, these values are not reported here. They are of little significance when pure electric vehicles are tested on a dynamometer within a closed building.

Simulation of the Rabbit forced-convection cooling (airflow as a result of driving) was accomplished through the placement of a large fan in front of the car. Although little heat is generated by electric vehicles, it was felt that the vehicle would run warmer on the dynamometer, as compared with the track tests, unless the fan was employed. Figure 4-1 shows the placement of the fan as well as an overall view of the dynamometer and vehicle test configuration.

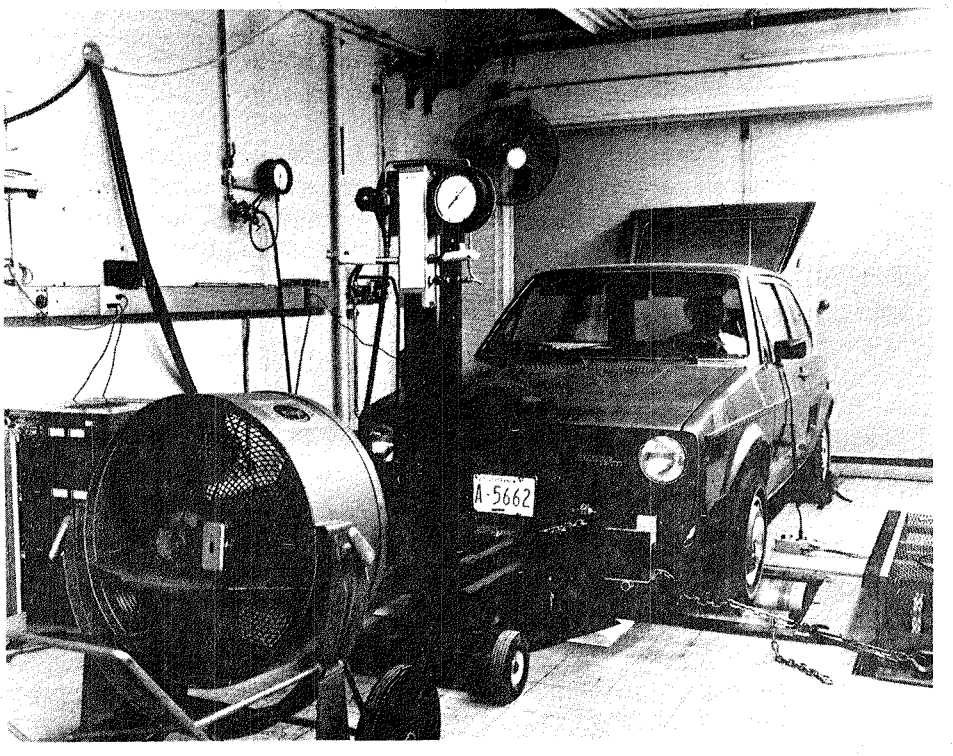

Figure 4-1. Vehicle During Dynamometer Tests

B. BATTERY CHARGING

As indicated in Section III-C, the on-board charger was not used because of an initial failure in the charger control circuit. Rather than delay testing of SCT-8 until the charger could be repaired, an off-board charger was employed. JPL's charger controller has sufficient flexibility that the Exide charge algorithm was readily emulated. The major reason for testing SCT-8 was to evaluate the LPAC; any charger that provided consistent battery capacity throughout the test program was satisfactory. Both the Lester and JPL chargers provide consistent battery performance within the context of the SCT-8 evaluation. It should be noted here that the Lester charger was repaired promptly and has operated reliably subsequent to this test program. In fact, it could have been used for the latter part of the SCT-8 test program except for JPL's desire to minimize the possible number of variables that could cloud the primary area of interest.

This three-stage charge algorithm is characterized as follows:

(1) Charge at a constant 25-A current until battery voltage reaches the prescribed voltage of 145.8 V (2.70 V/cell) referenced to 26.7°C (80°F).[4]

(2) The prescribed voltage (clamping voltage) is maintained for 2 h; current is allowed to taper to approximately 6 A. The charging voltage is continuously compensated for changing electrolyte temperature.

(3) Upon completion of the allotted 2-h constant voltage interval, initiate another constant current charge mode. This fixed 6-A current is maintained for 4.0 h before the charge is terminated.

The battery's response to this three-stage charge procedure is shown graphically in Figure 4-2. Typical load and battery charge characteristics are evident in this figure. The transition from stage 1 to stage 2 occurs when approximately 95% of the previous discharge has been replaced (on a coulombic basis). Because the first constant current charge stage lasts until the battery exhibits the rapid voltage rise at 95% state of charge, the charge algorithm automatically adapts to the battery's charge needs. The following two stages provide a fixed quantity of charge and are tailored to satisfy the overcharge needs of the battery and the requirements of the test program. The JPL charger, pictured in Figures 4-3 and 4-4, provided a very consistent charge to the Exide battery pack.

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[4]Battery voltage is adjusted by 0.004 V/°F/cell for electrolyte temperatures other than 26.7°C (80°F).

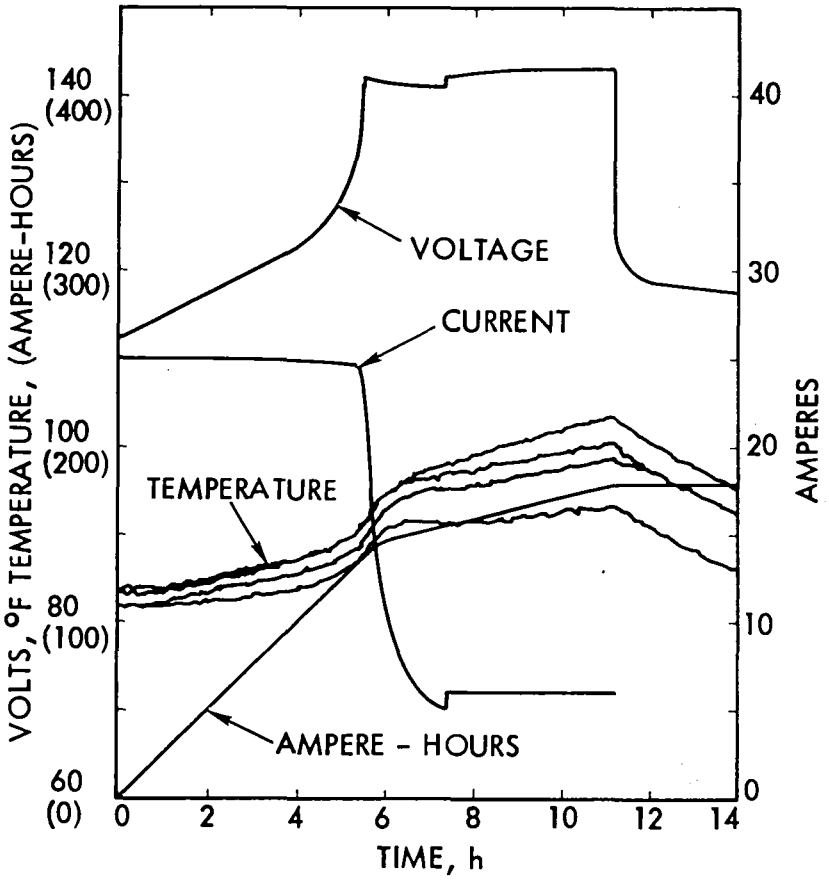

Figure 4-2. Battery Recharge Characteristics

C. BATTERY TEMPERATURE CONDITIONING

Energy capacity of Pb-acid batteries is dependent on several factors, including the electrolyte temperature. As a rule of thumb, a 1% change in battery capacity occurs for each 1°C change in temperature. This results in a 30% variation in battery capacity for the 30°C (54°F)[5] temperature range allowed for vehicle testing by the SAE 227a procedure. In order to reduce vehicle range variations resulting from battery temperature variations, a much narrower temperature range was selected for the tests described here.

After battery charge termination, the vehicle was allowed to soak in a temperature-controlled room until the average battery electrolyte temperature stabilized at 21 ±2.8°C (70 ±5°F). An entire day between each test day was specifically set aside for temperature stabilization. Even with this extra "soak" day, forced-convection cooling of the batteries had to be employed to satisfy the temperature criterion within the allocated time. The

[5]According to the SAE J227a any temperature between 5°C (41°F) and 35°C (95°F) is acceptable.

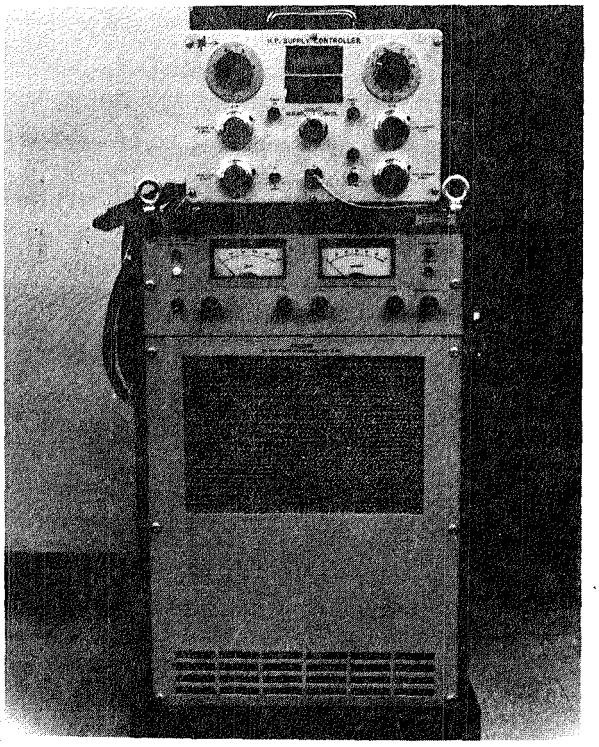

Figure 4-3. JPL Charger and Controls

final (equalization) portion of battery charging resulted in self-heating of the batteries to the point that they typically gained from 10 to 15°C (18 to 29°F) during the charging process. The electrolyte temperature at charge termination was generally about 38°C (100°F).

D. TEST TERMINATION CRITERIA

Three test termination criteria that differed slightly were used depending on the nature of the test; i.e., constant speed or cyclic. Constant speed tests were ended when: (1) the battery voltage decayed to 1.75 V/cell for more than 3 s (94.5 V for the total battery pack), (2) the battery or motor temperature exceeded the limit specified by the manufacturer, or (3) the vehicle speed could not be maintained within 95% of the specified velocity. Criteria (1) and (2), battery voltage and battery/motor temperature, were also employed for the cyclic tests. However, the battery voltage criteria were divided into two parts: (a) during accelerations, the minimum voltage allowed is 1.3 V/cell; and (b) during all other modes of operation, the minimum voltage is 1.75 V/cell. An additional criterion was used for the cyclic tests: The test was terminated when the acceleration part of any cycle could not be completed within 2 s of the time specified by the procedure. In actual practice, the constant speed tests were terminated by the battery voltage criteria, and the cyclic tests were ended by the vehicle's internal low-voltage limit of 78 V. This corresponds to 1.75 V/cell for constant speed tests and 1.44 V/cell for cyclic tests.

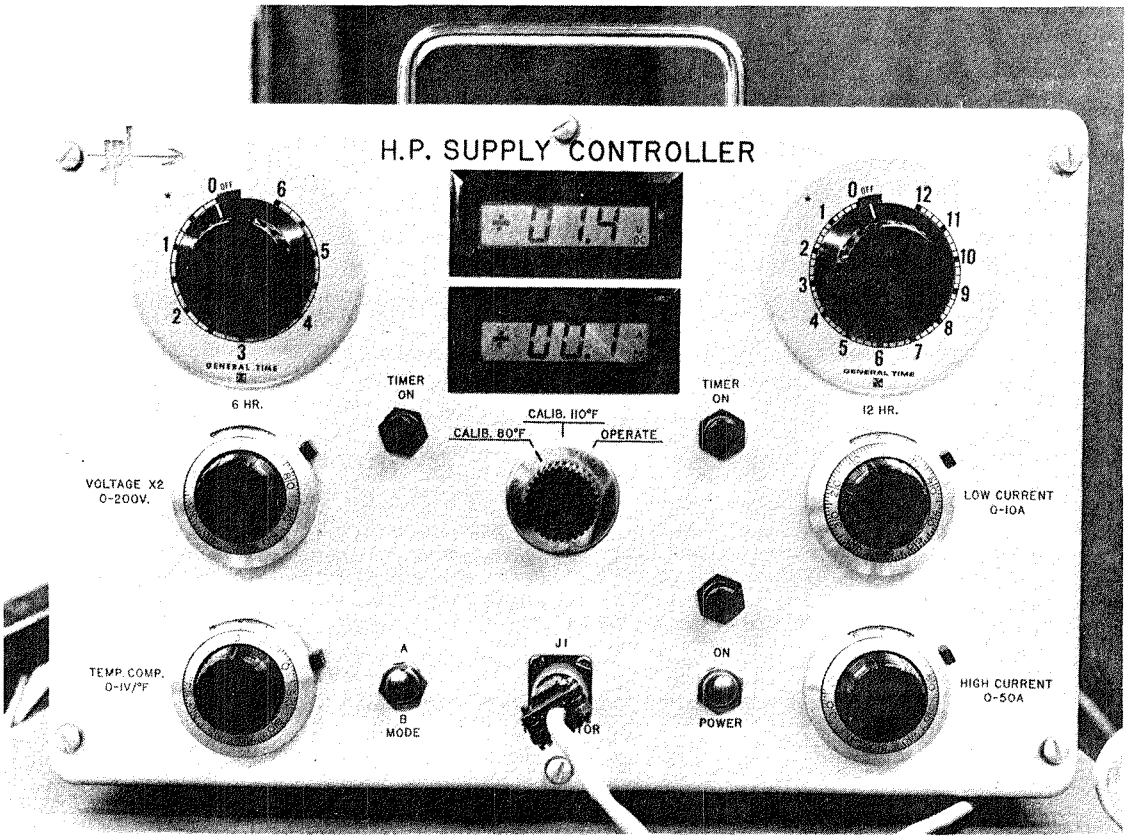

Figure 4-4. Details of JPL Charger Controls

E. INSTRUMENTATION AND DATA RECORDING

Both off-board and on-board recording of data were employed. Although most data were recorded automatically by means of strip charts and magnetic tape, manual recordings of several parameters were recorded before and after each test. Comprehensive data sheets were developed for the appropriate tests performed. Also, a separate vehicle log book was kept for a narrative description of testing activities, unusual events, vehicle problems, and repairs.

JPL's Automotive Research Facility is equipped with a comprehensive recording capability. Electric-vehicle-unique data, such as power, are measured with JPL-developed, wide-band wattmeters. Output signals from the wattmeters are recorded on both mechanical counters and magnetic tape. Parameters such as motor speed, electrolyte temperature, and vehicle speed are recorded directly on magnetic tape by the computerized data system. Additional details of the wattmeters and the data system are found in Appendix B and other JPL reports (see References 1 and 3).

F. VEHICLE CONDITIONING

To enhance test precision, the well defined procedures established during testing of earlier electric vehicles were followed. The vehicle was soaked in a temperature-controlled environment of 21 $\pm 3^{o}C$ (70 $\pm 5^{o}F$) until the entire vehicle was within this temperature range. As the largest thermal mass of an electric vehicle is the battery system, soak time is primarily driven by the battery thermal conditioning requirement (see Section IV-C). The second most important parameter affecting test precision is the dependence of tire losses on tire temperature. The minimization of test-to-test variability induced by differences in vehicle and ambient temperatures is a result of JPL's stringent test requirements. Therefore, the changes in vehicle performance caused by the addition of the LPAC reported here are not overshadowed by other vehicle parameters.

G. ROAD-LOAD DETERMINATION AND DYNAMOMETER LOAD ADJUSTMENT

Determination of road-load power requirements is a standard test specified in the SAE Test Procedure J227a. However, the intent of the procedure is to define road load for reporting purposes; in the context of this report, road load is established primarily for defining dynamometer adjustments. JPL had already tested two other SCT vehicles (SCT-1 and SCT-2; Reference 4). Road load for all of these vehicles was determined by conducting coast-down tests on an aircraft runway at Edwards Test Station (ETS). Because the primary purpose of this SCT-8 testing was to evaluate changes in vehicle performance with the LPAC, the relatively costly road-load determination process was not repeated. Instead, road-load data from SCT-2 was used to establish dynamometer adjustments for SCT-8. Inasmuch as the two electrified Volkswagens were unchanged in any manner that would affect road load, the use of SCT-2's road load had a negligible effect on the data presented in this report. In other words, any errors associated with the use of the SCT-2 road load would be comparable to the differences in road load from one vehicle to the next of the same model--negligible. Use of SCT-2's road load had no effect on the validity of the comparative performance of SCT-8 with and without the LPAC. All dynamometer adjustments were therefore matched to those required for SCT-2. Specifics of the road-load characteristics are provided in Table 4-1.

H. DYNAMOMETER TEST PREPARATIONS

The last step in preparing for a vehicle test is the calibration of the dynamometer. Flywheels that simulate the vehicle's inertial mass are engaged, and the dynamometer is warmed up by an external motoring capability for 5 min at 80 km/h (50 m/h) and then at 56 m/h (35 m/h). Once the losses in the dynamometer are thermally stabilized, the appropriate dynamometer adjustments are made to ensure a valid emulation of the SCT's road load. Following dynamometer calibration, the test vehicle is towed and/or winched onto the dynamometer to avoid use of the vehicle battery. Therefore, as no test vehicle warmup was conducted, all vehicle tests were initiated at the same "cold" 21 $\pm 3^{o}C$ (70 $\pm 5^{o}F$) drive train and battery temperature. Once the

Table 4-1. SCT Rabbit Coastdown Tests on Track
(Data from SCT-2 Tests)

Velocity, km/h(mi/h)		Sample Pairs, No.	Coastdown Time, s	Standard Deviation, %	Total Road Load, kW(hp)
From	To				
88(55)	72(45)	22	17.3	6.4	9.56 (12.82)
32(20)	16(10)	22	39.1	13.3	1.28 (1.72)

vehicle is on the dynamometer, a final check of vehicle test parameters (tire pressure, tire normal weight, etc.) is conducted. Additional information on JPL EV test procedures is given in References 1 and 3.

Steady speed and maximum acceleration tests were performed as specified in the SAE Test Procedure J227a. Driving schedule tests were performed as defined by the SAE J227a with the exception of the changes as outlined in Appendix B, "JPL Standardization of the SAE J227a Driving Cycles."[6]

The manufacturer's recommended shift points were utilized during the test phase and are as follows:

(1) First to second gear: 3200 rev/min (24 km/h, 15 mi/h).

(2) Second to third gear: 2600 rev/min (34 km/h, 21 mi/h).

(3) Third to fourth gear: 2600 rev/min (48 km/h, 30 mi/h).

[6]The SAE J227a D cycle is defined by the SAE only at certain transition points. JPL has interpreted and standardized the cycle to be consistent with acceleration and deceleration rates observed in EPA cycles. Details are contained in Appendix C.

SECTION V

TEST RESULTS AND DISCUSSION

A. MAXIMUM ACCELERATION

The procedure used in the maximum acceleration tests for the standard vehicle without armature chopper was:

(1) Depress clutch pedal.

(2) Energize main contactor by means of ignition switch.

(3) Place transmission in first gear.

(4) Engage clutch as rapidly as possible.[7]

(5) When clutch is fully engaged, fully depress accelerator pedal.

Acceleration continued to maximum speed of about 92 km/h (57 mi/h) using the shift logic defined later in this section. At this point the accelerator was released, and the vehicle was allowed to come to rest as rapidly as possible, a matter of about 12 s. After 2 to 4 s at rest, a second maximum acceleration run-up was made. Following this run-up, the vehicle speed was reduced to 56 km/h (35 mi/h) and maintained for 9 min until the next pair of acceleration run ups were begun. The sequence was repeated until the batteries were depleted to the point where maximum speed could no longer be reached. In other words, vehicle acceleration was evaluated as a function of battery state of charge.

When the vehicle system included the armature chopper, the driving procedure was slightly simplified. Because the clutch was no longer required to bring the vehicle up to a speed equivalent to motor base speed, it could be abruptly engaged once the main contactor had been energized.

Because of limitations on the high-speed power transistors used in the armature chopper, armature current was limited to 120 A (which resulted in 60 N-m of torque) below base speed. This compared to a limited of 300 A (160 N-m of torque) on motor current in the speed range above motor base speed for the vehicle without the armature chopper. A computer simulation by SCT indicated acceleration times to 10 km/h (6 mi/h) would be increased by about 1.1 s due to the reduced current limit when the armature chopper was used. This simulation assumed there were no other traction limitations and was compared to the 300-A current limit in effect during normal (no armature chopper) operation.

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[7]The clutch is used here to modulate the vehicle speed below motor base speed where field weakening begins.

Figure 5-1 is a plot of velocity versus time with and without the use of the armature chopper at 20% and 70% battery depth of discharge (DoD) up to the first shift point at 24 km/h (15 mi/h). At similar depths of discharge, the armature chopper causes a 2% decrement in acceleration performance up to 24 km/h (15 mi/h). Although the acceleration values at both DoDs with the active armature chopper are consistently lower than with it inactive, the 2% decrement is within the scatter of the data so the absolute value may not be significant. It is clear that the penalty in acceleration performance for the use of the armature chopper is small. It is, in fact, less than the effect on acceleration for maximum acceleration tests at 20% DoD compared to 70% DoD tests where a 6% decrement can be observed in Figure 5-1 by comparing the two curves with the LPAC inactive. The decrement for a similar comparison with active LPAC is 10%. This result is less than what was anticipated by the SCT computer simulation in their armature chopper proposal (shown in Figure 5-1 as the short-dashed line). The variation may have been more a drivability effect than a physical result of the design differences, since the acceleration performance without the armature chopper falls well below the idealized values.

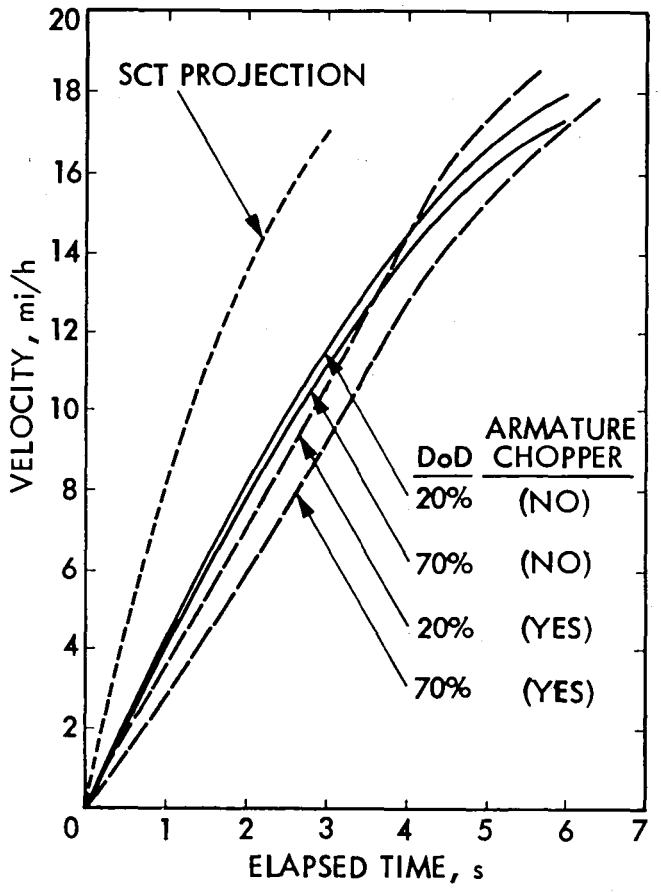

Figure 5-1. First Gear Maximum Acceleration With and Without the Motor Armature Chopper

Because the chopper is inoperative above the motor base speed, which is equivalent to 12 km/h (7.5 mi/h) in first gear, it should be noted that Figure 5-1 shows the entire effect of the armature chopper on acceleration. The transmission shift strategy was designed to preclude motor operation below base speed except when initially accelerating from a complete stop. In this manner, the penalties associated with armature chopper operation (i.e., reduced power capability and energy efficiency) are minimized. Figure 5-2 graphically demonstrates the shift strategy.

Figure 5-3 shows battery energy economy with and without the armature chopper for the maximum acceleration tests. It can be seen that addition of the armature chopper had no significant effect on the battery power during the maximum acceleration tests. The reason for the negligible effect on power is the small proportion of time that the armature chopper operates. Figure 5-2 shows just how little the armature chopper operates.

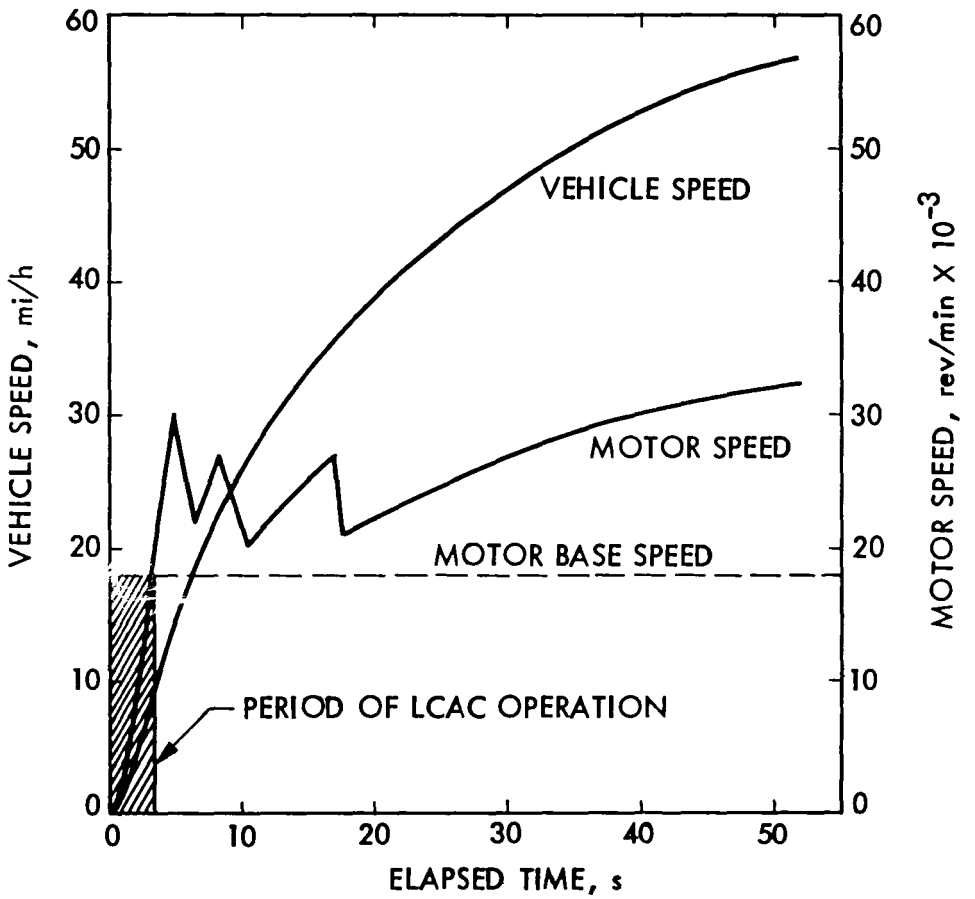

Figure 5-2. Vehicle and Motor Speed as a Function of Elapsed Time in a Maximum Acceleration Test

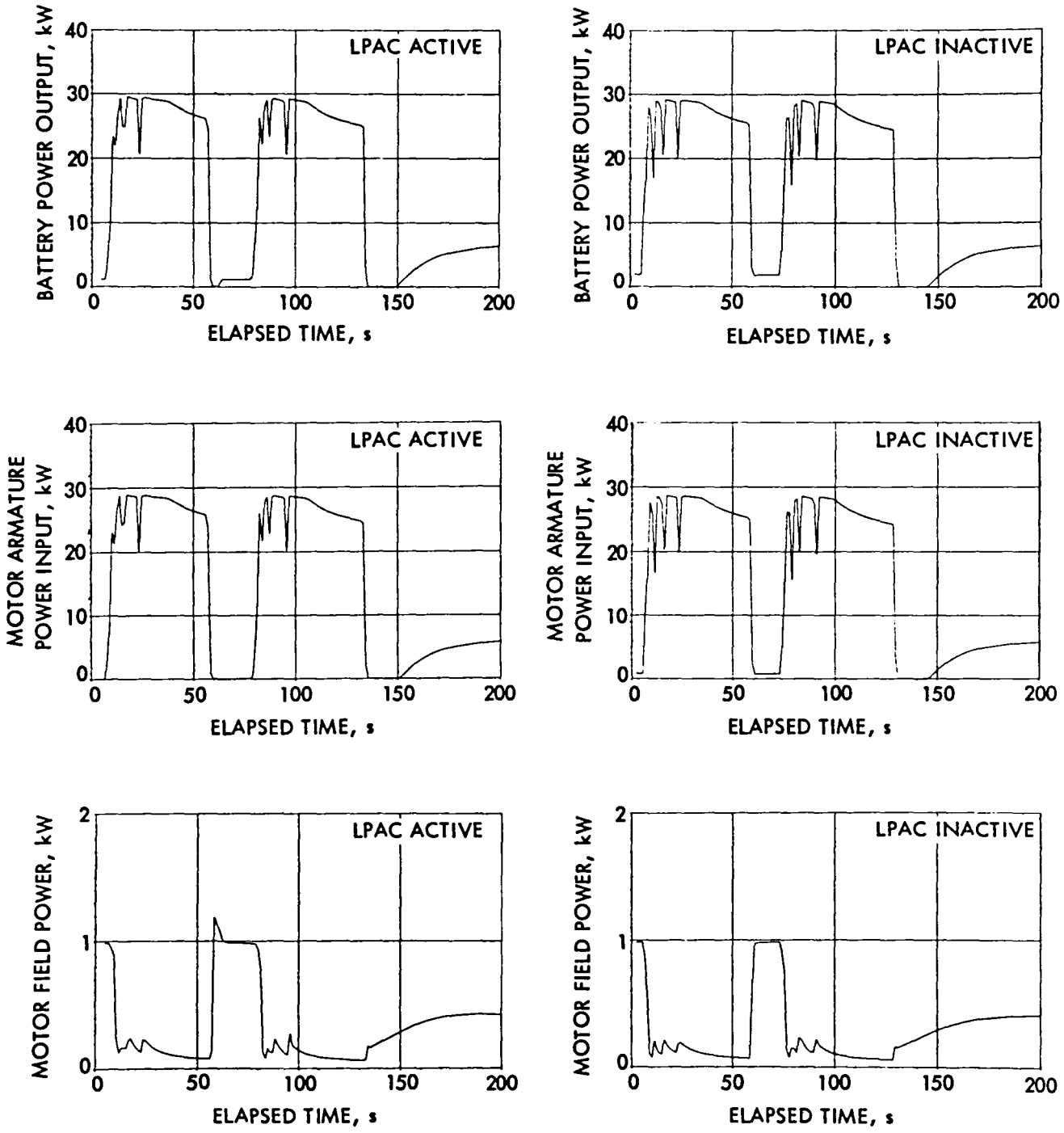

Figure 5-3. Comparisons Between Active and Inactive Motor Armature Chopper Performance for Maximum Acceleration

B. DRIVING CYCLES

Figure 5-4 and Table 5-1 show that the addition of the armature chopper results in an increase in battery energy economy of approximately 6% for the SAE J227a-C cycle and 3.5% for the J227a-D cycle. Figures 5-5a (C-cycle) and 5-6a (D-cycle) clearly show the reasons for this improvement. The battery power required during the idle segment of the cycles[8] is reduced by approximately 50%. This occurs because the motor no longer "idles" at its base speed and the high in-gear minimum speed has been eliminated. Also, power demand during the initial high-acceleration part of both cycles is somewhat reduced. Perusal of Figures 5-5b and 5-6b reveals that this saving occurs because the motor armature consumes no power during idle when the armature chopper is in use. Figures 5-5c and 5-6c are included to show that motor field power consumed during idle is unaffected by the use of the armature chopper, so the improvement is due entirely to the elimination of the armature power requirement.

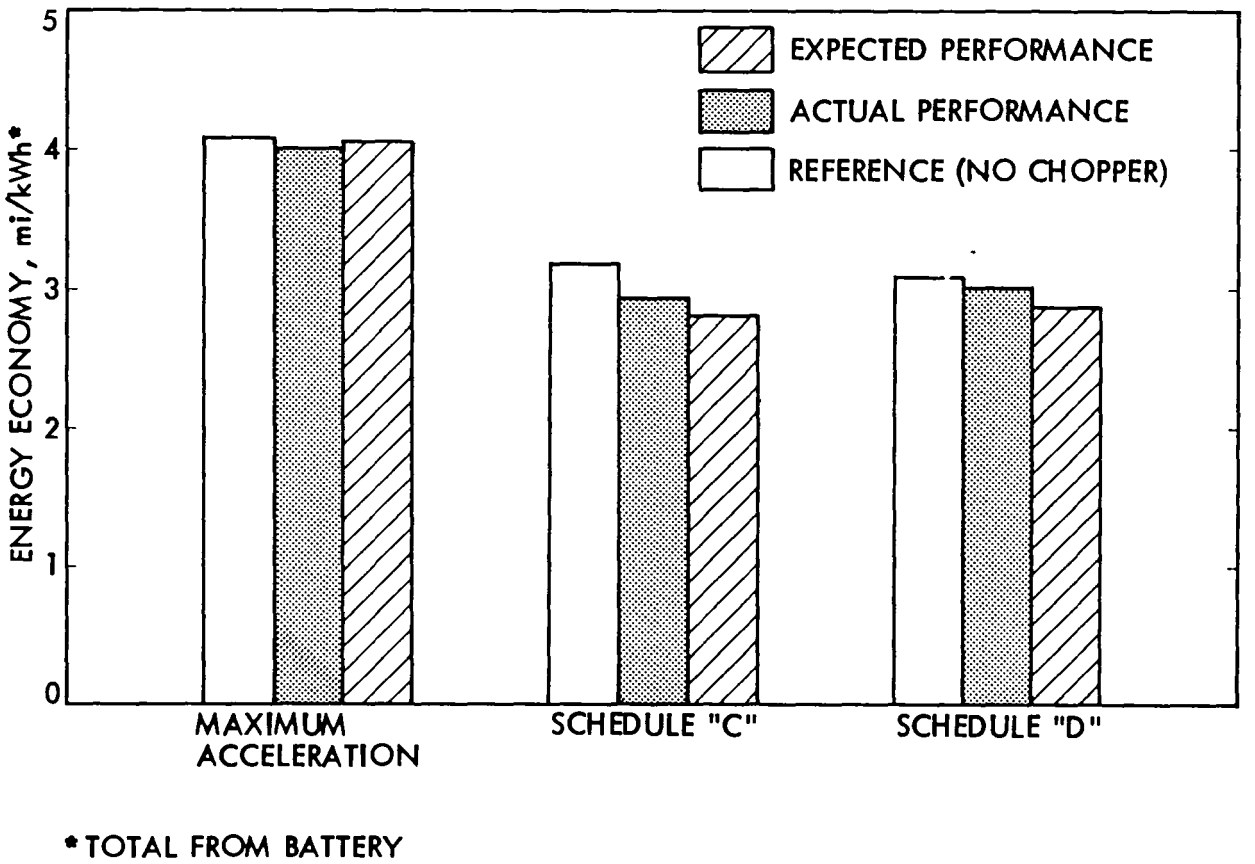

Figure 5-4. SCT-8 Low-Power Armature Chopper Energy Economy Comparisons

[8]Details of the SAE J227a driving cycles as defined by JPL are contained in Appendix B.

Table 5-1. SCT Rabbit Test Results With and Without Motor Armature Chopper

Test Type, mi/h	Test No.	Battery Energy Output, kWh	Range km	Range (mi)	Energy[a] Economy km/kWh	Energy[a] Economy (mi/kWh)	Armature Chopper
35	4	14.31	128.4	(79.77)	8.96	(5.57)	In
	7	14.46	126.3	(78.51)	8.74	(5.43)	
	Avg	14.385	127.4	(79.14)	8.85	(5.50)	
	5	15.089			8.47	(5.26)	None[b]
	7	15.226			8.96	(5.57)	
	9	15.038			8.61	(5.35)	
	Avg	15.118			8.68	(5.39)	
45[c]	1	12.57	97.6	(60.63)	7.76	(4.82)	In
	6	12.74	99.8	(62.00)	7.84	(4.87)	
	8	13.19	102.6	(63.74)	7.77	(4.83)	
	Avg	12.83	100.0	(62.12)	7.79	(4.84)	
55	3	9.92	61.6	(38.28)	6.21	(3.86)	In
	10	10.35	62.2	(38.64)	6.00	(3.73)	
	Avg	10.135	61.9	(38.46)	6.11	(3.795)	
	3	11.707			6.17	(3.83)	None[b]
	4	11.321			6.24	(3.88)	
	Avg	11.514			6.20	(3.85)	

[a]Based on total energy removed from the battery terminals.

[b]This data is for the SCT-2 (Reference 2).

[c]No 45 mi/h tests without armature chopper were run.

Table 5-1 (Cont'd)

Test Type	Test No.	Battery Energy Output, kWh	Range km	Range (mi)	Energy[a] Economy km/kWh	Energy[a] Economy (mi/kWh)	Armature Chopper
C	9	13.56	64.1	(39.81)	4.73	(2.94)	In
	11	13.48	64.0	(39.79)	4.75	(2.95)	
	Avg	13.52	64.1	(39.80)	4.74	(2.945)	
	Avg	11.514			6.20	(23.85)	
	13	13.93	61.1	(37.98)	4.39	(2.73)	Out
	16	14.08	64.5	(40.08)	4.59	(2.85)	
	Avg	14.005	62.8	(39.03)	4.49	(2.79)	
D	2	10.23	49.2	(30.58)	4.81	(2.99)	In
	5	9.93	47.8	(29.73)	4.81	(2.99)	
Avg	10.08	48.54	(30.16)		4.81	(2.99)	
	17	9.97	46.2	(28.69)	4.63	(2.88)	Out
	18	10.77	47.8	(29.69)	4.44	(2.76)	
	Avg	10.37	47.0	(29.19)	4.54	(2.82)	
Max Acc	12	13.33	87.6	(54.42)	6.57	(4.08)	
	20	13.60	86.2	(53.55)	6.34	(3.94)	In
	Avg	13.465	86.9	(53.985)	6.45	(4.01)	
	14	13.08	85.6	(53.19)	6.55	(4.07)	Out
	15	13.27	87.2	(54.17)	6.57	(4.08)	
	19	13.60	86.2	(53.55)	6.34	(3.94)	
	Avg	13.32	86.3	(53.64)	6.49	(4.03)	

[a]Based on total energy removed from the battery terminals.

Further improvement in battery energy economy (approximately 6%) would be possible if provision were made for shutting down field power during the idle phase of the driving cycles. Analysis made by SCT and EHV Systems Corp. concluded that there was little energy savings potential in turning off the field current. Furthermore, additional circuitry would be required to inhibit armature operation unless field power was present. Without these interlocks it would be possible for the motor to accelerate rapidly to maximum speed as soon as armature power is applied if field power was missing. Therefore, SCT and EHV Systems Corp. concluded that the added safety circuitry was not warranted because of the small power reduction gained by field shutdown. The shortcoming in this analysis lies in the values of armature and field power when motor is at, or below, base speed. During idle (base speed) the field consumes a minimum of 50% of the motor's total power requirements, an expenditure that could be eliminated by shutting down field power during idle.

C. STEADY SPEED TESTS

The SCT Rabbit with armature chopper was tested at steady speeds of 56.3, 72.4 and 88.5 km/h (35, 45 and 55 mi/h). The battery energy economies are tabulated in Table 5-1 and compared to equivalent values for another SCT Rabbit.[9] Because the results from the driving cycle tests (Figures 5-5 and 5-6) show that the armature chopper had an effect mainly during idle and very slightly during acceleration, the differences of 1.5 to 2.0% for the steady speed tests in Table 5-1 are not significant with regard to the LPAC. The armature chopper affected only the initial acceleration of SCT-8 as it approached the specified test speeds. Once above 12 km/h (7.5 mi/h), the LPAC was bypassed and SCT-8 operated the same as the conventional SCT vehicles. Therefore, no difference in performance was expected between the armature chopper and chopperless versions. Any differences in the SCT-8 to SCT-2 comparisons in Table 5-1 are a result of minor differences in internal vehicle losses and differences in battery capacity between the two vehicles.

D. DRIVABILITY

The comments in this section represent the subjective opinions of the JPL test drivers who have driven both the standard SCT electric Volkswagen and the SCT-8.

Drivability of the vehicle with the armature chopper is significantly improved as compared with the standard SCT electric Rabbit since no clutch modulation is required to accelerate the vehicle from rest and it is no longer necessary to downshift to maintain motor speed above base speed during deceleration to avoid excessive armature current.

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[9] JPL designation: SCT-2, which was a similar vehicle without armature chopper (see Reference 3). It was necessary to make the comparisons with the SCT-2, as only driving cycle and maximum acceleration tests were run with the LPAC disabled on the SCT-8. No comparison was possible at 45 mi/h, as no data without the LPAC were available for either vehicle.

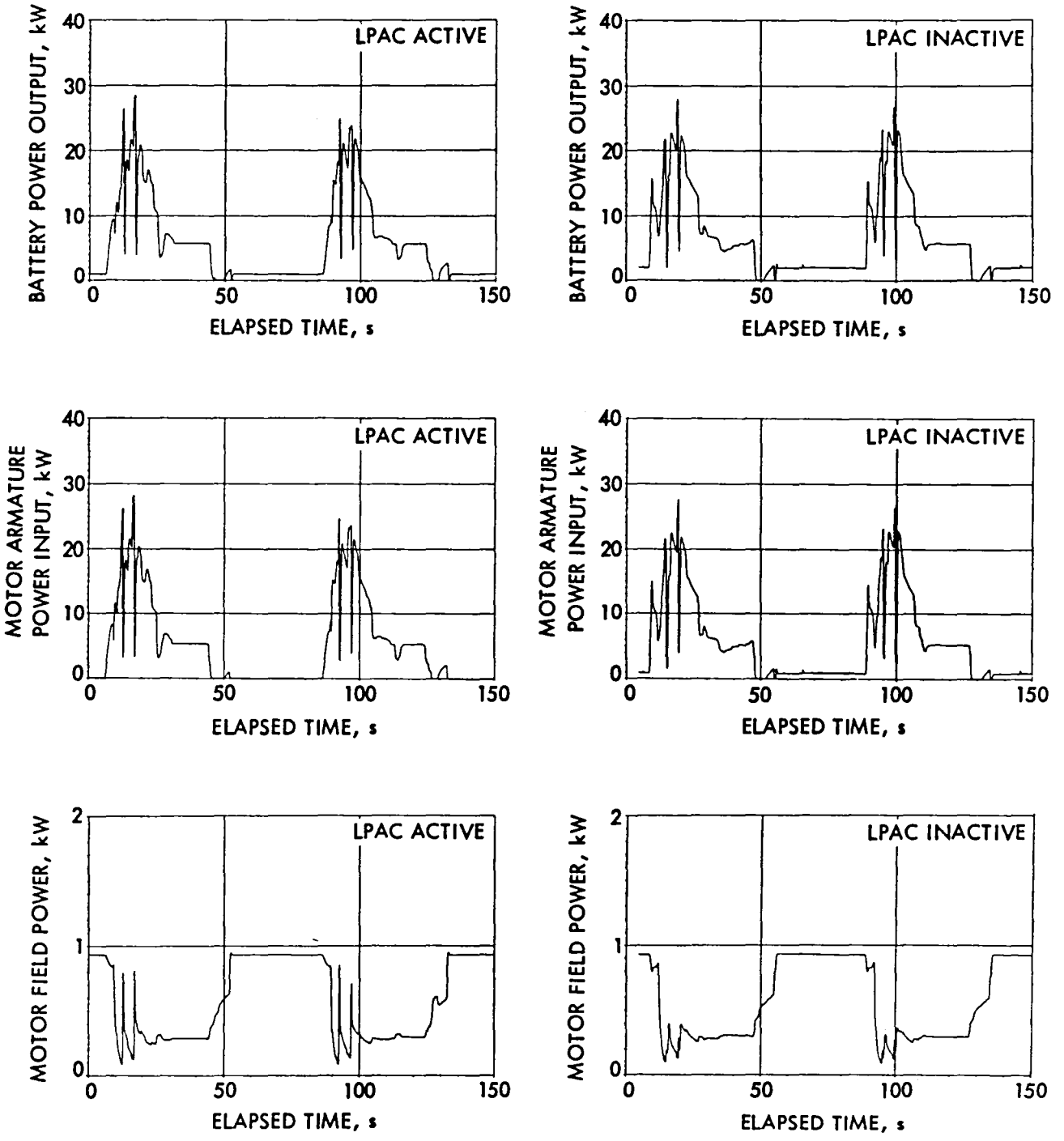

Figure 5-5. Comparisons Between Active and Inactive Motor Armature Chopper Performance for SAE 227a-C Driving Cycle

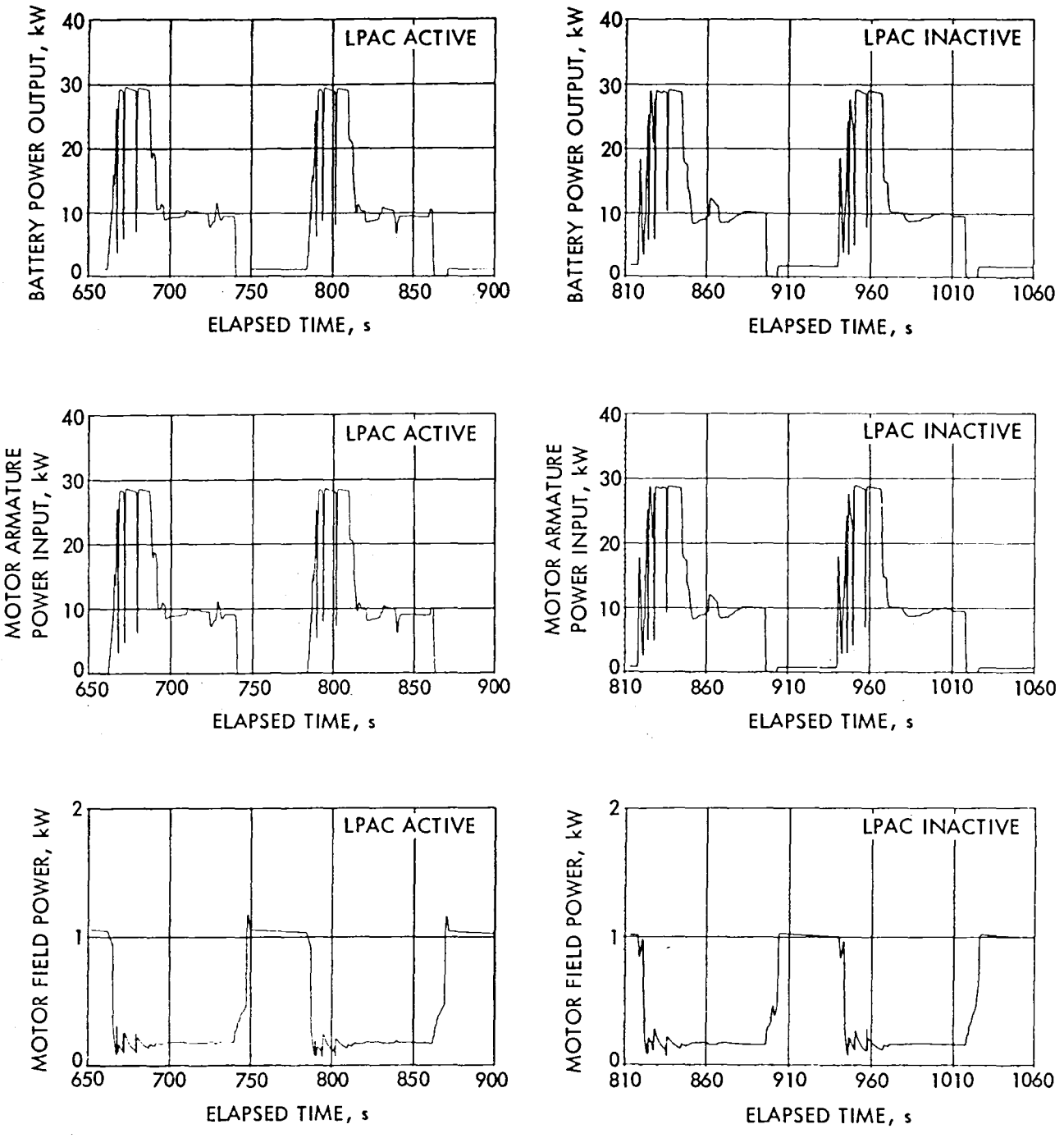

Figure 5-6. Comparisons Between Active and Inactive Motor Armature Chopper Performance for the SAE 227a-D Driving Cycle

One of the problems with the conventional SCT is the fact that the 1800-rev/min base speed results in a minimum 29-km/h (18-mi/h) (see Figure 5-2) vehicle speed. If one does downshift or declutch, excessive currents are drawn resulting in a vehicle shutdown. Cars would then have to go through the complete startup process. This "inconvenience" and the safety problems associated with a "stalled" vehicle are precluded by the addition of the LPAC. Also, vehicle energy economy and drivability would be enhanced if some kind of driver prompting was added as to when up and downshifts should be done. In this way, reduced performance in upper gears due to LPAC limitations would be minimized if the driver follows the prompting.

SECTION VI

CONCLUSIONS

In previous test reports of SCT Rabbits (References 1 and 3), JPL suggested that considerable energy economy improvements were possible by turning off the motor during non-motive operation. The greater the number of stops per mile, the greater the benefits of turning off the motor. Using the average values from the SCT-1 and SCT-2 test results (see References 1 and 3), the potential reductions in energy consumption were 16.8%, 12.0% and 4.4% for SAE J-227a Schedules B, C and D, respectively. Because of the implementation scheme employed by SCT/EHV Systems these levels of improvement were not obtained. Figure 5-3 compares the possible maximum energy economics postulated by JPL to those actually obtained (except for Schedule B tests). It can be concluded that the LPAC did indeed enhance the SCT's energy economy. However, further improvements in reducing energy consumption are readily achievable by adding the additional controls needed to turn off the field. These additional energy reductions will be approximately the same as those obtained by turning off the armature. Therefore, the relatively simple addition of field turn-off would double the energy economy benefit obtained through armature control.

It is JPL's opinion that drivability was substantially improved through the addition of armature control. Even though power is limited during armature operation, proper shifting will limit this disadvantage to first gear only. In first gear, the performance penalty is minor from 0 to 12 km/h (0 to 7.5 mi/h). Above 12 km/h (7.5 mi/h) performance is equal to conventional SCTs. The fact that the operator no longer needs to downshift or declutch at relatively high vehicle speeds more than offsets any performance penalty in the 0- to 12-km/h (0- to 7.5-mi/h) speed range.

Because of the quiet operation of the armature chopper, it is difficult for the driver to determine when it is operating. Only when the LPAC is commanded to provide substantially greater current than allowed by the 120-A limit is its operation discernible to the driver. It is felt that the addition of a visual display indicating appropriate shift points would be beneficial. This display would be relatively inexpensive to implement and would improve drivability and enhance energy economy.

SECTION VII

RECOMMENDATIONS

Because very little driving time is spent in the armature chopping mode (0 to 7.5 mi/h), the efficiency advantage of the transistorized system has little overall effect on energy economy. On the other hand, throughput power of the armature chopper can easily be increased with the lower cost SCRs.

Even though the full extent of the expected energy consumption improvements were not demonstrated, sufficient gains were realized to validate the postulated benefits. Therefore, little would be gained by further development of the LPAC. As such, it is suggested that no further development be pursued in the near future. However, the improved drivability advantages available through the LPAC may be beneficial to the SCT vehicles operated in the Test and Evaluation Program.

Should additional LPACs be deployed in field operations, the following modifications are recommended:

(1) Controls should be added to turn off the field in addition to the armature controls. This relatively low-cost addition will double the benefits in energy economy realized by turning off the armature.

(2) A visual display to prompt the driver as to the best shift points should be developed. Generally speaking, optimum performance and energy economy occur simultaneously in the SCT vehicles. Therefore, the small additional cost of these displays will ensure both maximum performance and energy economy.

(3) The possibility of using silicon-controlled rectifiers (SCRs) instead of transistors for the armature chopper should be considered.

REFERENCES

1. Price, T.W., Shain, T.W. and Bryant, J.A., Vehicle Test Report: South Coast Technology Electric Conversion of a Volkswagen Rabbit, JPL Publication 81-28, Jet Propulsion Laboratory, Pasadena, California, February 1981.

2. Kurtz, D.W., The DOE ETV-1 Electric Test Vehicle, Phase III Final Report, Performance Testing and System Evaluation, JPL Publication 81-93, Jet Propulsion Laboratory, Pasadena, California, December 1981.

3. Hewitt, R, and Bryant, J., Testing of the Eagle-Picher Nickel-Iron, the Globe ISOA Lead-Acid, and the Westinghouse Nickel-Iron Battery Subsystems in an Electric Vehicle Environment, JPL Publication 82-91, Jet Propulsion Laboratory, Pasadena, California, July 15, 1982.

4. Marte J., and Bryant, J., Correlation of Performance Testing Between Track and Dynamometer Test Techniques for the DOE ETV-1 Electric Test Vehicle, JPL Publication 83-20, Jet Propulsion Laboratory, Pasadena, California, December 1982.

APPENDIX A

LOW-POWER ARMATURE CHOPPER OPERATION

Figure A-1 shows a simplified schematic for one of the four identical phases of the armature chopper. Each phase employs its own closed-loop control logic and operates independently of the other three phases.

The control strategy used in this design is unique in that each of the four phases operates independently, and switches on and off in such a way as to produce a constant amplitude current ripple through each phase. Computer simulation was used to determine the required on and off times as a function of armature voltage producing the curves of Figure A-2. Because the off-time curve is essentially exponential, it was implemented with a simple R-C network. The advantages of this type of control are low cost, simple circuitry, and good control of transistor operating regimes. Also, the four phases, due to the independent switching, produce a very smooth armature current flow with very low ripple and unusually quiet operation. The armature chopper is, in fact, virtually silent in operation.

Referring to the schematic of Figure A-1, the circuit operates as follows:

Current feedback is provided by Shunt S1 through scaling amplifier A1 to one input of comparator A2 where it is compared to the current limit command signal from the logic and control board. The output of comparator A2 indicates whether current is greater than, or less than the command current to control turn-off of the power transistor Q1. When Q1's emitter current exceeds the command current, the output of A2 will go to a low logic level setting flip-flop (FF1) and thus causing Q1 to turn off. Gate OR1 provides a means of disabling the armature chopper by inhibiting base drive to Q1.

At the time FF1 is set, transistor Q5 is turned off, and the circuit consisting of Q5, C1, R1 and provides a 30- to 40-μs one-shot to control the minimum off-time of Q1 to ensure full discharge of its series inductor L1. After the 30- to 40-μs delay, transistor Q6 will be turned off, allowing C2 to charge through R2 from the propulsion battery.

C2 is allowed to charge until its voltage exceeds the scaled armature voltage being applied at one input of comparator A4, at which time the output of A4 will go to a low logic level causing FF1 to reset, turning Q1 on, and Q5 and Q6 on to discharge C1 and C2, starting the cycle over again. The circuit consisting of Q6, R2, C2 and A4 provides the response shown earlier in Figure A-2.

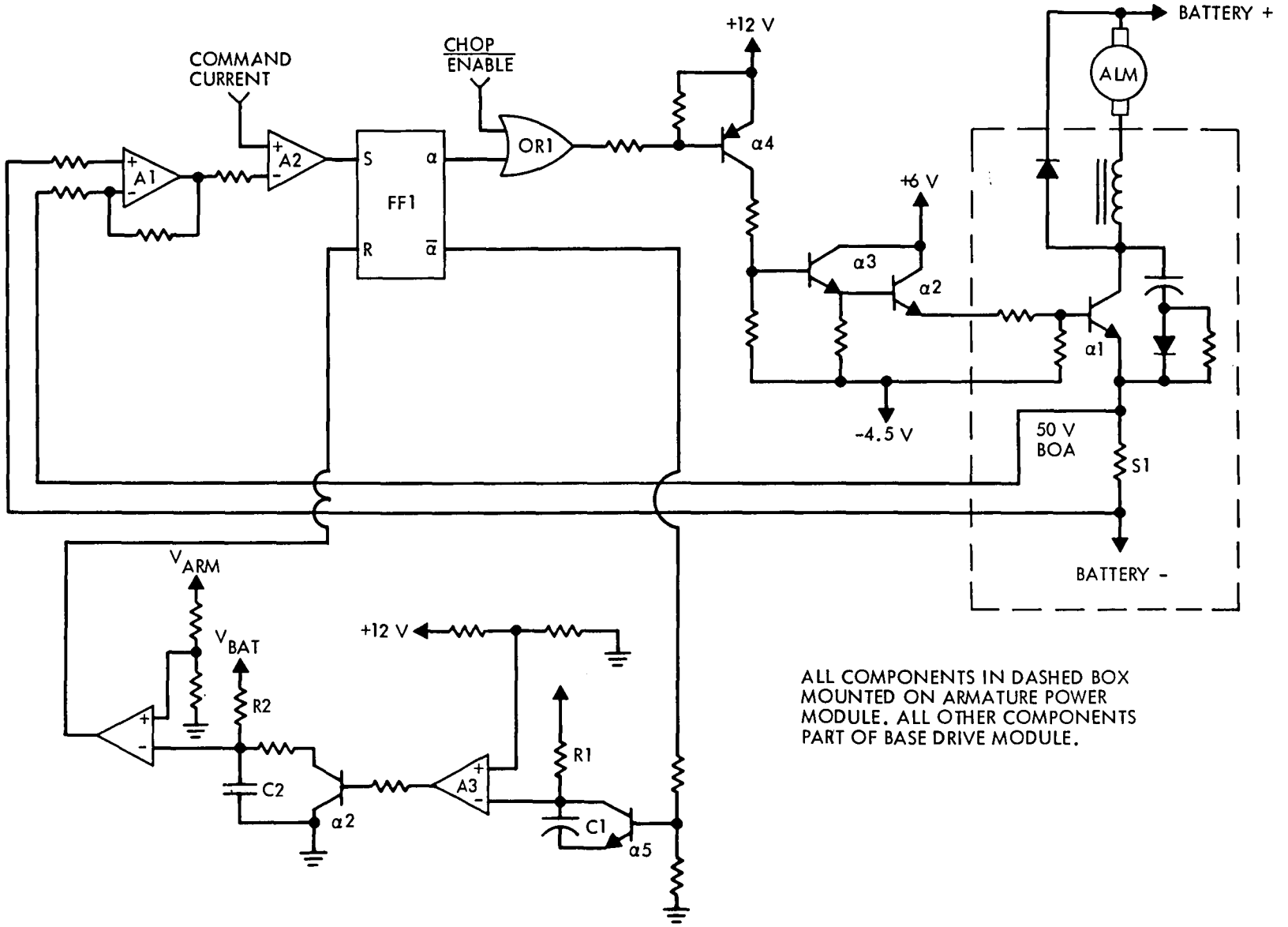

Figure A-1. Armature Power Circuits : Simplified Schematic

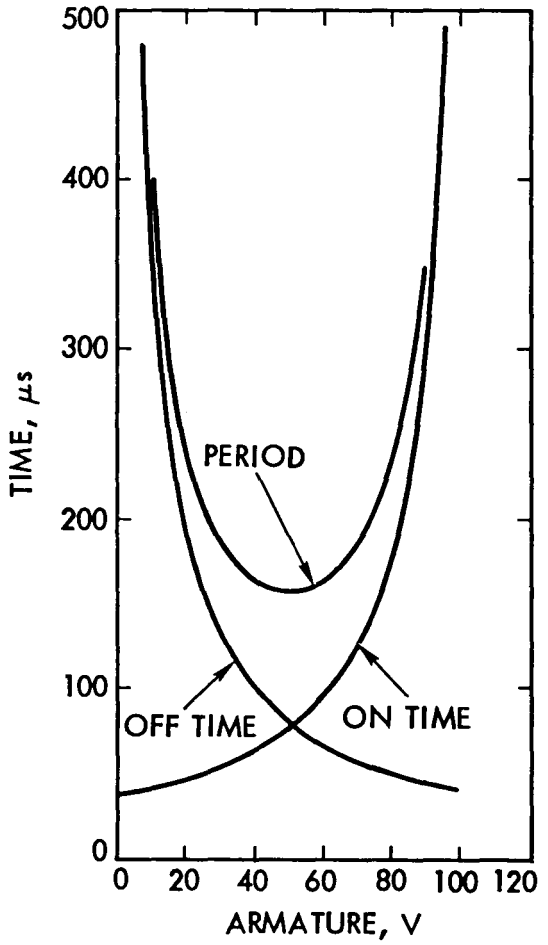

Figure A-2. Relationship of Switch Timing for One of Four Phases

The LPAC controller consists of four major functional blocks:

(1) Logic Power Supply and DC-DC Converter.

(2) Control Logic and Field Driver.

(3) Armature Control Logic and Base Drivers.

(4) Armature Power Modules.

The logic power supply/DC-DC converter is a conventional switch-mode supply utilizing an LSI pulse-width modulation controller to regulate the primary winding of a transformer. Output windings provide the necessary AC voltages to provide DC outputs of +6 V, -4.5 V, +12 V and +16 V.

The field driver section is identical to that used in the production SCT R-1, with the exception of the additional control logic required to interface to the armature chopper. Additional circuitry has also been added to provide

the armature chopper command signals as well as to handle the transitions from armature to field chopping and vice versa. These transitions are made based on the following criteria:

(1) The armature chopper is bypassed when the armature voltage is greater than 85 V.

(2) The circuit is opened when either the armature current is greater than 350 A or the voltage in the control circuit is less than 4 V and the armature current is greater than zero for more than 0.2 s.

Armature bypass occurs only when all the necessary conditions are satisfied.

APPENDIX B

INSTRUMENTATION AND DATA RECORDING

A relatively large general purpose, Integrated Data Acquisition and Control (IDAC) system is an integral part of the JPL Automotive Research Facility. The digital recording system is used to record data for all tests conducted on the chassis dynamometer. Approximately 40 data channels are routinely recorded. The digitally formatted energy data are sampled 10 times per second to permit good time resolution of the transients during a test. Each analog data channel is also sampled about 10 times per second.

Data recording is accomplished in two ways: high-speed printer (on paper) and magnetic tape. The bulk of the recording is done with the magnetic tape while the direct printing is used for a "quick look" immediately after test completion. Subsequent data reduction of the magnetic tapes provides a detailed tabular printout of the data as well as plots of pertinent parameters.

Slices of data are acquired at various time intervals. The exact time within the test depends on the type of test. For instance, during constant-speed tests, data are recorded once every 30 s. During the driving schedule tests, the 30-s interval data are supplemented by several continuous recordings of two complete sequential repetitions of the driving cycle. These continuous recordings are intended to occur at 6 discrete levels of battery depth of discharge, however, the time at which these levels of depth of discharge occur must be estimated prior to the test. The procedure is illustrated in Figure B-1.

During the chassis dynamometer tests, approximately 40 parameters were measured and recorded. The key measurements were those of voltage, current, energy and power for the battery, motor armature and the motor field, motor and half-axle rotational speed, aerodynamic horsepower, vehicle velocity and distance traveled, and battery electrolyte temperature. Each of these is discussed in more detail below.

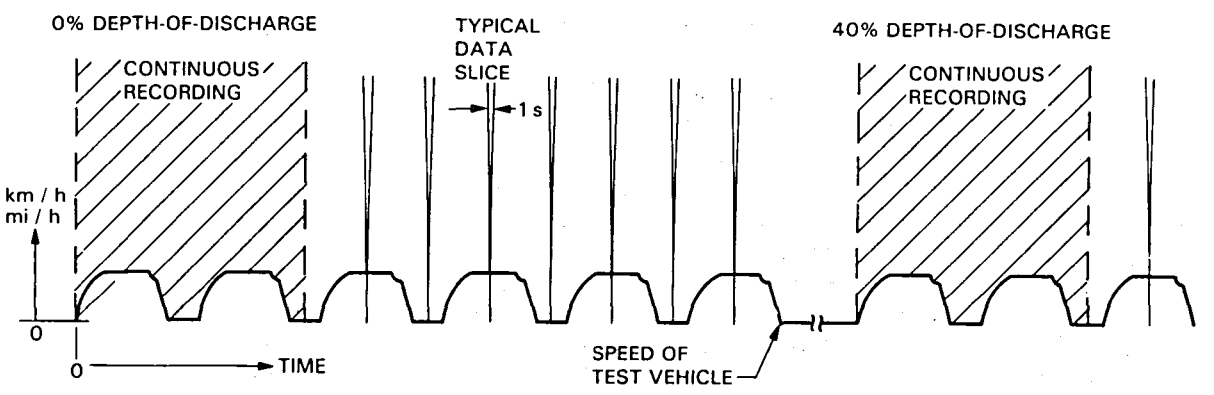

Figure B-1. Typical Data Recording Format

1. Voltage, Current, Power, and Energy

These four parameters are intimately related and are discussed in common. The power and energy measurements were made using instruments designed and fabricated at JPL. They are discussed in detail in Reference B-1.

The power measurement system consists of three physically separate parts: the charging power unit, the measurement chassis, and the counter chassis. The charging power unit measures electrical power consumed during recharge of the vehicle batteries and can be used in conjunction with either on-board or off-board chargers. The internal design of the charging power unit is identical to those of the measurement chassis, therefore both electrical output, signals, and performance of the charging unit are identical to those of the measurement chassis.

The standard technique of multiplying the voltage and current signals to obtain an analog signal proportional to power is used. The analog output signal of power is sent to two voltage-to-frequency converters (one for each signal polarity) to convert the analog power signal to a frequency. The frequencies are then sent to the counter chassis and to the output connector for recording by the data system.

The current circuit up to the multiplier includes three amplification stages and the voltage channel two. This circuitry removes any common mode voltage, amplifies the signal and directs the high-level signal to both the multiplier and to output connectors as the high-frequency output signal. A buffer stage with a gain of one is used to provide the low-frequency output signal. This stage and its separate power supply are necessary to eliminate any common mode voltages that may exist between the points where the high-frequency outputs are being used, which is typically in the chassis dynamometer room, and the data system which is in an adjacent room.

Provision is made for a jumper change to permit the measurement of ampere hours instead of power. In this manner, battery ampere-hour data during charging and discharging are provided.

2. Motor and Half-Shaft Rotational Speed

The Siemens' motor used by SCT includes a tachometer generator. For the purpose of the baseline testing this signal was used as an indication of the motor speed and was routinely recorded. The rotational speed at the output of the transmission is also useful since it provides a means of deducing the gear being used at any time, and also makes a historical record that will allow clutch failures to be detected. Because the Rabbit uses a transaxle, there is no ready access to the transmission output shaft. Therefore, the wheel half-shaft speed was measured by attaching alternating strips of reflective and optically black tape to the half-shaft. A photo optical sensor was used to monitor the black-to-reflective transitions and thus provide a signal proportional to the shaft rotational speed.

3. Vehicle Velocity and Distance Traveled

Each of the two dynamometer rolls is equipped with a digital transducer which produces a pulse proportional to each centimeter of distance traveled. These pulses are recorded as a rate (mi/h) and integrated with a counter (mi). Although the pulse signals from both dynamometer rolls are recorded, only the data on the idle roll are used for reporting purposes. Data from the other dynamometer roll (absorption roll) are used for engineering information and to adjust the dynamometer aerodynamic load simulation.

4. Torque and Aerodynamic Horsepower

The reactive torque which results from energy being dissipated in the dynamometer absorption unit is measured by a precision load cell. Using torque and dynamometer rev/m the IDAC data system calculates horsepower in near real time (within 0.1 s). This permits accurate adjustments of the dynamometer aerodynamic horsepower.

5. Miscellaneous Measurements

Additional recorded measurements include battery temperatures, motor case temperature, atmospheric pressure, calibration voltages and several other parameters.

REFERENCE

B-1. Price, T.W., Shaiu T.W., and Bryant, J.A., Vehicle Test Report: South Coast Technology Electric Conversion of a Volkswagen Rabbit, JPL Publication 81-28, Jet Propulsion Laboratory, Pasadena, California, February 1981.

APPENDIX C

JPL STANDARDIZATION OF THE SAE J227a DRIVING CYCLES

In order to provide a well defined baseline from which to measure the performance of the near-term batteries, a set of test procedures which are repeatable and which can easily be maintained constant over a long calender time are a necessity. An important part of these consistent procedures is the specific driving schedules to be used. The SAE J227a driving schedules provide a good basis for the required consistency, but as currently designed by the SAE they are not totally adequate. The principal deficiency (for the purposes of the testing described here) is the lack of definition of the time/speed profile path to be followed for the acceleration, coast, and brake portions of the cycle. Therefore, those portions of the J227a driving schedules were defined by JPL for the purpose of the tests described here. The complete -C and -D cycles are shown in Tables C-1 and C-2 and in Figure C-1. Some of the considerations that affected the final choice are discussed below.

The primary constraint (self-imposed) used in deriving the time/speed traces of Figure C-1 was that they should reflect the practice and expectations of the "average" driver, (i.e., deceleration rate during braking and coast should not be excessive, the transitions from one mode to another should be smooth and continuous, etc). The acceleration paths chosen were taken from the Federal Test Prodedure, normalized to the J227a schedule requirements. A maximum deceleration rate of 3.3 mi/h/s was allowed for the braking mode. An asymptotically decaying velocity was selected for the coast mode. This is a composite of coasts from an electric Corvette and several IC-powered vehicles. Again the expectations of the "average" driver when the accelerator pedal is released were the rationale, but with an additional consideration that the coast should allow as much regeneration as practical for those vehicles so designed. The coast-brake portion of the "D" cycle presented a special problem in that all the constraints touched on above and the J227a times for coast and brake could not be simultaneously satisfied. The compromise reflected in Table C-2 and Figure C-1 was that the 3.3 mi/h/s deceleration rate was maintained, the brake time lengthened by 3 s, and the coast time shortened by 3 s. The overall coast-brake time for the "D" cycle, is as specified by the J227a, and except for the coast-brake of the "D" cycle, all the schedules of Tables C-1 and C-2 meet the letter of the J227a document.

Table C-1. Schedule "C"

Time, s	Speed, mi/h	Time, s	Speed, mi/h	Time, s	Speed, mi/h
0	0.00	21	30.00	54	2.89
1	2.65	↓	↓	55	0.00
2	5.31			56	0.00
3	7.97			57	0.00
4	10.60	37	30.00	58	0.00
5	13.05	38[a]	30.00	59	0.00
6	15.28	39	29.19	60	0.00
7	17.33	40	28.52	↓	↓
8	19.18	41	27.89		
9	20.89	42	27.40		
10	22.43	43	26.98	78	0.00
11	23.83	44	26.59	79	0.00
12	25.08	45	26.27	80[a]	Repeat cycle starting at 0 s
13	26.21	46	26.00		
14	27.20	47	23.11		
15	28.07	48	20.22		
16	28.82	49	17.33		
17	29.45	50	14.44		
18[a]	30.00	51	11.56		
19	30.00	52	8.67		
20	30.00	53	5.78		

[a]Denotes transition points from one mode to another (i.e., acceleration to cruise).

Table C-2. Schedule "D"

Time, s	Speed, mi/h	Time, s	Speed, mi/h	Time, s	Speed, mi/h
0	0.0	25	43.31	91	19.00
1	2.56	26	43.93	92	15.83
2	5.12	27	44.49	93	12.67
3	7.68	28	45.00	94	9.50
4	10.24	29	45.00	95	6.33
5	12.80	30	45.00	96	3.17
6	15.36	↓	↓	97	0.00
7	17.79			98[a]	0.00
8	20.08			99	0.00
9	22.24	75	45.00	100	0.00
10	24.28	76	45.00	↓	↓
11	26.20	77	45.00		
12	28.01	78[a]	45.00	120	0.00
13	29.72	79	43.53	121	0.00
14	31.34	80	42.33	122[a]	Repeat cycle starting at 0 s
15	32.85	81	41.33		
16	34.27	82	40.40		
17	35.60	83	39.53		
18	36.85	84	38.73		
19	38.01	85[a]	38.00		
20	39.09	86	34.83		
21	40.08	87	31.67		
22	41.00	88	28.50		
23	41.85	89	25.33		
24	42.61	90	22.17		

[a]Denotes transition points from one mode to another (i.e., acceleration to cruise).

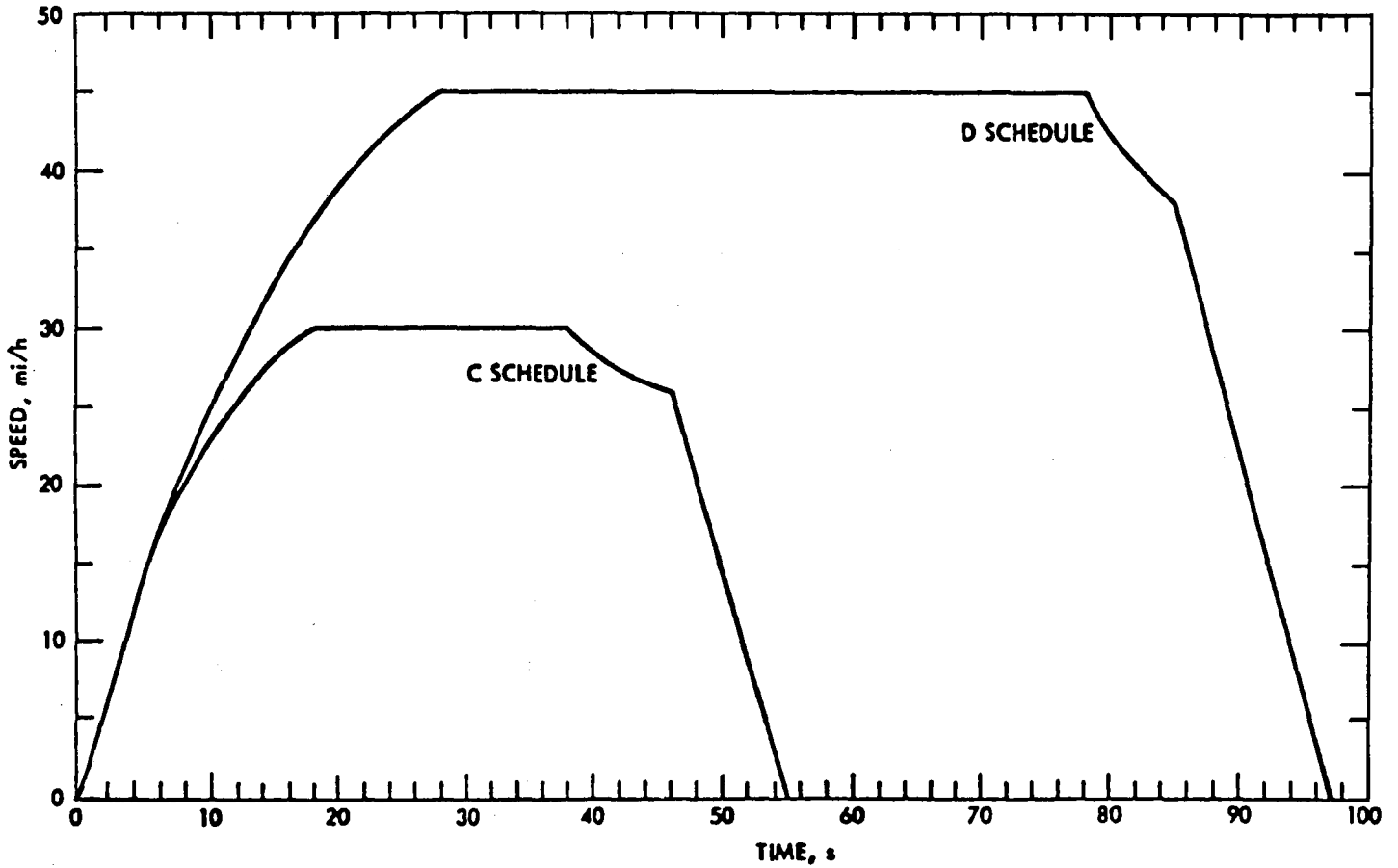

Figure C-1. JPL Standardization of the SAE J227a-C and -D Driving Cycles

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