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# PERFORMANCE CHARACTERISTICS OF A BATTERY CHARGER AND STATE-OF-CHARGE INDICATOR

By
D. Edwards
J. Klein

September 30, 1984

Work Performed Under Contract No. AI01-78CS54209

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Pasadena, California



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ABS: A battery charge/state of charge indicator (BC/SCI) system for electric vehicle use was developed. The original and subsequent objectives for the BC/SCI and the rationale for those objectives are described. The requirements generated from the objectives are listed and a description of the BC/SCI is provided. The power section problem, the tests, and the test results are discussed.

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# Performance Characteristics of a Battery Charger and State-of-Charge Indicator

D. Edwards
J. Klein

September 30, 1984

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## ABSTRACT

A device suitable for battery charging and a device that predicts the state of charge is complex. To reduce the number of components, an effort was initiated to combine the battery charger and a state-of-cycle indicator because the sensors, processor, displays, and controls can be shared. State-of-charge information can be used by the battery charger for better charging procedures. Also, the computational capability of the state-of-charge indicator can also be used by the charger to optimize charge control. These considerations prompted the U.S. Department of Energy (DOE) to direct the Jet Propulsion Laboratory (JPL) to develop a battery charger/state-of-charge indicator (BC/SCI) system for electric vehicle use under contract to Gould Laboratories.

This report describes the original and subsequent objectives for the BC/SCI and the rationale for those objectives. The requirements generated from the objectives, both the original and reduced, are listed. A description of the BC/SCI is provided. A complete discussion of the power section problem is given and recommendations made for solving that problem. Other recommendations are provided for the state-of-charge indicator. One section of this report deals with the tests performed by JPL on the BC/SCI. This section gives an explanation for the tests and discusses the test results. The last section summarizes the conclusions and recommendations of the previous sections.

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# SECTION I

# INTRODUCTION

The most critical component of any electric vehicle is the battery. The battery, which, more than any other component, limits vehicle performance and increases the vehicle's cost. The largest operating expense of an electric vehicle is the battery's depreciation costs. A charger, using improved charging procedures that reduce maintenance and prolong the life of the battery, would make the electric vehicle more cost effective. An accurate state-of-charge (SOC) indicator would allow an operator to fully utilize the battery's limited energy. Due to the limited range and the long recharge time associated with present electric vehicles, inaccuracies in estimating the battery's energy will result in either a reduction in the vehicle's range or stranded vehicles along the roadway.

A device suitable for battery charging and a device that predicts the state of charge is complex. To reduce the number of components, an effort was initiated to combine the battery charger and a state-of-cycle indicator because the sensors, processor, displays, and controls can be shared. State-of-charge information can be used by the battery charger for better charging procedures. Also, the computational capability of the state-of-charge indicator can also be used by the charger to optimize charge control. These considerations prompted the U.S. Department of Energy (DOE) to direct the Jet Propulsion Laboratory (JPL) to develop a battery charger/state-of-charge indicator (BC/SCI) system for electric vehicle use under contract to Gould Laboratories.

The adaptability of the BC/SCI is a direct result of its microprocessor-based design and modular construction. Charging procedures and methods for determining state of charge are easily modified by altering the microprocessor's software. The modular construction with well defined interfaces allows different power sections to be used in the BC/SCI. Power sections that are specialized for a particular battery or that have higher charging capabilities can be substituted for the existing one and are easily interfaced to the BC/SCI. It was also anticipated that the BC/SCI would be interfaced with external chargers. The BC/SCI is, therefore, a testbed that demonstrates technology that can be directly adapted into a prototype version of a BC/SCI. Because of its adaptability, the BC/SCI will not become outdated.

This report describes the original and subsequent objectives for the BC/SCI and the rationale for those objectives. The requirements generated from the objectives, both the original and reduced, are listed. A description of the BC/SCI is provided. A complete discussion of the power section problem is given and recommendations made for solving that problem. Other recommendations are provided for the state-of-charge indicator. One section of this report deals with the tests performed by JPL on the BC/SCI. This section gives an explanation for the tests and discusses the test results. The last section summarizes the conclusions and recommendations of the previous chapters.

# SECTION II

## OBJECTIVES

In establishing the BC/SCI requirements, a basic problem was writing specifications that would allow the system to be adaptable. Adaptability is required to ensure that the system can be used with a number of different vehicles and batteries and will not become outdated. Various vehicles will operate at different voltages and have batteries from different manufacturers. The BC/SCI should be compatible with any lead-acid battery whose nominal voltage is over 75 V as well as near-term, advanced batteries (i.e., nickel-zinc or nickel-iron).

In general, safety and utility interface requirements have yet to be well-defined. JPL's requirements in these areas are stringent enough so that the BC/SCI should meet any future regulations. It was also anticipated that the BC/SCI would be used with external chargers. The system must, therefore, have the capability of interfacing with external chargers.

The on-board battery charger was developed to improve battery maintenance and life and to maximize power to the battery from the "standard" receptacle (115 V, 20 A, 60 Hz). Because this most accessible power in the United States has a limited charging capacity, it is important to maximize power to the battery from this circuit, thereby minimizing charge time and making the electric vehicle more convenient for the consumer.

The range limitation of electric vehicles makes accurate estimation of the state of charge very important. An accurate estimation of the distance the vehicle can travel is probably even more important. The BC/SCI will accurately estimate both the range of the vehicle and the state of charge of the battery.[1]

Appendix A defines the functional requirements of the original contract as well as the reduced requirements for the contract continuation. The original contract was reduced in scope when a problem in the power section surfaced. This problem, along with a limitation on the availability of funds, caused the original power requirements of the BC/SCI to be reduced. The requirements for the BC/SCI, including the reduced power requirement, were achieved with a continuation of the original contract. The contract was continued for five months and required additional resources. The reduced requirements call for the power section to operate at 1 kW and have a 90% efficiency at that power. The lower efficiency requirement results from the power section operating at a reduced power. The accuracy requirement for the

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[1]The largest operating expense of an electric vehicle is the battery depreciation costs. A charger, using improved charging procedures that reduce maintenance and prolong the life of the battery, will make the electric vehicle more cost-effective.

state-of-charge indicator was not changed but was recognized as a difficult one to achieve in the contract continuation.

In summary, the BC/SCI should have the following capabilities:

(1) Estimating battery state of charge with a tolerance of 0 to -10%.

(2) Providing high quality interface to the utility (i.e., power factor = 0.94 lagging or better at full load, harmonic currents less than 100 mA, and harmonic voltages less than 100 mV).

(3) Operating at 90% efficiency when input power is 1 kW.

(4) Operating from a conventional house receptacle.

(5) Interfacing with external chargers.

(6) Performing all functions for various battery types.

# SECTION III

# BATTERY CHARGER/STATE-OF-CHARGE INDICATOR SYSTEM

## A. DESCRIPTION

A block diagram of the BC/SCI is shown in Figure 1. The major components of the system are the power section, sensors, control module (microprocessor), and communications panel (both displays and controls). The system is modularly constructed with clearly defined interfaces. Opto-isolators act as the interface between the power section and the control module. An interface module (Figure 2) contains the current shunt and provides a simple means for connecting the power and sensor cables. The display module is physically separated from the other BC/SCI components and would be mounted on the dashboard of an electric vehicle. The control panel is located on the main enclosure, which houses both the power section and control module.

The main enclosure is shown in Figure 3. The power section is located on the left-hand side of the enclosure and represents most of the BC/SCI's weight and volume. The control module is located on the right-hand side and consists of four circuit cards. The control panel is directly in front of the control module. The panel consists of four light-emitting diodes (LEDs), a button for the operator to defer an equalize charge, and a rotary switch to set the charging current for the line current. The four LEDs indicate when the charger is operating, when the charger is equalizing the battery, the need to water, or a fault.

The display panel, indicating the battery's state-of-charge, is shown in Figure 4a. Ten bars are used to display the SOC in 10% increments. When the battery's state of charge reaches 20%, the SCI begins to flash, alerting the operator to the low battery conditions. The push-button on the display is used to request an estimate for the miles the vehicle can travel before the batteries are discharged. Figure 4b shows the display of remaining miles. The remaining miles are only displayed for a few seconds upon the operator's request. The range estimate is based on vehicle speed and energy consumption. Fault codes are displayed in the same area of the panel as the remaining miles (Figure 4c). The BC/SCI has 32 separate fault codes to assist the operator if problems occur. On the left-hand side of the display, the words "water," "equalize," "ac on," and "warning" can be illuminated to provide status of the battery and BC/SCI.

The weights and dimensions of the BC/SCI components shown in Figure 2 are provided in Table 1. The total weight of the BC/SCI is less than 35 lb.

## B. POWER SECTION

### 1. Technical Description

The two main components of the BC/SCI are the power section and the control module. The power section operates from a 115-V, 60-Hz circuit

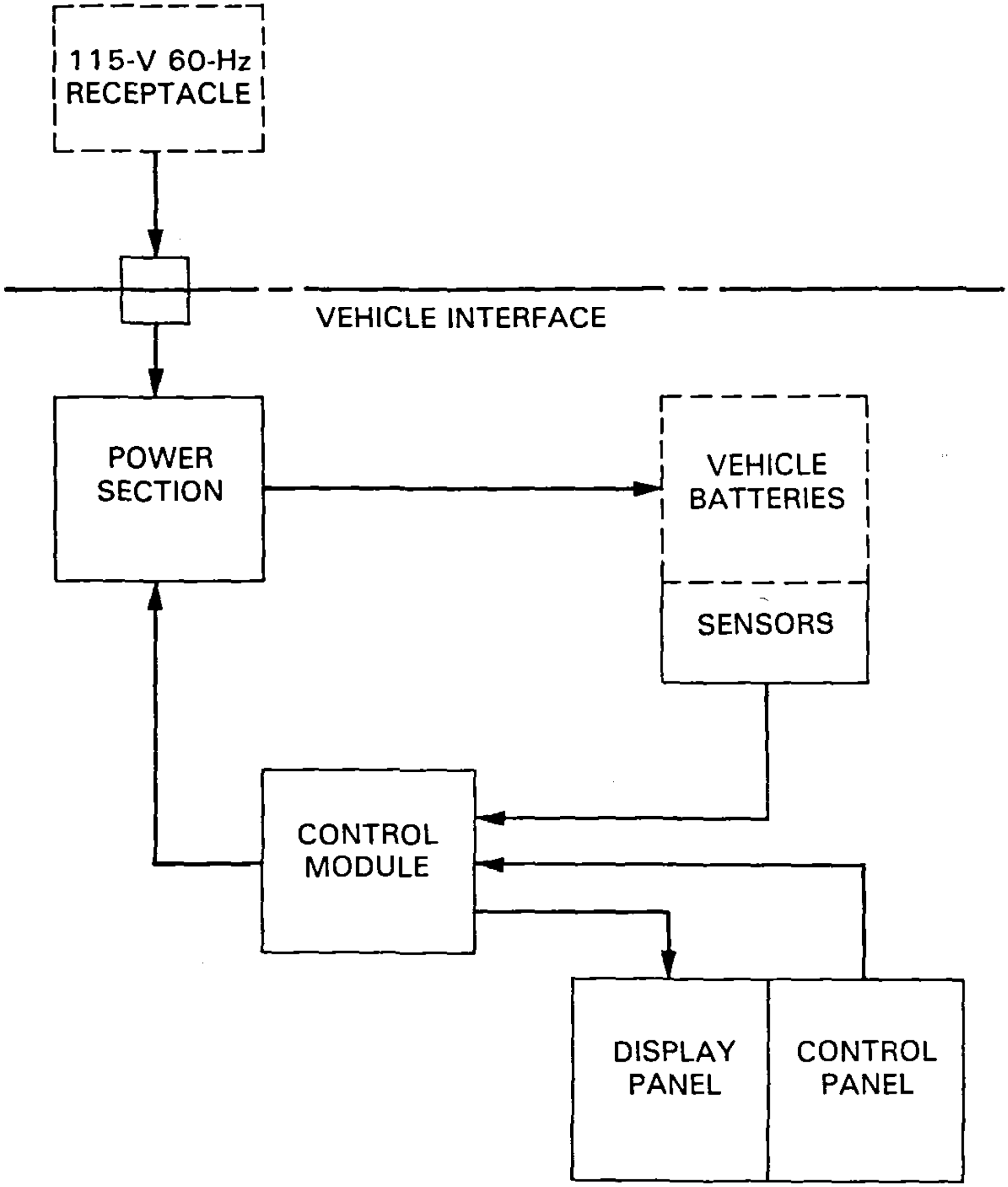



Figure 1. Block Diagram of the Battery Charger/State-of-Charge Indicator

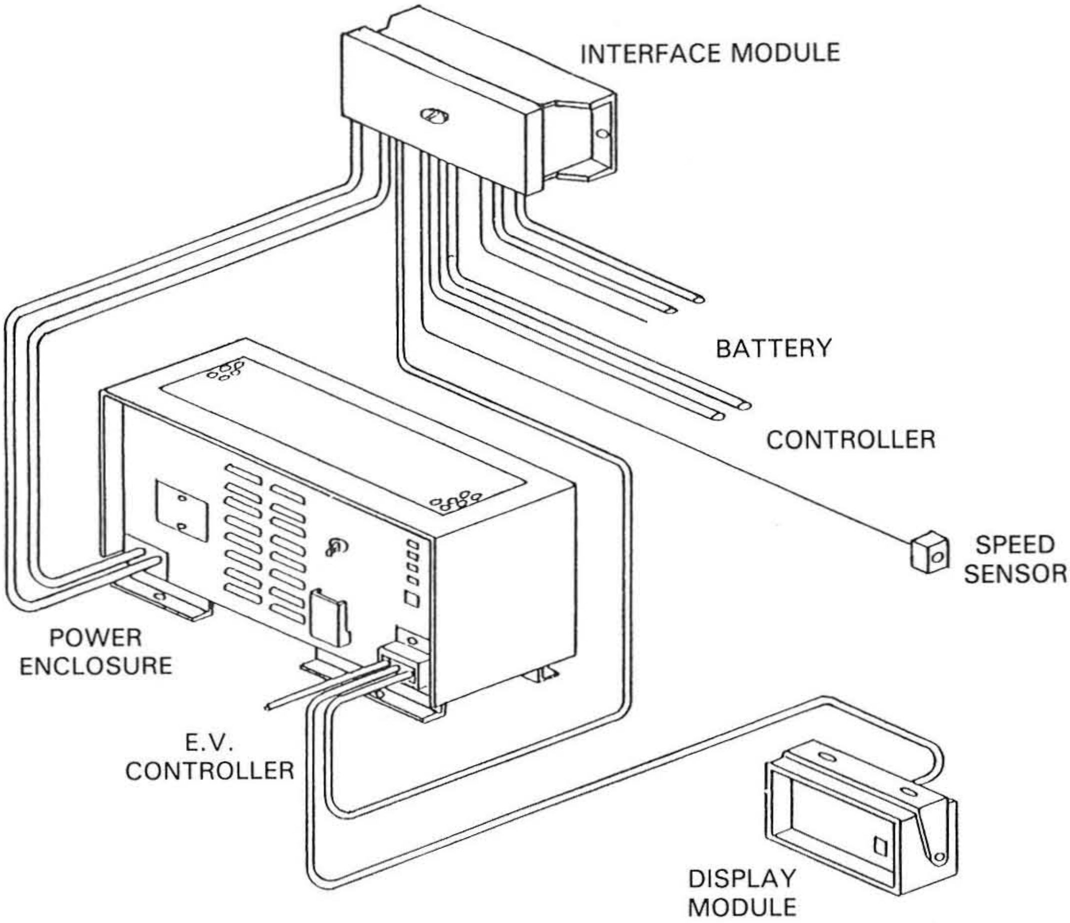



Figure 2. Battery Charger/State-of-Charge Package Design

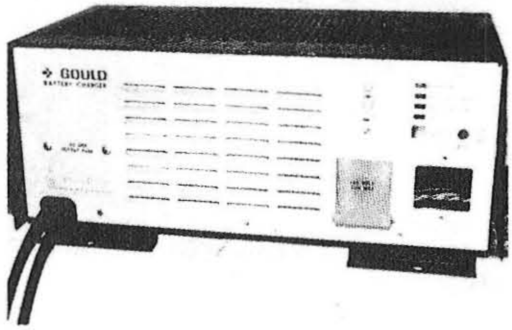
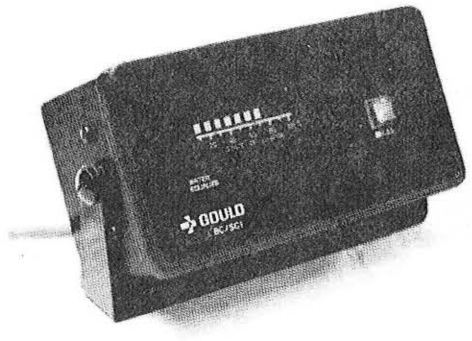
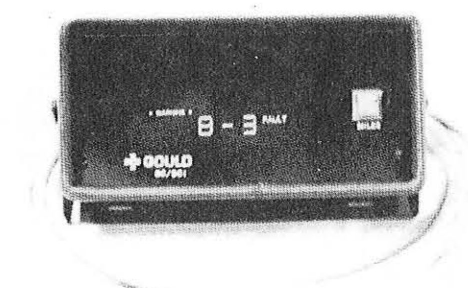



Figure 3. Main Enclosure



4a. State of Charge

4b. Miles Remaining



4c. Fault

Figure 4. Display Pictures

Table 1. Battery Charger/State-of-Charge Indicator Package

| | |
|---|---|
| **Main Enclosure** | |
| | 18.5 in. long x 10 in. deep x 8.6 in. high |
| | 20.7 lb (Components) |
| | 9.3 lb (Enclosure) |
| | 30.0 lb Total |
| **Display Module** | |
| | 6 in. long x 2.5 in. deep x 3 in. high |
| | 0.5 lb (Components) |
| | 0.8 lb (Enclosure) |
| | 1.3 lb Total |
| **Interface Module** | |
| | 8.8 long x 3.8 deep x 2.8 high |
| | 0.8 lb (Components) |
| | 1.2 lb (Enclosure) |
| | 1.1 lb (Hardware) |
| | 11.9 lb Total |
| **Total System** | |
| | 32.2 lb |

and provides electrical isolation for the battery. The electrical isolation is achieved with a high-frequency (20-kHz) transformer so that a significant weight penalty is not incurred. A high power factor is achieved by controlling the input current to follow the ac line voltage (Reference 1). The power section operates with continuous input current so that noise conducted onto the line is minimized.

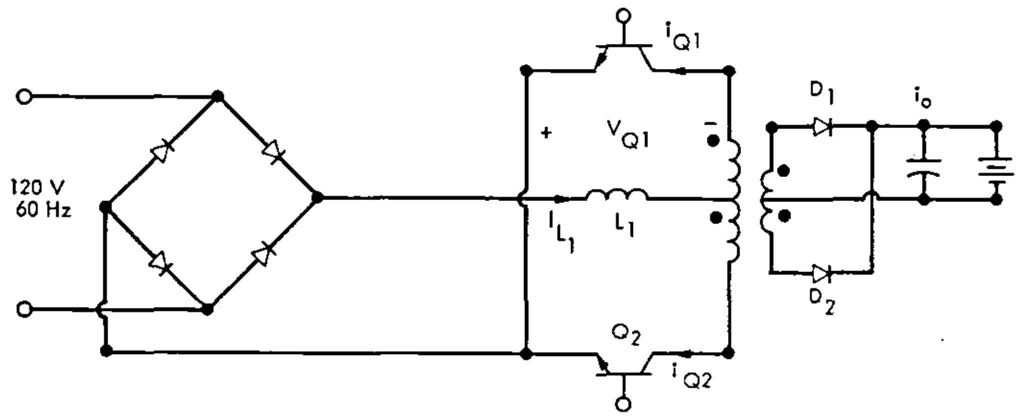
Because it operates at a high power factor and conducts very little noise onto the grid, the battery charger provides an accommodating load for the utility. At present, the utility companies in this country do not have regulations governing conducted noise, but with large-scale introduction of electric vehicles, regulations are certain to follow. Safety is another area in which future regulations might impact the BC/SCI. Safety requirements for on-board battery chargers have not been completely established to date. Isolation was made a safety requirement for this contract so that the BC/SCI could meet any possible future regulations.

a. Original Power Topology. Designing a power section to meet simultaneously all the requirements of the contract is a difficult task. The power circuit that was proposed originally by Gould Labs is shown in Figure 5a. The current-mode, parallel-bridge converter has a number of desirable features. Only one power transistor lies between the source and output, which minimizes the converter's losses resulting from device voltage drops. Only two devices are required, so the complexity and the power semiconductor costs are reduced. The transformer core is fully utilized.

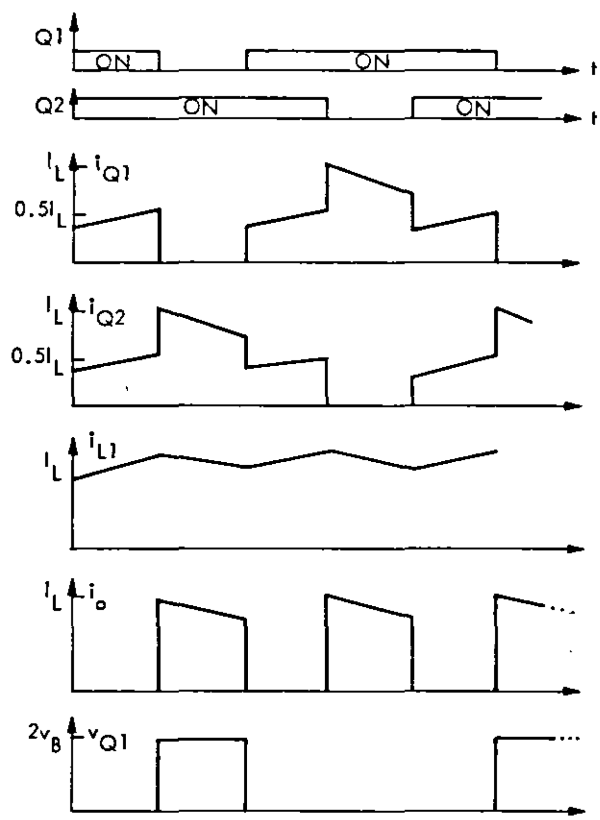
The operation of the proposed circuit can be visualized by examining the waveforms of Figure 5b. When both switches are turned on, the input inductor is charged. When one switch is turned off, the inductor current is transferred to the other switch, and power is transferred to the output. Although the transistors experience twice the reflected load voltage, they only switch half the load current. The switching losses are therefore equivalent to a one-switch circuit operating at twice the transistor switching frequency. The ripple frequency for both input and output is twice the transistor switching frequency, which provides for easier filtering. The proposed converter appeared capable of meeting the cost, weight, and efficiency goals of the power section.

The most difficult problem encountered in implementing the proposed circuit was the excessive voltage stress on the transistors. The current-fed circuit is a boost circuit in which the output voltage (reflected load voltage) must always exceed the input voltage (line voltage). The reflected voltage for a low battery must, therefore, exceed the high line voltage. The maximum reflected load voltage occurs when the battery voltage is at its highest:

$$V_{LOAD} = \frac{V_{HIGH}}{V_{LOW}} V_{LINE} \tag{1}$$




5a. Power Circuit




5b. Switching Waveforms

Figure 5. Proposed Power Section

$V_{LOAD}$ = Highest Reflected Load Voltage

$V_{HIGH}$ = Highest Cell Voltage (2.75 V/cell)

$V_{LOW}$ = Lowest Cell Voltage (2.00 V/cell)

$V_{LINE}$ = High Line Voltage (1.1 x 120  2 = 187 V)

$$V_{LOAD} = 257 \text{ V}$$

The transistor voltage will be twice the reflected load voltage:

$$V_{TRAN} = 2\ V_{LOAD} \qquad (2)$$
$$= 514 \text{ V}$$

When safety margin and other considerations are included, the transistor voltage rating will be 600 to 800 V. High-voltage transistors have slow switching speeds and, therefore, high switching losses. Because no transistor could be found that had the required high-voltage rating and fast switching speeds, an alternative approach was attempted.

The circuit shown in Figure 6 is a modified version of the proposed circuit. This circuit employs a parallel bridge configuration with a third switch, $F_1$. The third switch is a field effect transistor (FET) while the other two switches, $Q_1$ and $Q_2$, are high-voltage Darlington transistors (750-V, $V_{CED}$ Rating).

The FET is revolutionizing power electronics with its high switching speed (typically 100 ns) and ruggedness. In the circuit, the FET is used primarily for switching; the Darlington transistors are used for carrying the current. An ideal situation, therefore, exists because the on-state losses are determined by the Darlington transistors, the switching losses are determined by the FET, and the switching stresses are carried by the FET. Because the switching stresses on the Darlington transistors are minimal, snubbers are unnecessary and off-load efficiency is high.

Several other reasons exist for choosing the FET as the third switch in the circuit. The voltage on the FET is only about half that of the Darlington transistors. The FET is used on an overloaded, pulsed basis so that only two FETs are required. Cost of the FETs is, therefore, acceptable (Toshiba FETs presently cost less than $5.00). FETs are also easy to parallel and easy to drive.

Using the FET in the switch circuit solved the problem associated with the slow-switching Darlington transistors. However, the new configuration caused another problem. In the original circuit, only half the load current was switched. In the three-switch circuit, the third switch (the FET) picks up the full load current each switching interval. When this current is

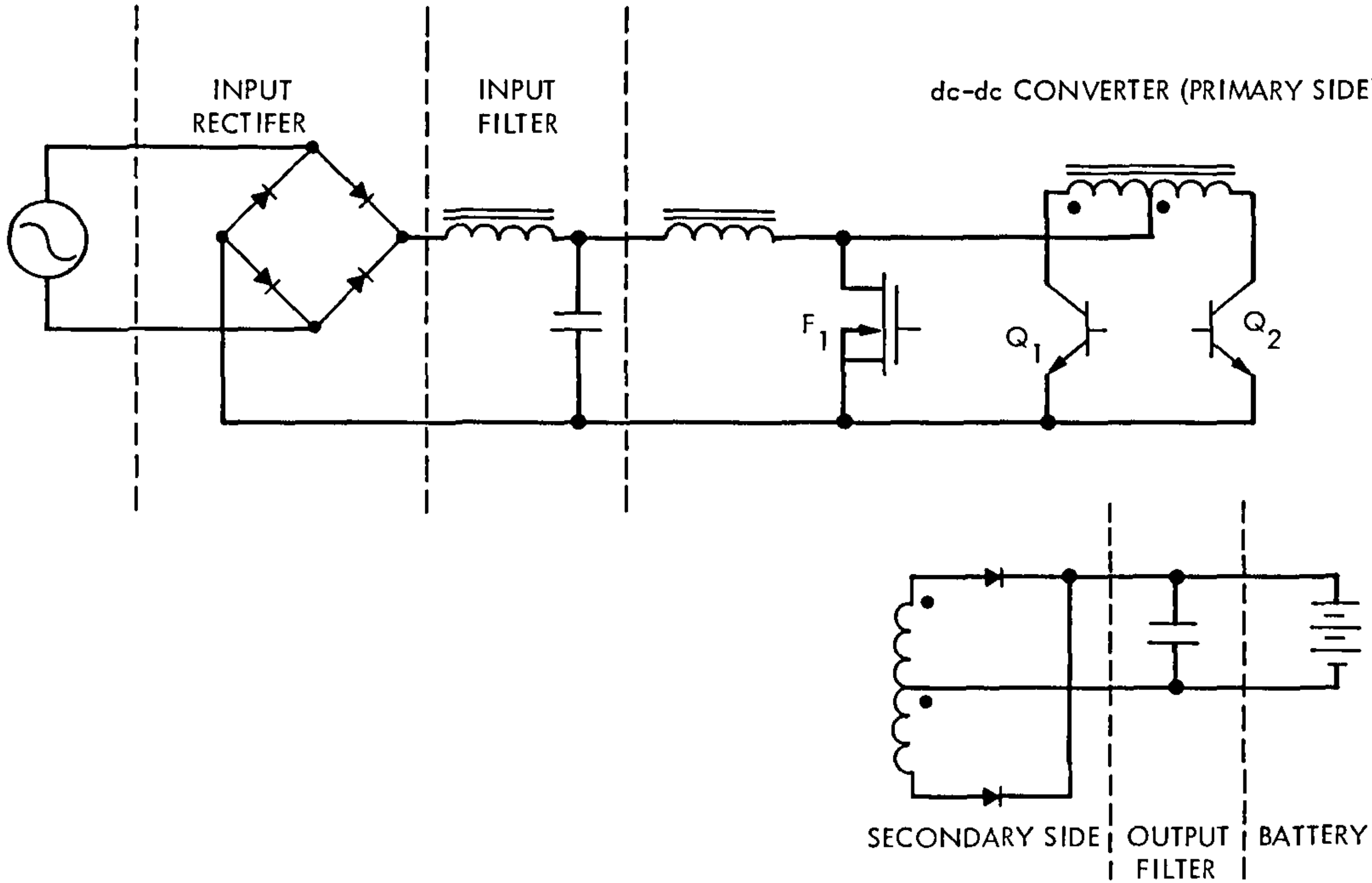



Figure 6. Power Circuit Schematic

transferred to one leg of the transformer, the energy dissipated in overcoming the leakage inductance of the transformer is excessive. The energy dissipated in the three-switch circuit is four times that of the original circuit because the leakage energy is proportional to the square of the current ($E_L = 1/2\ L\ I^2$).

The losses associated with the transformer's leakage inductance can be calculated if it is assumed a Zener diode with voltage $V_Z$ is used to dissipate the power. The energy loss ($E_Z$) of each switching event is:

$$E_Z = \underbrace{V_Z(I/2)}_{\substack{\text{Average}\\ \text{Power}}}\underbrace{IL(V_Z - V_{LOAD})}_{\substack{\text{Time Required for}\\ \text{Current Transfer}}} \tag{3}$$

where

$I$ = Load Current (22 A)

$V_{LOAD}$ = Reflected Load Voltage (227 V)

$L$ = Leakage Inductance (5 $\mu$H)

$V_Z$ = Zener Voltage (375 V)

Because the above energy is dissipated twice each cycle, the average power dissipated on the Zener diode is:

$$P_Z = 2E_Zf = \frac{V_Z I^2 L\ f}{(V_Z - V_{LOAD})} \tag{4}$$

where $f$ = Inverter Frequency (20 kHz)

The power which the Zener diode would need to dissipate for the average values provided in parenthesis is 122 W. At 3 kW, this loss constitutes a 4% reduction in efficiency.

b. Loss Reduction Alternatives. Two approaches to reduce the losses associated with the transformer's leakage inductance were suggested. One approach was to use a regenerative rather than a dissipative snubber. The regenerative snubber, which has no magnetics, is shown in Figure 7. The FET switch, S1, is operated so that it is closed whenever the FET, Q3, is opened and vice versa. The switches S1 and Q3 cannot both be closed at the same time. When Q3 is opened, current from the inductor flows into the capacitor C1 until the leakage inductance of the transformer is charged. The switch S1 is closed when Q3 is opened, but no current initially flows through the switch because the diode D2 is back-biased. After the leakage inductance is charged,

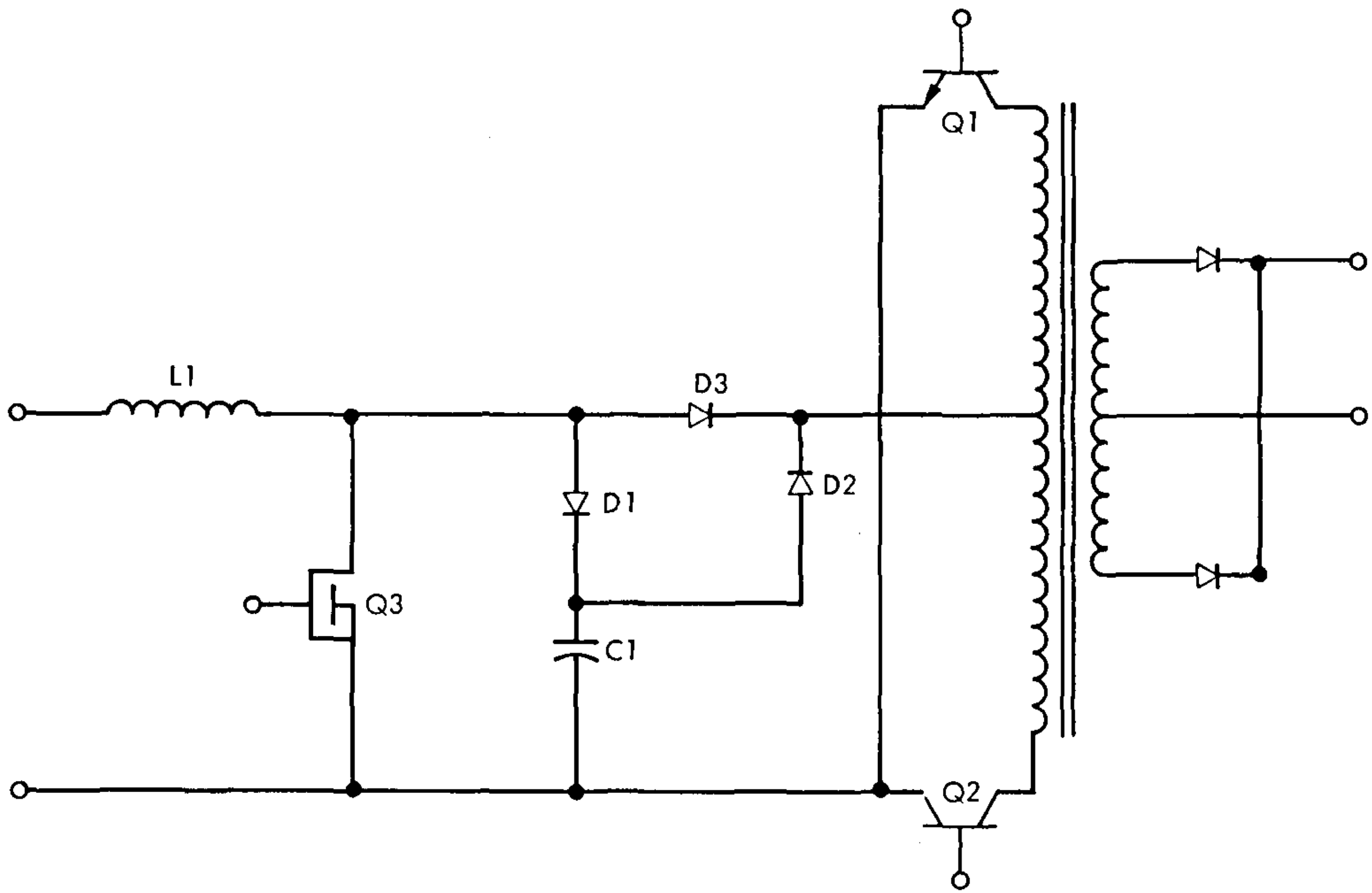



Figure 7. Regenerative Snubber

the energy that had been stored in capacitor C1 is transferred to the output via the switch S1. The switch S1 is opened prior to closing Q3, thus beginning another cycle. Although the regenerative snubber is simple and probably could have been made to work, it does require added components and an isolated drive circuit for the FET switch S1.

The other approach, which required no additional components, was to design and fabricate a low-leakage transformer. Analysis has shown that it was possible to build a transformer with a leakage inductance of less than 0.5 μH. The losses associated with such a low-leakage transformer were acceptable. The regenerative snubber solution, therefore, became a backup for the low-leakage transformer solution.

A transformer was wound with a leakage inductance of approximately 0.5 μH. The final breadboard assembly was redesigned to minimize stray leakage inductances. When the low-leakage transformer was assembled in the final version of the breadboard, the measured parasitic inductance for the entire circuit was approximately 1 μH. When an attempt was made to operate the final power circuit breadboard, however, another problem surfaced.

The recovery time of the output diodes was greater than the turn-on time of the FET. This difference resulted in currents circulating in the primary side of the transformer in a direction opposite to that which is normal. Power was being transferred from the battery to the primary side of the transformer. The circulating current dissipated power and increased the device stresses. It became impossible to operate the circuit except at low power levels.

The problem had not appeared previously because the leakage inductance of the initial transformer allowed the output diodes to recover before current could begin flowing in the primary side. It was only after the final breadboard was assembled and tested at the end of the contract that the problem was recognized. The decision was made to continue the contract so that the BC/SCI system could be made operational. The power requirement, however, was reduced to 1 kW. The emphasis of the contract continuation was to demonstrate the capabilities of the BC/SCI system and not to continue the development of the power section.

c. Final Power Topology. The circuit that was finally used in the BC/SCI is shown in Figure 8. The diode D3 is used to prevent currents from circulating in the primary side of the transformer in a direction opposite to that which is normal. The capacitor C1 with diodes D1 and D2 form a regenerative snubber. The capacitor is charged through diode D1 and discharged through diode D2. The diode D3 prevents the capacitor from discharging through the FET when it is turned on. A thorough discussion of this power section is provided by T. Latos (Reference 2).

Although the BC/SCI presently operates at 1 kW, the original goal was that it would be capable of drawing 25 A (i.e., operate at 3 kW) from a receptacle with a power rating higher than the "standard." A 30-A or a 230-V service that uses an external transformer to provide 115 V could be used for

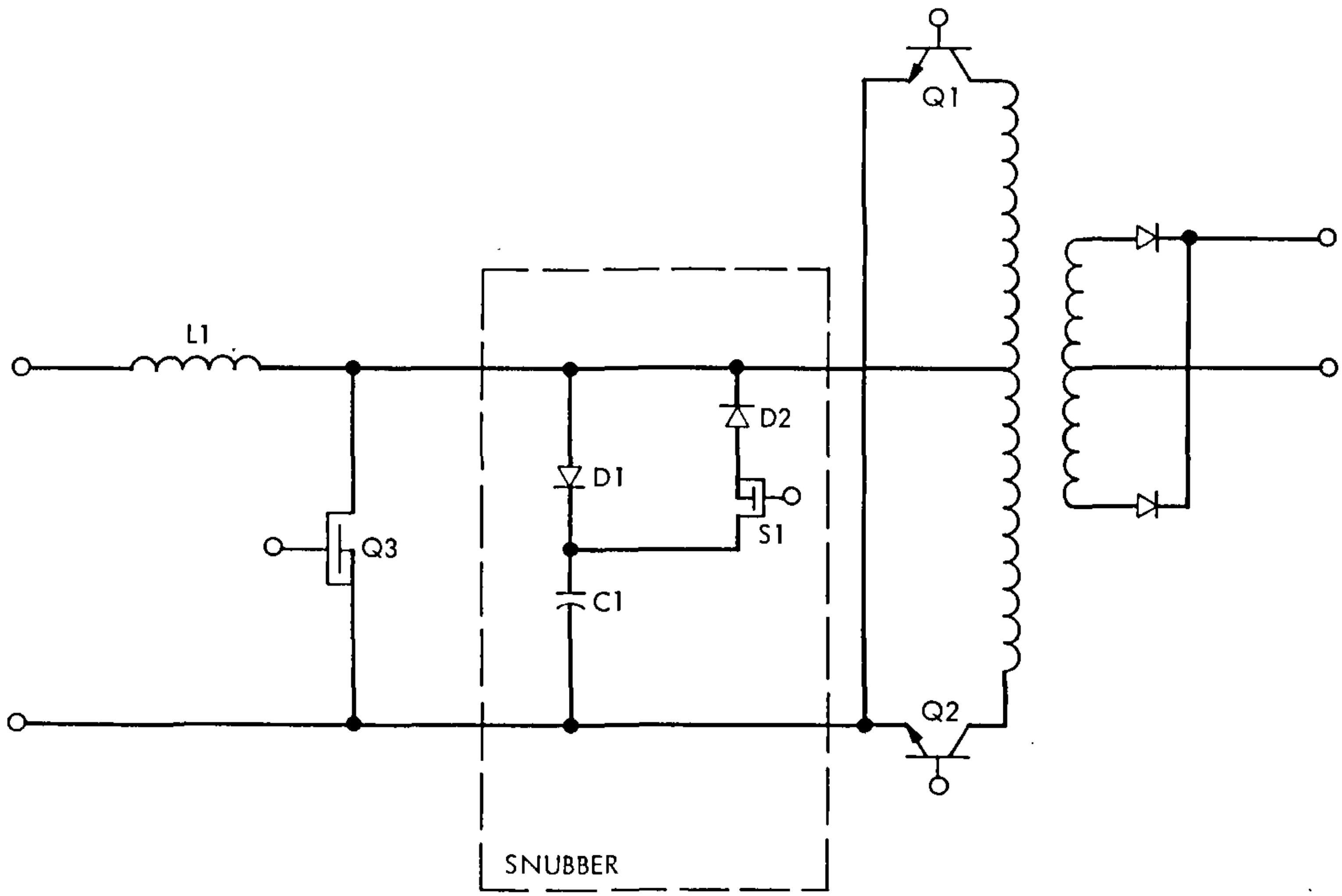



Figure 8. Final Power Circuit

charging at higher rates. If even higher charging rates are desired, it would be possible, with the modular design of the BC/SCI, to provide an optional power section of higher power.

d. Power Topology Upgrade. Work was begun, but then cancelled, on an optional power section at JPL that would have had high charging capability (3.5 to 4.0 kW) and would have interfaced with the BC/SCI. This power section could also have been operated as an external charger. The circuit used in this power section is shown in Figure 9. It consists of two stages. The first stage is a boost converter. This stage draws continuous current from the line and provides a high power factor. The second stage is a series resonant converter that acts as a down converter and provides isolation. The series resonant converter developed by Ray-O-Vac, Inc., under a contract to the Department of Energy (DOE) was to be the second stage (Reference 3). The plan was to provide a boost front end to the Ray-O-Vac converter and then interface it to the BC/SCI. This task was cancelled soon after it was started due to project redirection.

The two-stage converter (see Figure 9) has some deficiencies and some attractive features. The circuit has more devices and, therefore, more losses than that of the current-mode, parallel-bridge circuit. However, the circuit does have the same number of devices in the two-stage circuit as there are in the present circuit of the BC/SCI. The resonant circuit does not fully use the transformer's core and requires extra capacitors, which add weight. The parasitic resistances of the capacitors and transformer also reduce efficiency. The circuit is tolerant of transformer leakage inductance and, in fact, uses it in the resonant circuit. The boost- and the series-resonant circuit are well understood and widely employed in a number of applications. Phillips, Ltd., (Holland) built and tested a two-stage converter in which transistors were used in both the boost- and series-resonant stages. The most attractive feature of the two-stage converter, however, is that it makes 115- and 230-V operation possible. The 230-V operation would provide greater recharge capability although it is not generally required for daily charging.

Daily charging requirements can be deduced from the daily travel distances of a "typical" family vehicle. Figure 10 shows the driving pattern of a "typical"[2] family car. The left-hand axis of Figure 10 plots the percentage of days in which a vehicle is driven a certain distance as a function of that distance. The right-hand axis plots the percentage of the year in which a given distance is not exceeded. Figure 10 shows that most daily driving distances are short. Ninety percent of daily driving distances are under 104 km (65 mi) and 80% are under 64 km (40 mi). At 45 mph, the ETV-1 (Electric Test Vehicle-1) travels about 4 mi for every kilowatt-hour the battery receives. Because the BC/SCI will be capable of delivering about 2 kW of power to the battery from the "standard" circuit, the ETV-1 can travel about 8 mi for every hour of charging. In a 12-h, overnight charge, it would be possible to provide enough energy to the ETV-1 to travel 96 mi (154 km) if its battery could accept 2 kW during the entire charging period. The "standard" circuit is capable of providing enough energy during an overnight recharge to meet most daily charging requirements.

[2] The source for Figure 10 is Reference 4. It was selected as being "typical" because it represents a family vehicle whose yearly mileage is above average.

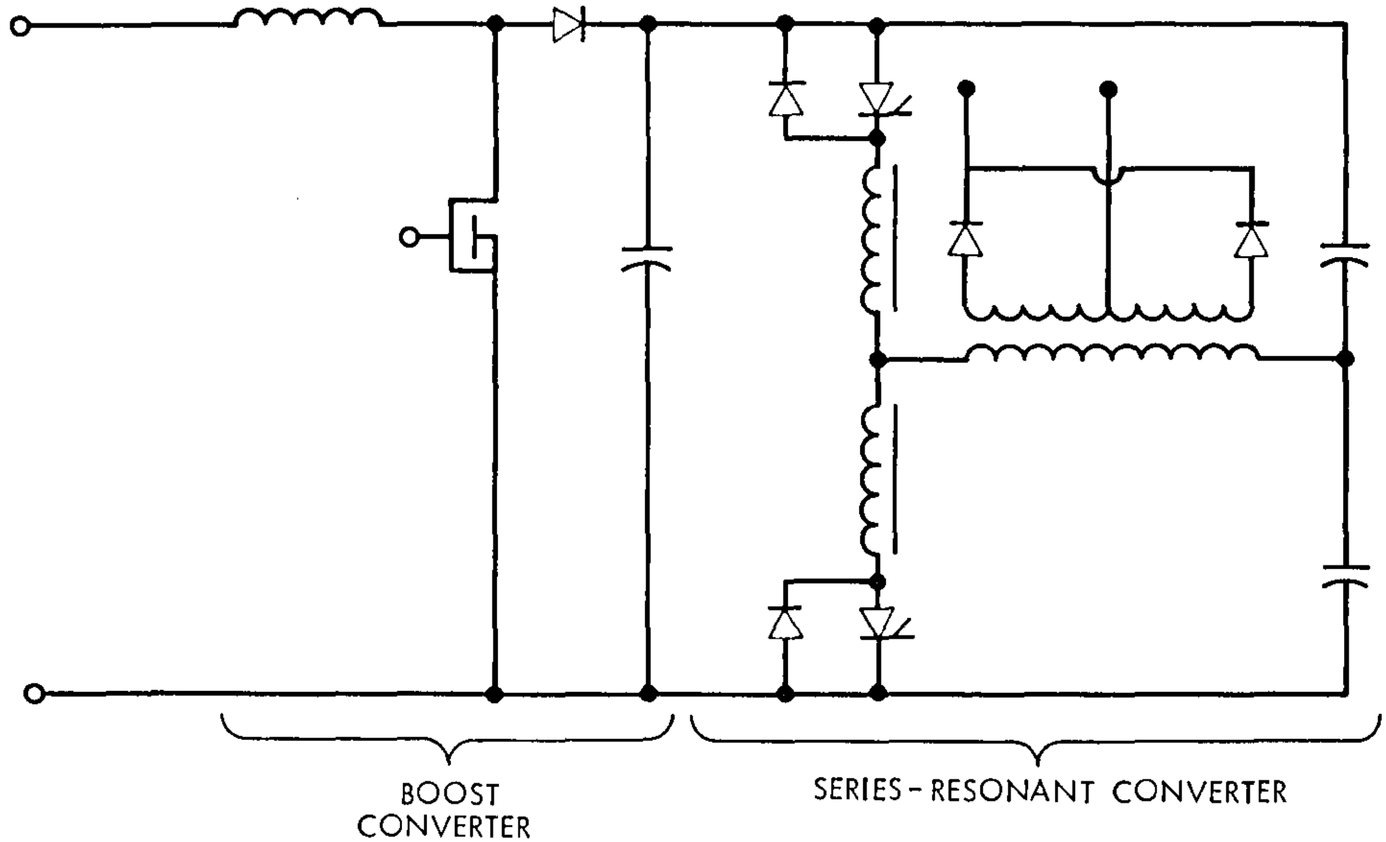



Figure 9. Two-Stage Converter

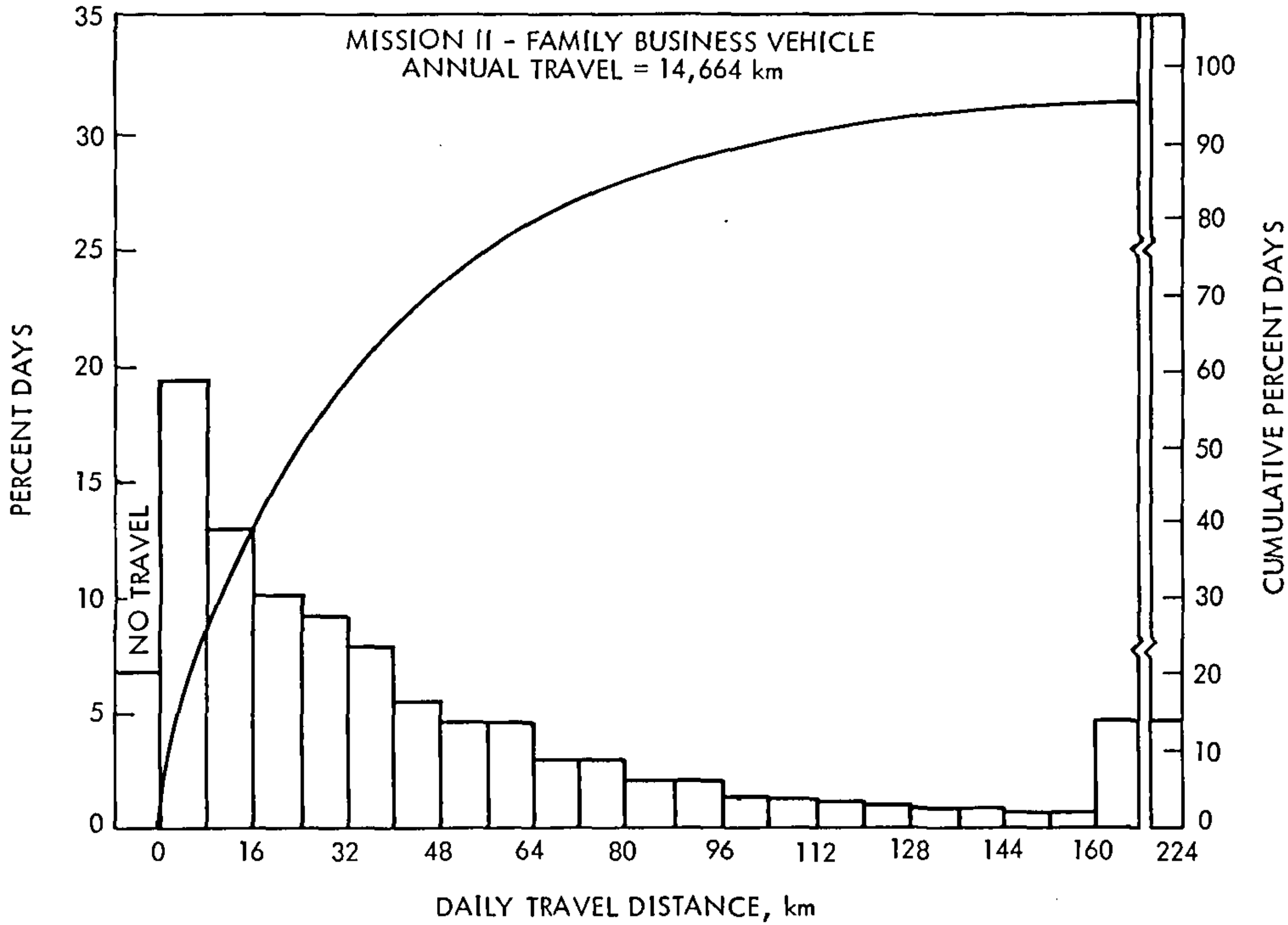



Figure 10. Annualized Daily Driving Patterns

The on-board battery charger will be capable of fulfilling 90% of the daily charging requirements. The remaining daily driving and charging requirements could be met with external chargers operating from higher power sources than the "standard" circuit. A battery that has been partially discharged can be rapidly recharged to an approximate 80% charge. External chargers would be used primarily for extending range although, if owned by the operator, they could be used for overnight charging. An external charger operating from household circuits could, depending on the power available, provide 15 to 50 mi (24 to 80 km) of additional range for every hour of charging. The added driving range that an approximate hour of charging provides would enable the electric vehicle to complete all the daily driving and charging requirements, except the requirement for cross-country travel.

Because the sensors and microprocessor used for controlling battery charging are located on the vehicle, an interface must be provided between the vehicle and an external charger so that the batteries can be safely charged.

### 2. Recommendations

The transformer increases device stress, reduces efficiency, and adds weight. Whenever possible, the transformer can be eliminated. The isolation requirement is, in general, needed for conventional flooded batteries where leakage currents are prevalent. In specialized applications, in which ground-fault protection can be achieved, the isolation requirement can be eliminated. The sealed battery is one important specialized application in which isolation will not be required because leakage currents are small (see Reference 1). It is recommended that a non-isolated power section be developed for the BC/SCI.

However, when isolation is required, the two-stage converter should be used. The two stages, as well as the boost- and the series-resonant converter are well understood. The transformer has a benign effect on the series-resonant converter when its leakage inductance is part of the resonant circuit. The two-stage converter can also be made to operate from either the 115- or 230-V line. Development work is required to build and test such a two-stage converter.

## C. STATE-OF-CHARGE INDICATOR

### 1. Technical Discussion

The control module is based on the MC6809 microprocessor. The microprocessor, along with its memory, provides the BC/SCI with its computational capabilities. The microcomputer uses the MC6821 interface adapter, which is software-programmable, to communicate with all peripheral parts. The display panel is connected to the microprocessor with a serial data communications path. One circuit board holds all the signal-conditioning circuitry required for interfacing the sensors to the microprocessor. The measured parameters include battery voltage, current, and temperature. The voltage and current must be recorded to 10-bit accuracy to implement some of the algorithms. A 12-bit A/D converter was therefore required. The algorithms also require a real-time clock and non-volatile memory, which are incorporated in the BC/SCI.

The BC/SCI software consists of both the 6809 assembly and FORTRAN programming languages. The software was structured so that the highly mathematical subroutines, such as determining state of charge, use FORTRAN. Programs that operate in real time, such as the executive program, use assembly language. The real-time executive program is the primary software module. It calls five FORTRAN subroutines in which the mathematical computations are performed. This structure allows continued algorithm development because modifications to the FORTRAN subroutines can be easily made. Software changes are implemented by programming a new EPROM for the BC/SCI. This method is also the way in which the BC/SCI can be easily adapted to different batteries. A complete description of the BC/SCI, both software and hardware, can be found in Gould's Final Report (see Reference 3).

The amount of energy a battery can deliver depends on the rate in which it is removed. The definition for a battery's state of charge must, therefore, be based on an assumption of how that battery is to be discharged. The following definition for SOC was used to specify the energy capacity of the battery:

> State of Charge (SOC) - The amount of energy that can be extracted from the battery if the battery is discharged to a specified cutoff voltage at a constant power corresponding to the power required to maintain a vehicle speed of 55 mph (assumed to be 10 kW for BC/SCI development activities).

The state-of-charge indicator is based on the assumption that the battery will be discharged at a power that corresponds to maintaining the vehicle at freeway speeds. A vehicle may be able to travel some distance at reduced speeds even after the SCI reads zero.

The SCI does provide an estimate, upon operator request, of the distance the vehicle can travel before the battery is discharged. This estimate is based on the power consumption and speed of the vehicle averaged over a 30-s time interval prior to the operator's request. The SCI operates by predicting the future battery voltage and current required to maintain constant power as well as the time to end of discharge. When the constant power is the vehicle's power averaged over 30-s, the predicted range is the product of the predicted time to end of discharge and the velocity. If the constant power is the power used for the state of charge, the product of the predicted time and power (10 kW) is the energy remaining in the battery. The SOC and range predictions are, therefore, very similar.

The SOC and range estimates are based on a modified form of the Shepard equation (Reference 5). The modified Shepard equation used by the SCI is as follows:

$$V_p(t) = V_o - \frac{V_1}{Q_1} Q(t) - \left[R_1(L_f,T) - R_o\right] I_f(t) - R_o I(t)$$
$$- \frac{R_2(I_f,T)Q_2(I_f,T)}{Q_2(I_f,T) - Q(t)} I_f(t) \qquad (5)$$

where

$$\tau \frac{dI_f(t)}{dt} + I_f(t) = I(t) \tag{6}$$

The current I(t) is the battery current, $I_f$ is the filtered current, and $\tau$ is a characteristic time constant of the battery. The voltage $V_p(t)$ is the predicted battery voltage, Q(t) is the charge withdrawn from the battery, and $V_o$, $V_1/Q_1$, $R_o$, $R_1$, $R_2$, and $Q_2$ are parameters of the battery. The first term in Equation (1) is the fully charged, open-circuit voltage. The second term accounts for the decline in voltage due to the reduction in electrolyte concentration as the battery is discharged. The third term represents a voltage drop due to the ionic part of the battery's impedance. The fourth term is the voltage drop due to the constant part of the battery's impedance. The last term represents a voltage drop that increases as Q(t) approaches Q2.

The parameters $V_o$, $V_1/Q_1$, and $R_o$ are constant or have a small dependence on temperature whereas the parameters $R_1$, $R_2$, and $Q_2$ are functions of the filtered battery current, $I_f$, and the temperature, T. Table 2 gives the battery parameters of the Gould PB-220 golf-cart battery for various discharge currents and electrolyte temperatures. Linear interpolation is used to determine the battery parameters for other values of current and temperature. Temperature has a significant effect on some battery parameters (Reference 6) and cannot be ignored. The parameters were curve-fitted to data obtained from constant-current discharges performed at the various temperatures. A minimum number of 12 constant-current discharges are required for determining the parameters shown in Table 2. These types of tests could be done by the battery manufacturer and would only need to be done once for a specific battery type.

The filtered battery current, $I_f$, used in Equation (5) and defined in Equation (6), allows the Shepard equation, which was derived from constant-current discharges, to be modified for discharges where the current varies. The time constant $\tau$, associated with the filtered current, is a consequence of the ionic diffusion process that occurs in the plates. This time constant is similar to others reported in the literature (see Reference 5).

The battery voltage is affected by the diffusion process and does not respond immediately to changes in current. If a load on a battery is suddenly removed, the battery voltage initially rises quickly but only approaches the open-circuit voltage after several minutes. The initial rise in voltage is associated with the constant-resistance term, $R_o$, while the slower rise in voltage is associated with the diffusion-dependent terms $R_1$, $R_2$, and $Q_2$. With these diffusion-dependent terms, the predicted voltage of Equation (3) provides a reasonable approximation to the measured voltage even for discharges with varying current.

A number of tests were performed at Gould Labs to measure the diffusion time constant, $\tau$. The results of those tests (see Reference 4) indicate that the time constant for the Gould PB-220 batteries varied from less than 5 to over 20 min. The time constant was found to be a function of the charge state with the longer time constants associated with the more deeply discharged batteries. The present SCI uses a time constant of 6 min. Because a 10-kW

Table 2. Battery Parameters for the Gould PB-220 Battery

| Current, A | Electrolyte Temperature 9°C | 20°C | 40°C |
|---|---|---|---|
| 20 | R1 = 2.7293 m/cell<br>R2 = 0.5078 m/cell<br>Q2 = 125.8769 Ah/cell | R1 = 2.9568<br>R2 = 0.3792<br>Q2 = 164.4615 | R1 = 2.2395<br>R2 = 0.2180<br>Q2 = 188.8593 |
| 80 | R1 = 1.8282<br>R2 = 0.2137<br>Q2 = 83.0000 | R1 = 1.7384<br>R2 = 0.1732<br>Q2 = 109.4000 | R1 = 1.3714<br>R2 = 0.1794<br>Q2 = 141.3512 |
| 130 | R1 = 1.6844<br>R2 = 0.1198<br>Q2 = 69.3520 | R1 = 1.5260<br>R2 = 0.1216<br>Q2 = 91.8800 | R1 = 1.3090<br>R2 = 0.1331<br>Q2 = 121.0732 |
| 200 | R1 = 1.6320<br>R2 = 0.0940<br>Q2 = 70.7200 | R1 = 1.2800<br>R2 = 0.1600<br>Q2 = 84.8000 | R1 = 1.2854<br>R2 = 0.1331<br>Q2 = 98.2439 |

$$V_o = (2.161 - 5.16 \times 10^{-4}T) \text{ V/cell}$$

$$V1/Q1 = (1.217 \times 10^{-3} - 7.42 \times 10^{-6}T) \text{ V/cell/Ah}$$

$$R_o = 0.75 \text{ m/cell}$$

discharge for the PB-220 batteries lasts about an hour, a time constant of 6 min. corresponds to about 10% of the total discharge time.

With the present approach, effects due to variations in discharge rates are transient unless they occur within several time constants of the cutoff voltage. Any permanent effects resulting from varying discharge rates cannot be accounted for with this approach. Gould performed some work on a model that could account for permanent changes in the electrodes resulting from different discharge rates (Reference 6).

The SCI uses an adaptive algorithm to account for effects not modeled by the present approach. The adaptive algorithms compare the predicted and measured voltage so that the charge withdrawn, $Q(t)$, can be corrected accordingly. A quantity, $Q_o$, is calculated so that it is substituted into Equation (7) for $Q(t)$. The predicted voltage is the same as the measured voltage. The SCI uses the following equation to adapt its estimates:

$$Q' = Q(t) + w\,[Q_o - Q(t)] \tag{7}$$

where

$$w = \frac{0.5}{1 + q}$$

$$q \approx \text{Absolute Value of } [(I_f - I),\ \text{SOC}]$$

The quantity $Q'$ is a corrected $Q(t)$ based on a confidence factor, $w$. For a low confidence factor, $w = 0$, which occurs when the SOC is high and the difference between the filtered and actual current is large, $Q'$ reduces to $Q(t)$. When the SOC is low and the filtered and actual currents are equal, $Q'$ is corrected to a value which is halfway between $Q(t)$ and $Q_o$. This voltage adaptation scheme is only employed when the battery is being discharged (i.e., not used during charge or regenerative braking) and the filtered current is not zero. The measured battery voltage must also be less than the predicted voltage (20 mV/cell) before the scheme is utilized. This last condition means no correction is made when it appears that the SCI will under-predict the battery's capacity. It should also be noted that the present scheme does not remember its best correction. When a change in current occurs, the confidence factor, $w$, becomes small and $Q'$ is set equal to $Q(t)$. The current must remain constant for several seconds before the SCI will begin to adapt. The corrected quantity, $Q'$, is used in estimating both the state of charge and range of the vehicle.

Gould Labs also developed methods for adapting the battery parameters, $R_1$, $R_2$, and $Q_2$, from the difference in the predicted and measured battery voltage (Reference 7). These methods would have corrected the SCI for aging and other detrimental, long-term effects. The SCI tested at JPL did not correct battery parameters but did utilize the adaptation method of Equation (3). A follow-on contract to Gould Labs from JPL will implement an algorithm for adapting the battery parameters.

Corrections to Q(t) are also performed during the charge and rest modes. A simple charge acceptance algorithm is used to correct the SCI for gassing. The charge acceptance is assumed to be unity until the battery reaches a specified charge state (≈N 80%) where it decreases linearly to zero at the 100% charge state. The charge state for which the charge acceptance begins to decrease depends on temperature. Accurate charge corrections are required for the SCI to properly track the battery's SOC between equalizing charges (Reference 8). The SCI also uses the battery's open-circuit voltage to help establish the correct charge state. If a large enough difference exists between the predicted and measured voltage 2 h after a discharge, some adjustments to Q(t) are made.

The problems of defining a general charge-acceptance curve are eliminated with the BC/SCI because the charge profiles are defined and known to the SCI. In fact, the SCI controls the charger to provide the proper charge profiles. The charge profiles for both the standard and equalized charge consist of a constant-power (1-kW) segment, followed by a constant-voltage segment. The charger is turned off after a specified charge has been returned. The constant voltage and returned charge are different for the standard and equalized charges and depend on temperature.

The machinery, both hardware and software, used by the BC/SCI to determine a battery's SOC has been described. The algorithms implemented by the BC/SCI can be viewed as a first approximation to the desired algorithms. Because most of the algorithms can be modified easily with software changes, the BC/SCI can be used to improve the algorithms. Test data, however, is required to evaluate the present system properly.

## 2. Recommendations

The only major recommendation is that an adaptive algorithm be developed and implemented in the SCI.

## SECTION IV

## BATTERY CHARGER/STATE-OF-CHARGE TESTS

### A. TEST DESCRIPTION

The ability to accurately predict the SOC of a full battery pack (18 modules) is a more difficult task than predicting the SOC of a single module. The modules of a battery pack exhibit differences in their parameters as a result of manufacturing tolerances and quality control. Temperature differences between modules also cause variability in module capacities. These differences become accentuated between equalized charges.

One objective of this series of tests was to evaluate the accuracy of the SCI with a full battery pack that was not equalized for every discharge. In accordance with this objective, the batteries used in the JPL pack tests were bought from a local distributor. The single modules used by Gould Labs to establish the battery parameters were manufactured approximately one year before the batteries used in the JPL pack. The batteries were not selected or conditioned and were used as received. The only attempt made to minimize the variability within the pack was to separate the modules with a space of approximately 2.5 in. It was hoped that this separation would help the center modules remain cool. The batteries were equalized automatically once a week by the BC/SCI.

A second objective of the tests was to determine the SCI accuracy under varying discharge rates. To achieve this aim, a variable load was used to control the battery's discharge rate. The load was manually operated to control the discharge power and had a worst-case accuracy of about $\pm 1$ part in 80. The data was recorded in 10% increments when the display status changed. Data from precision ampere-hour and watt-hour integrators were recorded on a data logger at the appropriate times. Temperature data gathered from thermocouples tracked the temperature of the module used by the BC/SCI to characterize the temperature of the battery pack. All tests were terminated when the battery's voltage reached 1.44 V/cell (78 V for an 18-module battery) as measured by a digital voltmeter. The variable load was capable of dissipating 18 kW, which allowed the batteries to be discharged at rates higher than the standard 10-kW rates.

### B. TEST RESULTS

The various tests performed to determine SCI accuracy are shown in Table 3.

#### 1. Constant Discharge

A standard discharge rate of 10 kW was used to establish the baseline SCI accuracy for a full battery pack. A typical plot for a 10-kW-rate discharge is shown in Figure 11. The left-hand axis of the plot is the

Table 3. Battery Charger/State-of-Charge Indicator Test Results

| Test No. | Temp. Start, °C | Discharged Energy, kWh | Temp. End, °C | Discharged, Ah | Charged, Ah | Overcharge,[a] % | Type of Discharge |
|---|---|---|---|---|---|---|---|
| 3 | - | 10.2 | - | 102 | 138 | 135 (E) | 10 kW |
| 4 | - | 9.7 | - | 97 | 154 | 158 (E) | 10 kW |
| 5 | 22.9 | 10.5 | 28.1 | 105 | 160 | 152 (E) | 10 kW |
| 6 | 22.5 | 10.5 | 28.7 | 106 | 108 | 102 | 10 kW |
| 7 | 24.8 | 10.3 | 29.5 | 103 | 112 | 109 | 10 kW |
| 8 | 23.9 | 10.5 | 28.7 | 104 | 112 | 108 | 5 kW to 50%, 10 kW |
| 11 | 25.9 | 9.8 | 32.8 | 101 | 109 | 107 | 15 kW to 50%, 10 kW |
| 12 | 26.8 | 9.4 | 32.0 | 96 | 150 | 156 (E) | 15 kW to 50%, 10 kW |
| 13 | 31.3 | 10.6 | 36.8 | 108 | 108 | 100 | 15 kW to 50%, 10 kW |
| 14 | 24.5 | 10.4 | 29.1 | 102 | 120 | 117 | 5 kW to 50%, 10 kW |
| 15 | 24.5 | 9.7 | 30.4 | 98 | 104 | 106 | 15 kW to 80%, 10 kW |
| 16 | 27.0 | 9.9 | 31.7 | 98 | 105 | 106 | 5 kW to 80%, 10 kW |
| 17 | 27.1 | 8.4 | 33.4 | 88 | 121 | 137 (E) | 15 kW to 20%, 10 kW |
| 18 | 29.2 | 11.7 | 31.8 | 113 | 113 | 112 | 5 kW to 20%, 10 kW |
| 19 | 23.7 | 9.3 | 30.1 | 94 | 104 | 110 | 10 kW |
| 20 | 28.7 | 8.7 | 34.9 | 90 | 105 | 116 | 15 kW to 20%, 10 kW |
| 21 | 27.2 | 10.4 | 30.3 | 101 | 107 | 106 | 5 kW to 20%, 10 kW |
| 22 | 28.0 | 8.8 | 32.4 | 88 | 120 | 136 (E) | 15 kW to 80%, 10 kW |
| 23 | 30.3 | 10.3 | 34.9 | 103 | 119 | 116 | 5 kW to 80%, 10 kW |

[a]Denotes equalized charge.

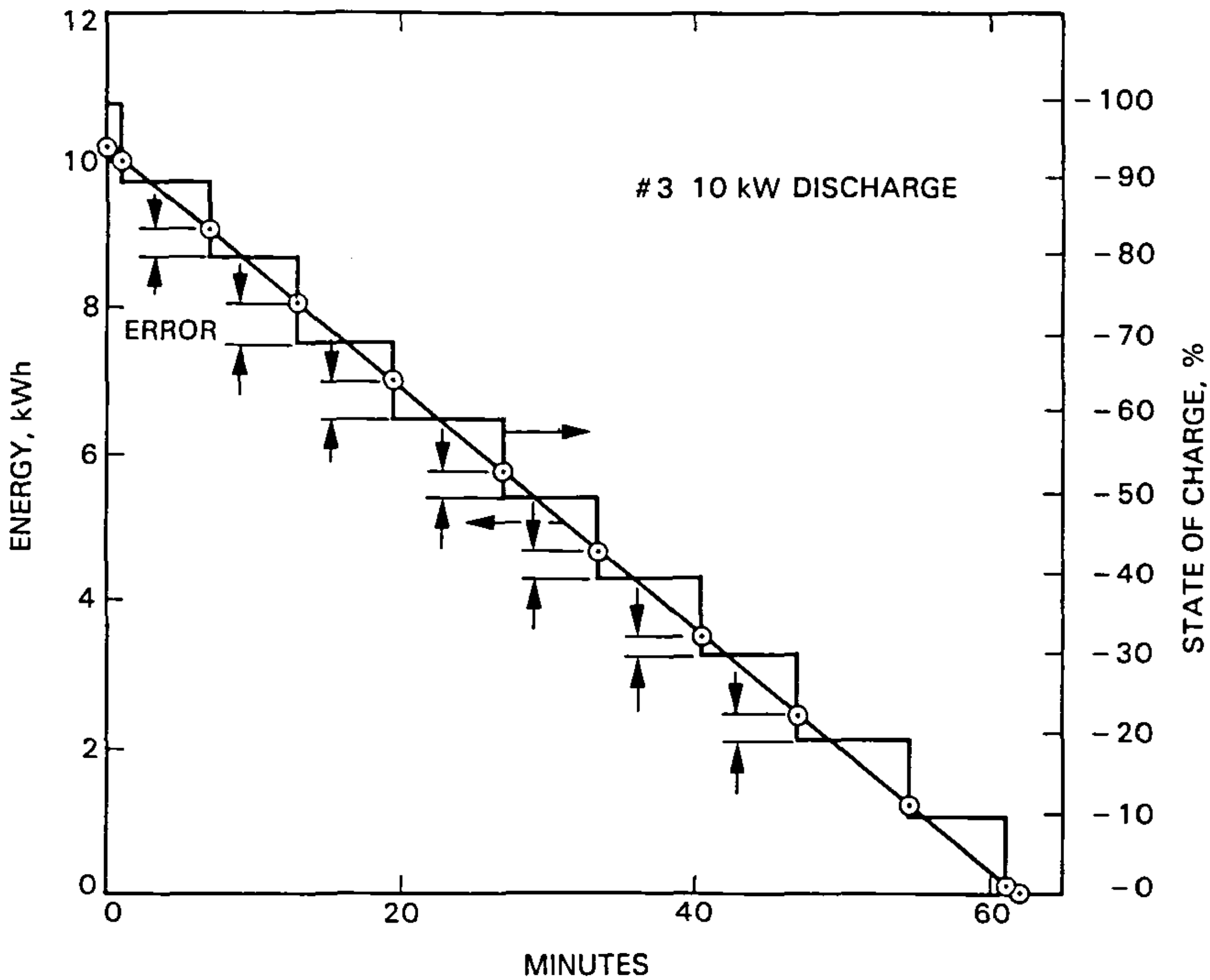



Figure 11. Typical Standard Rate Discharge (10 kW)

actual energy remaining in the battery, the right-hand axis is the SOC displayed by the SCI, and the horizontal axis is the time from the start of the discharge. The straight line drawn through the points of Figure 11 represent the actual discharge of the battery as a function of time. The stairstep curve represents the SCI's estimate for the remaining energy because the energy is displayed by the SCI in 10% increments. The difference in magnitude between the bottom of the stairstep and the constant discharge curve is the error in the SCI prediction (see Figure 11).

Eliminating the time axis and plotting the actual versus the predicted SOC will determine if the SCI meets the 0 to -10% specification. Figure 12 is such a plot for the 6 constant 10-kW discharge tests. The dotted lines show the permissible range as set forth in the specification. In general, the results show that, under constant discharge, the SCI meets the 0 to -10% prediction accuracy as spelled out in the specification.

2. Variable Discharge

The variable-rate discharge tests consisted of discharging the batteries at either a 5-kW or 15-kW rate to a specified charge state as displayed by the SCI. The battery was then discharged at the 10-kW rate to the cutoff voltage. The specified charge state was either 80, 50, or 20%. At least two tests were completed for each charge state. A standard 10-kW discharge test was performed midway through the variable-rate discharge tests to confirm the battery's condition.

Figure 13 shows a typical discharge curve. As was shown in Figure 11, the actual SOC, the SCI predicted SOC, and time of occurence for the prediction are plotted. The stairstep occurs again due to the 10% increment displayed by the SCI. The error in prediction is again noted.

A summary of the 5-kW variable rate tests are shown in Figure 14. Again the 0 to -10% boundaries for actual versus predicted SOC are shown by dotted lines. All the points for the 5-kW-rate discharges fall within the 0 to -10% boundaries except for the points associated with one discharge. The charge state to which the battery was discharged at the 5-kW rate did not seem to influence the accuracy of the SCI, which had a slight tendency to underestimate the energy remaining in the battery. The voltage adaptation scheme is not used when the SCI underestimates the energy capacity of the battery. The SCI, therefore, could not respond when the discharge was more favorable than anticipated.

A summary of the 15-kW, variable-rate tests are shown in Figure 15. Although the SCI was accurate for most of the discharges, it had a tendency to overestimate the energy capacity of the battery. This tendency was especially evident when the 15-kW rate was used to discharge the battery to the 20% charge state. The voltage adaptation scheme did not seem to respond to the lower-than-anticipated battery voltage. It is worthwhile to examine one of these discharges in detail.

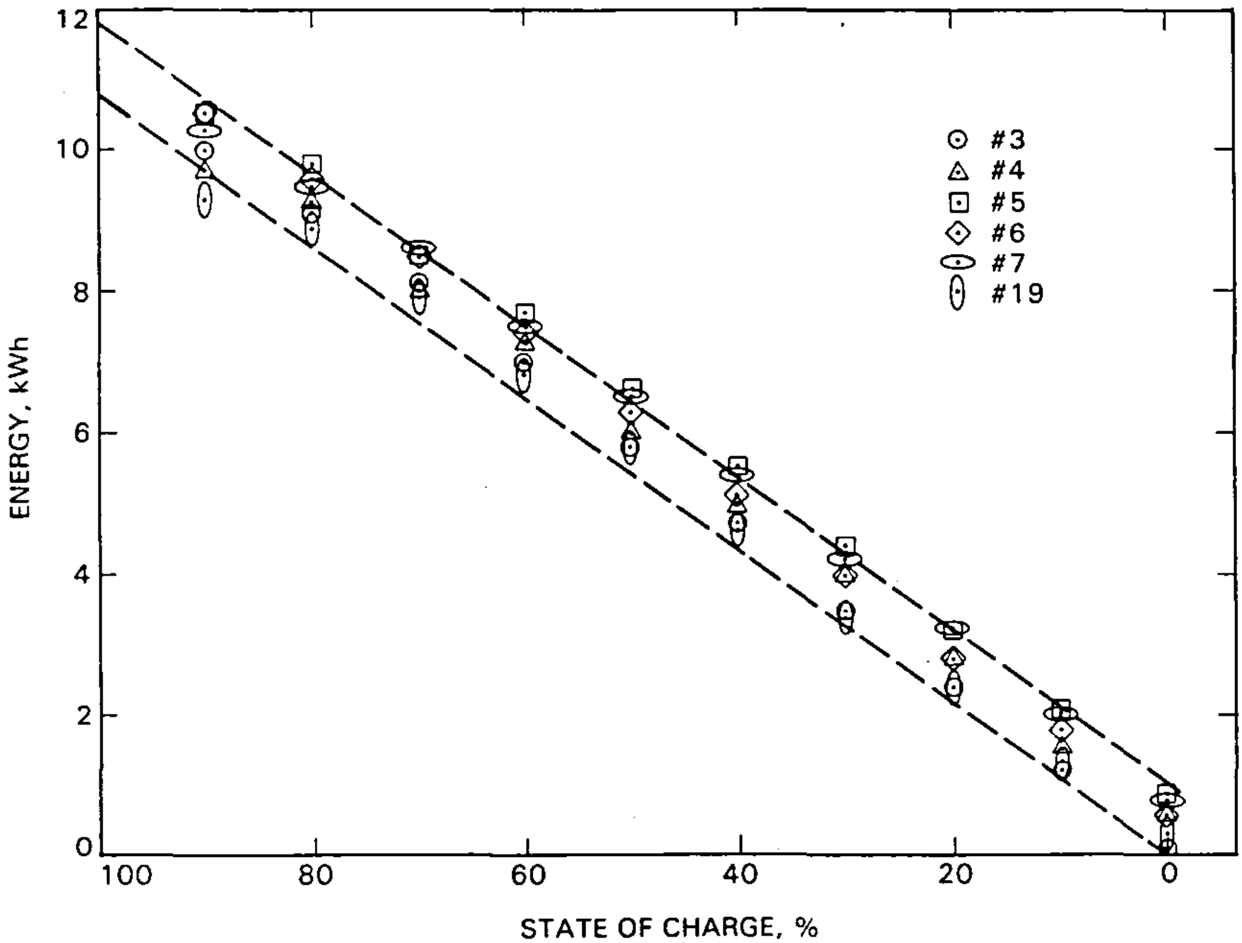



Figure 12. Composite Plot of Standard Rate Discharges (10 kW)

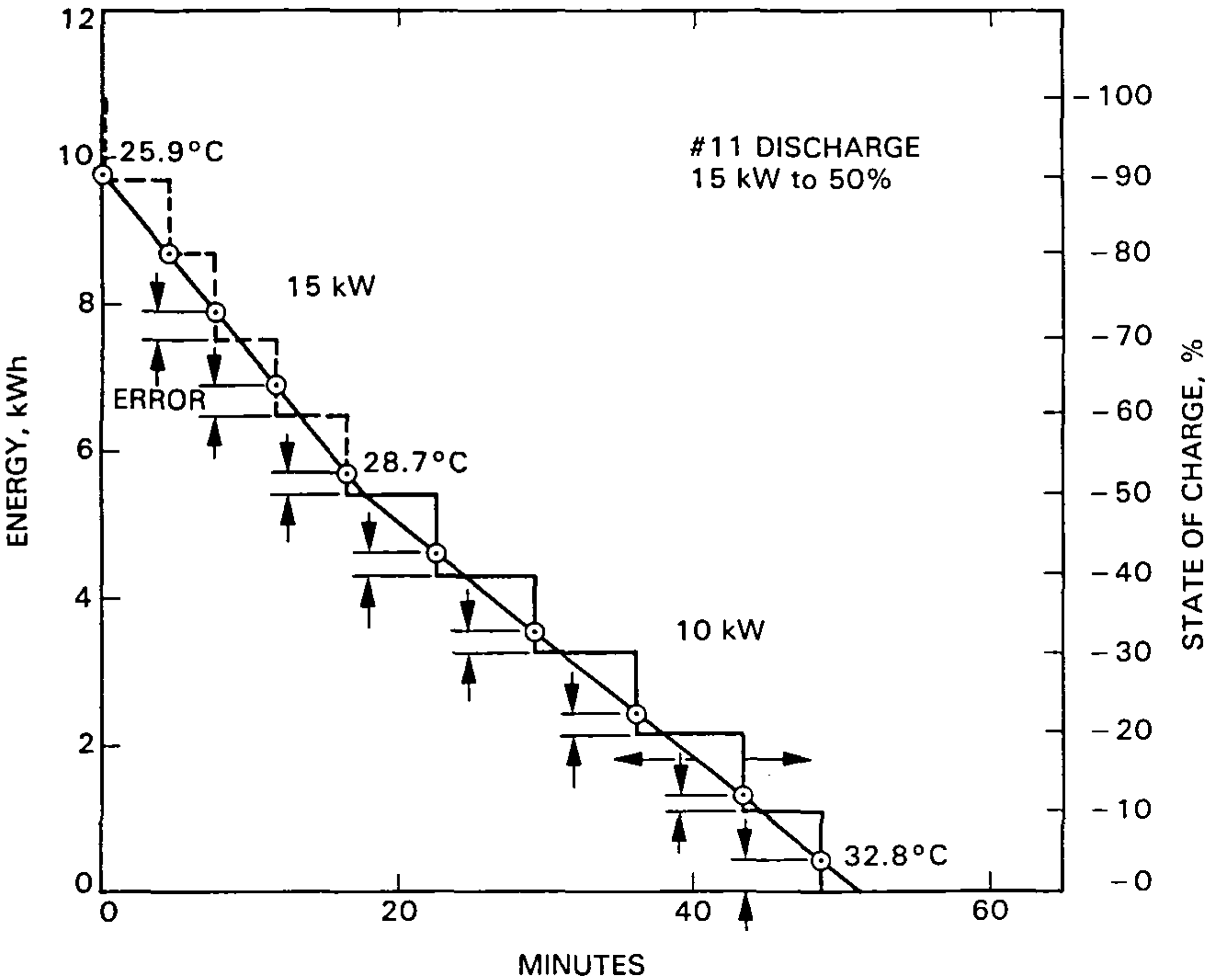



Figure 13. Typical Variable Rate Discharge (15 kW)

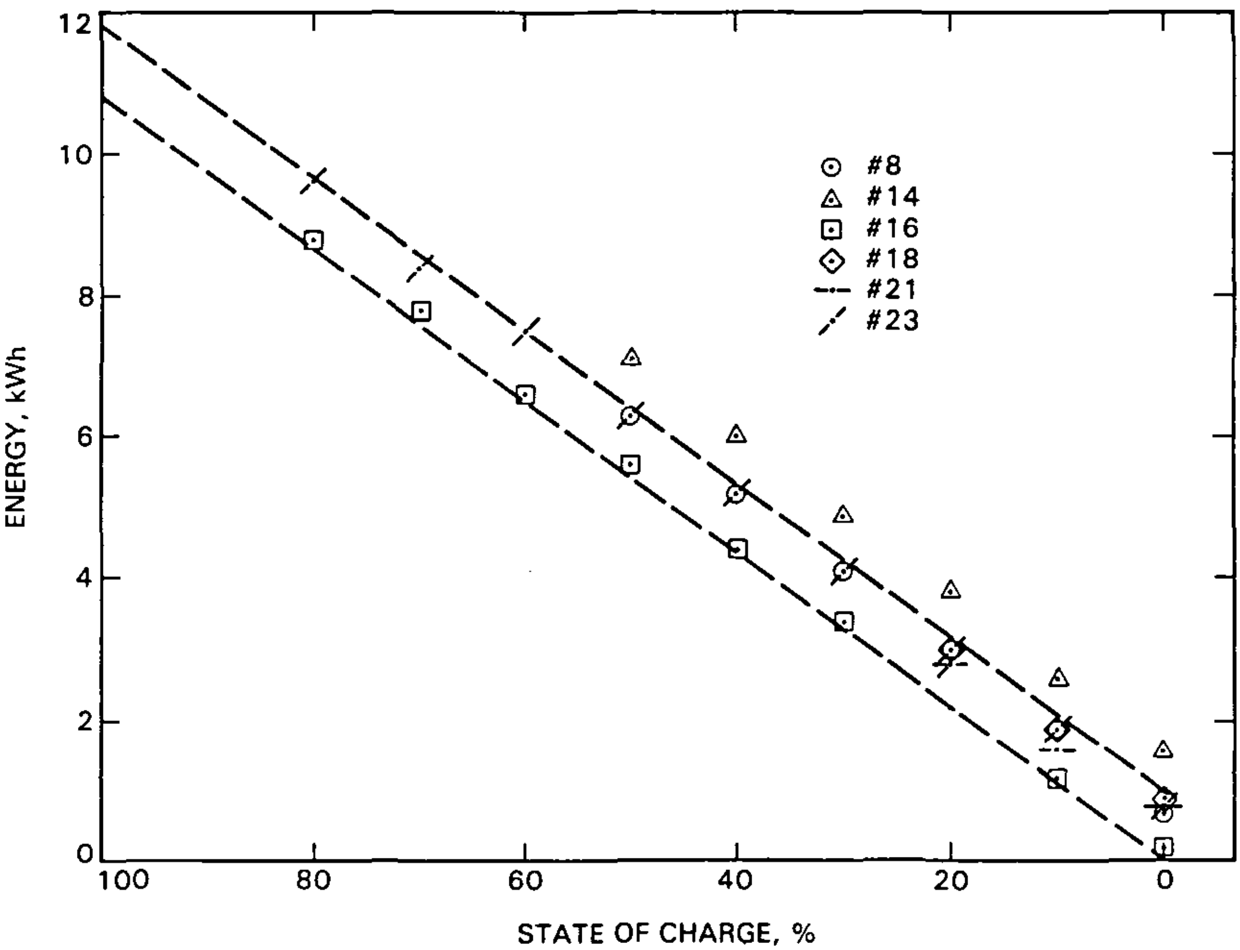



Figure 14. Composite Plot of Variable Rate Discharge (5 kW)

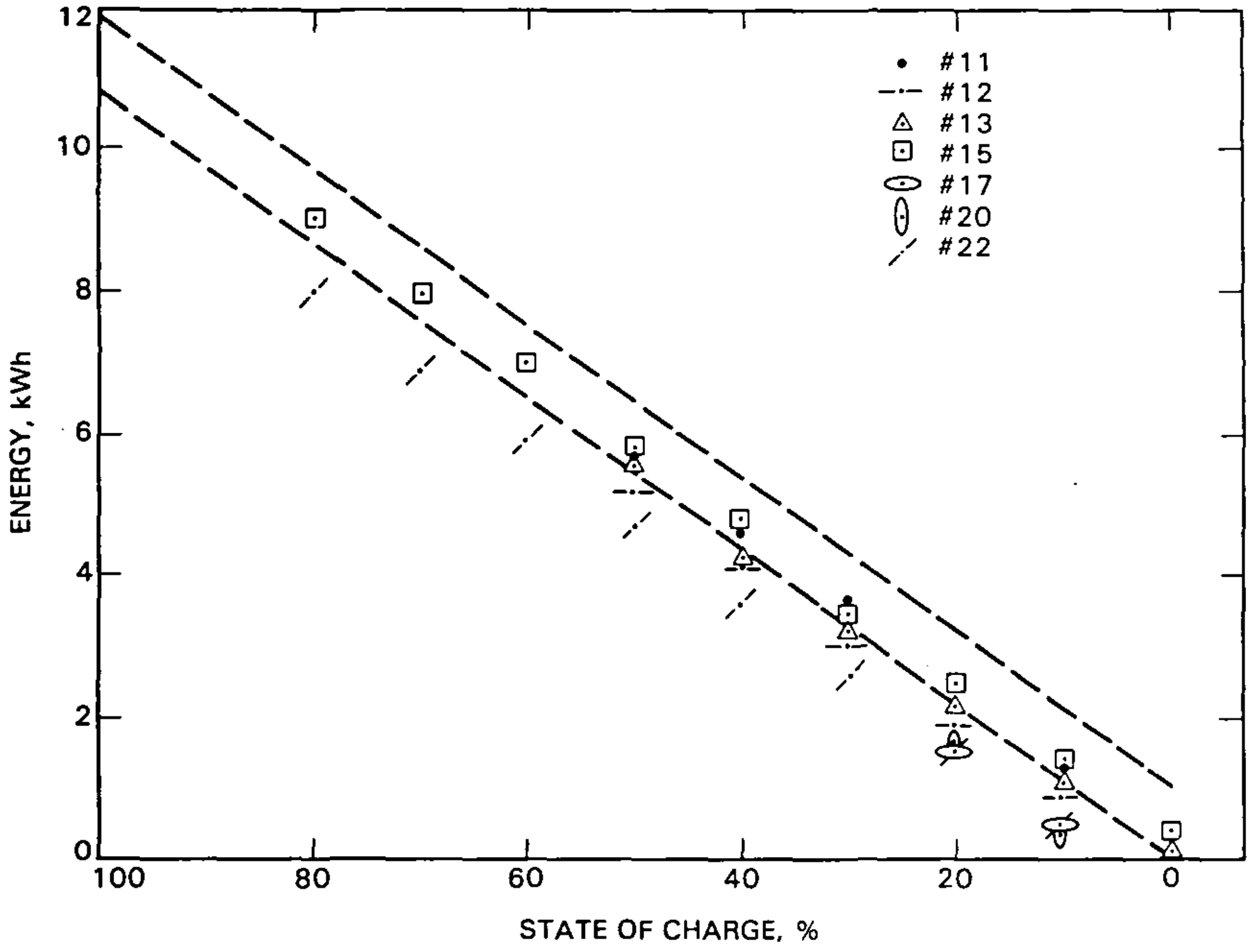



Figure 15. Composite Plot of Variable Rate Discharge (15 kW)

Figure 16 shows one of the two 15-kW-rate discharges to the 20% charge state as a function of time. The figure shows that the SCI does, at the last moment, adjust to the lower battery voltage. This is to be expected because the confidence factor, w, increases at the lower charge states. The SCI was also adjusting at the higher charge states. However, when the discharge rate is changed from 15 to 10 kW, the SCI prediction becomes less accurate and does not correct itself until the end of the discharge cycle because the confidence factor is decreased, and the SCI stops correcting. Furthermore, the SCI does not remember its best correction, the SCI will provide the standard estimate for the remaining energy in the battery. It will take the SCI at least one time constant ($\tau = 6$ min.) to respond to the low battery voltage.

### 3. Accuracy Following Equalization

It is also desirable to understand how the accuracy of the SCI varies as a function to the discharge cycles following equalization. To obtain the necessary data, those runs that were the first after discharge were compiled together and plotted (Figure 17). Similar steps were taken for the second, third, fourth, and fifth discharge (Figures 18 through 20). It seems that the SCI tracks the battery capacities very well until the fifth discharge after equalization.

### 4. Efficiency

Performing tests upon the battery charger shows the average efficiency to be 81%, which was obtained by measuring the input power from the 120-Vac source and by measuring the dc output. Losses occur primarily in the transformer and the switching circuit. Table 4 shows the results for 20 tests for which the efficiency was recorded. The charge efficiency as a function of time for two charge cycles is shown in Figure 21. Note that the efficiency is extremely flat with a value of 83% except where various fault conditions arose.

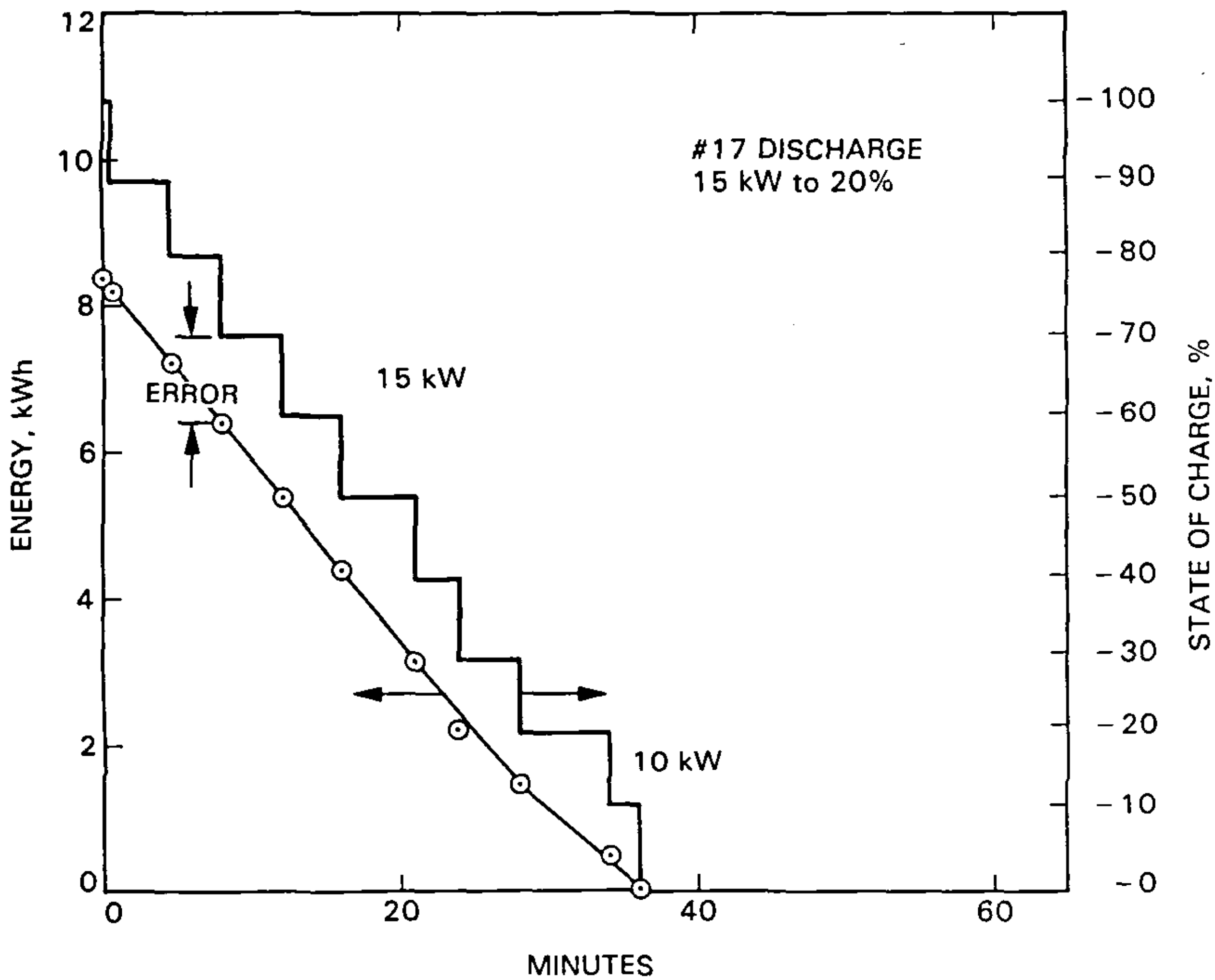



Figure 16. Variable Rate Discharge (15 kW to 20%)

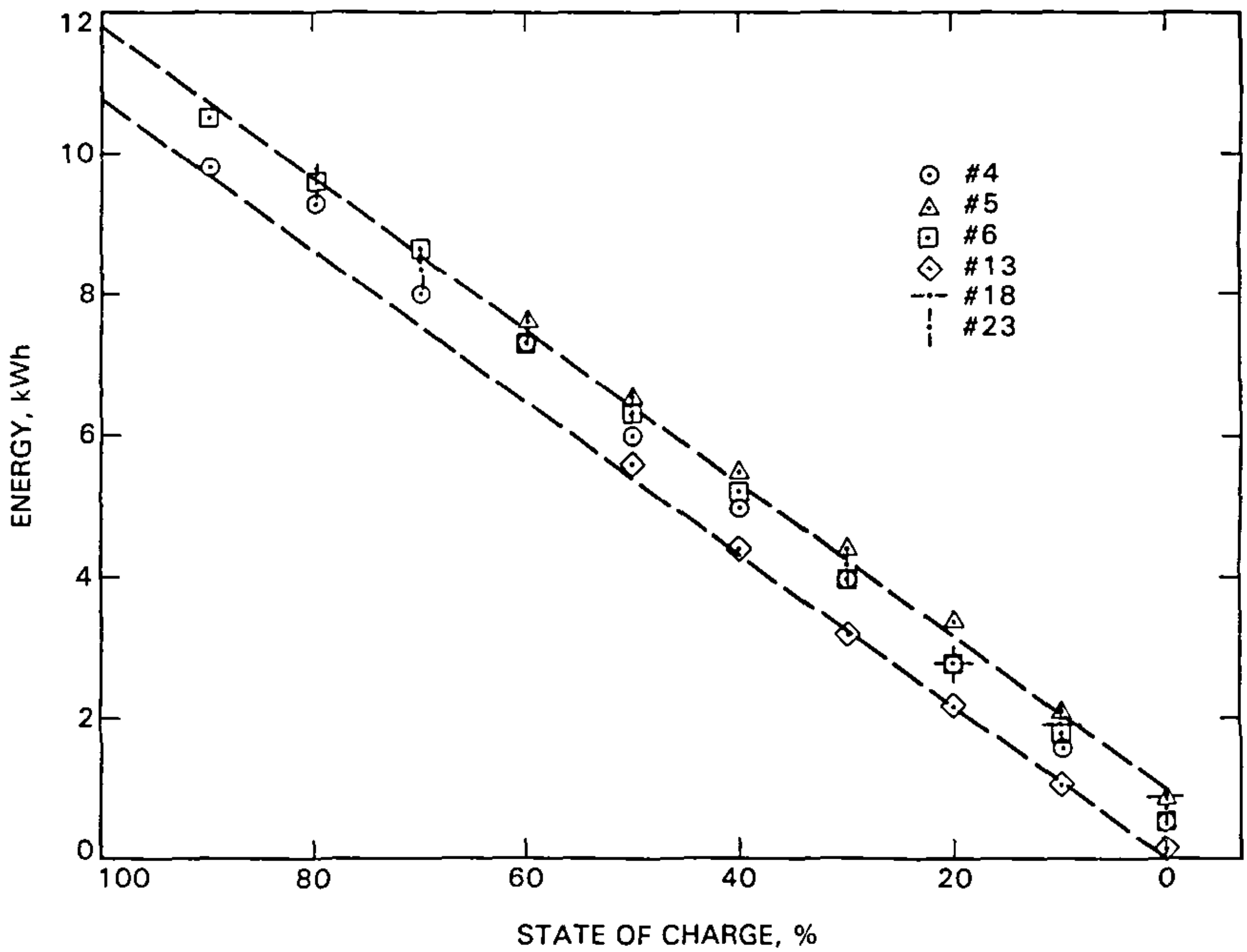



Figure 17. First Discharge after Equalization

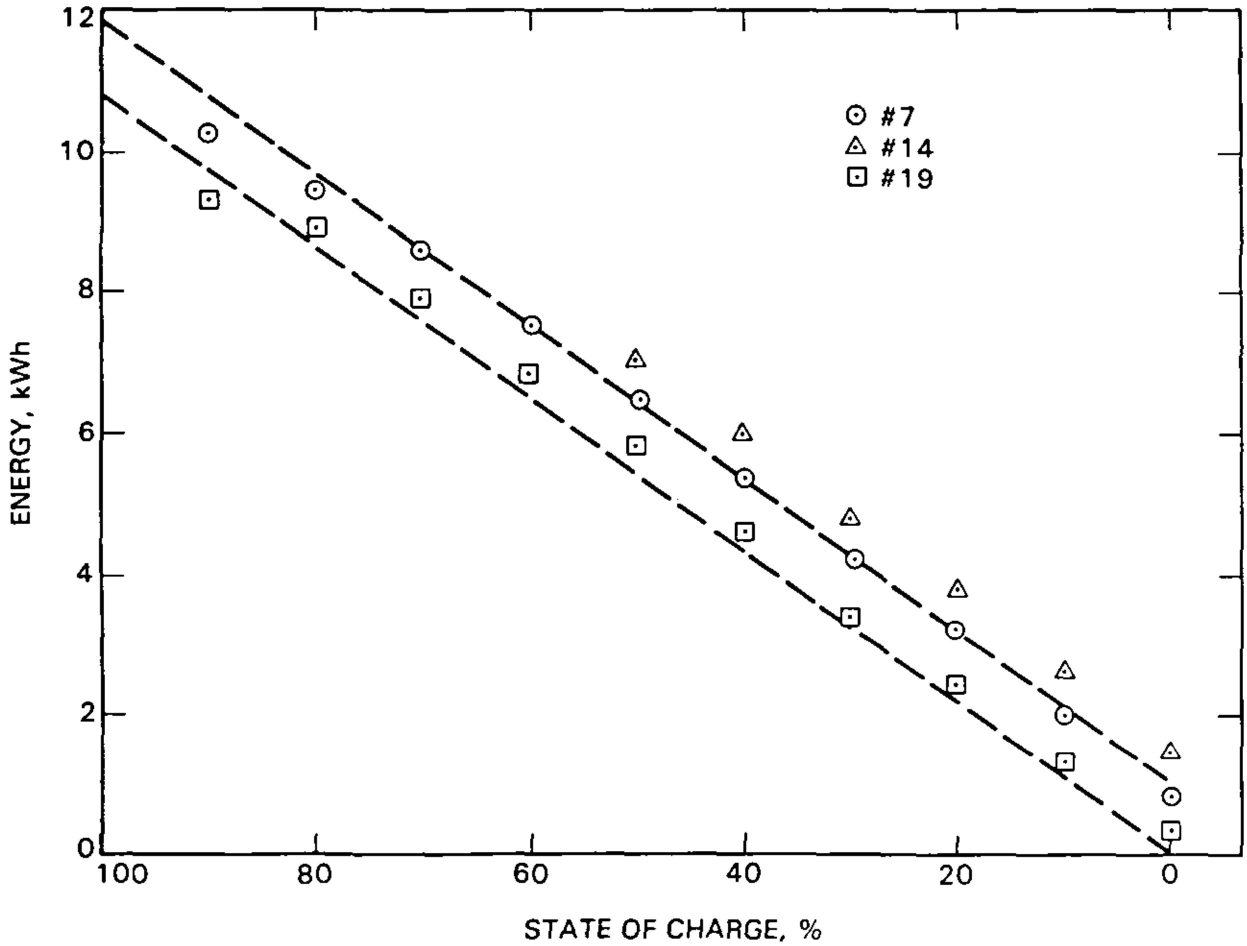



Figure 18. Second Discharge after Equalization

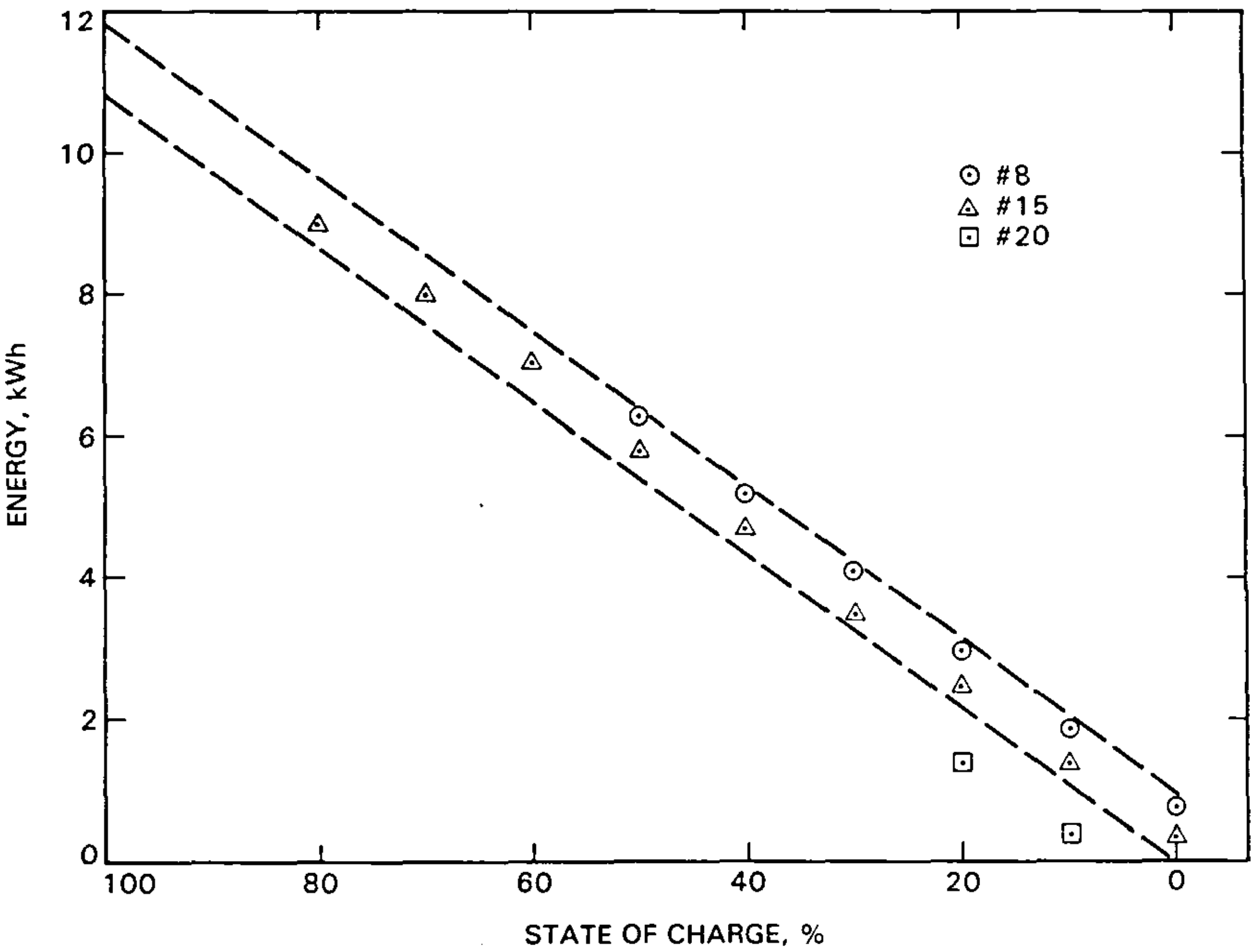



Figure 19. Third Discharge after Equalization

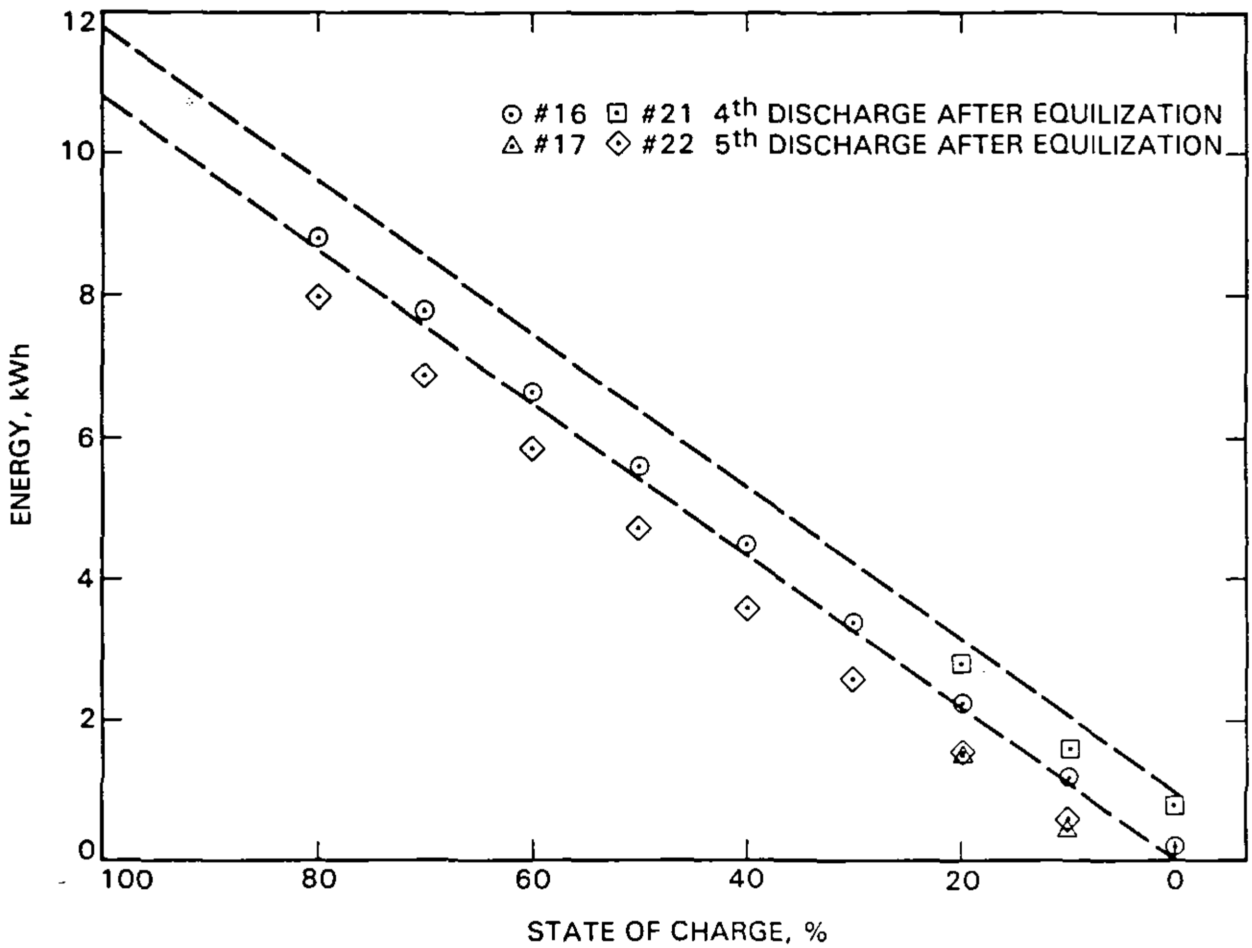



Figure 20. Fourth and Fifth Discharge after Equalization

Table 4. Gould Charger Efficiency

| Test No. (Charge) | Overcharge [a], % | ac Input Energy, kWh | dc Output Energy, kWh | Charger Efficiency, % |
|---|---|---|---|---|
| 4 | 35E | 28.0 | 17.8 | 63.6 |
| 5 | 58E | 24.1 | 19.1 | 79.3 |
| 6 | 52E | 24.2 | 20.1 | 83.1 |
| 7 | 2 | 13.1 | 11.0 | 84.0 |
| 8 | 9 | 16.3 | 13.5 | 82.8 |
| 9 | 8 | 16.2 | 13.4 | 82.7 |
| 12 | 7 | 15.8 | 13.1 | 82.9 |
| 13 | 56E | 22.7 | 18.9 | 83.2 |
| 14 | 0 | 15.4 | 12.8 | 83.1 |
| 15 | 17 | 17.8 | 14.5 | 81.5 |
| 16 | 6 | 15.0 | 12.3 | 82.0 |
| 17 | 6 | 15.1 | 12.4 | 82.1 |
| 18 | 37E | 18.1 | 14.7 | 81.2 |
| 19 | 12 | 18.7 | 15.2 | 81.3 |
| 20 | 10 | 15.1 | 12.3 | 81.5 |
| 21 | 16 | 15.1 | 12.4 | 82.1 |
| 22 | 6 | 15.3 | 12.6 | 82.4 |
| 23 | 36E | 17.6 | 14.4 | 81.8 |
| 24 | 16 | 19.0 | 14.1 | 74.2 |

[a] E = equalized charge.

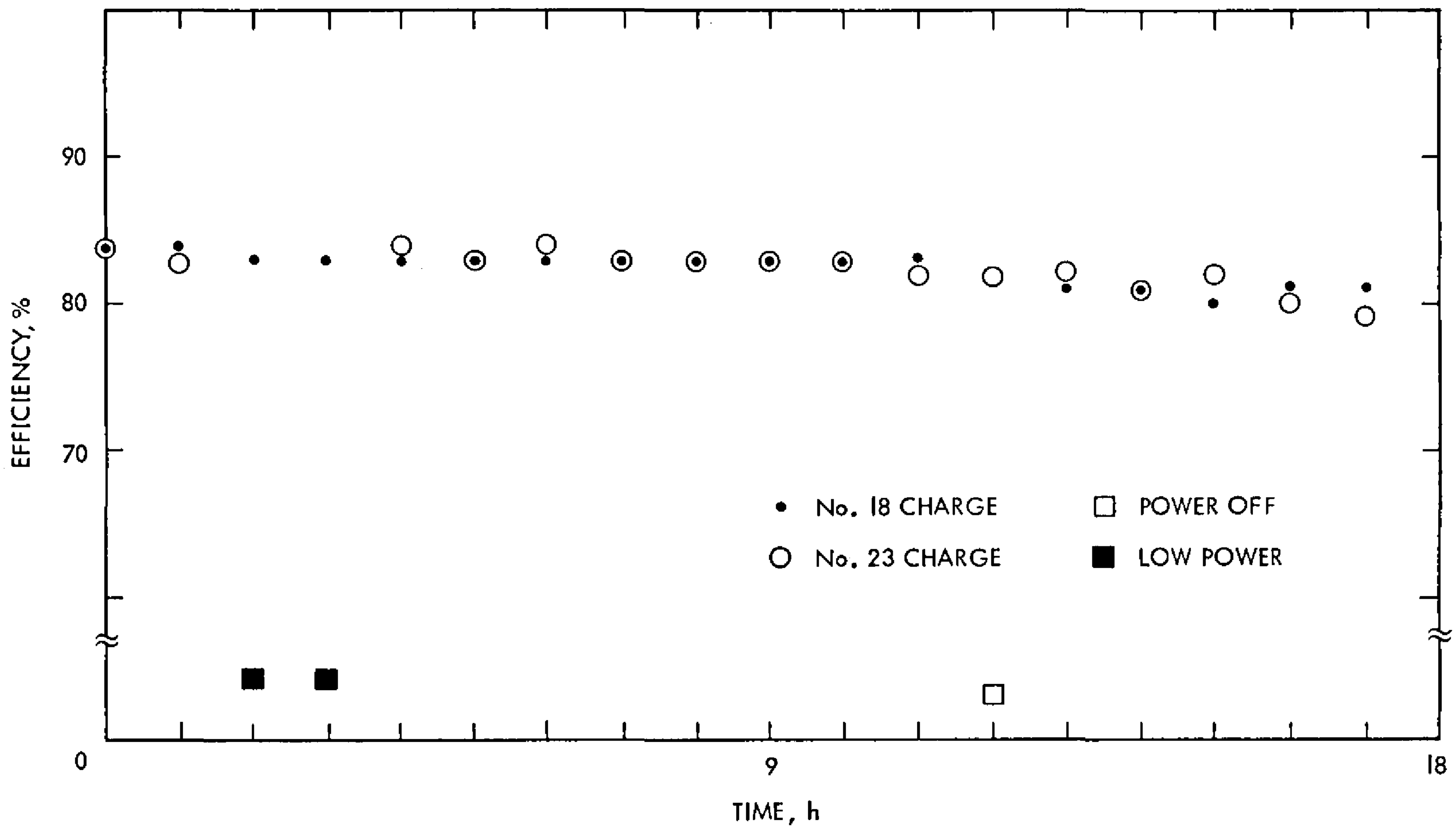



Figure 21. Charger Efficiency versus Time

## SECTION V

## SUMMARY/CONCLUSIONS/RECOMMENDATIONS

Of the six specifications presented in Section II, specifications 1, 3, and 4 were tested successfully. The results of the test program designed to verify the BC/SCI performance are discussed below:

(1) The BC/SCI successfully estimated the state of charge with a tolerance of 0 to -10% up to the fifth discharge cycle following equalization. While some errors did occur, they were self-corrected by the SCI to yield accurate answers.

(2) As measured, the average efficiency of the BC/SCI was 81% when the input power was 1 kW.

(3) The BC/SCI was operated from a 120-Vac power source.

(4) Power factor and harmonic content were not measured.

(5) The tests were not performed with other chargers or other battery types.

(6) The weight of the total BC/SCI unit was 32.2 lb.

While the BC/SCI met the SCI performance goals, the BC section needs further development. It is recommended that a non-isolated power section be developed for batteries whose leakage currents can be mechanically isolated from the chassis. A ground-fault interrupter can then be used for safety. For batteries where this is not possible, the two-stage converter previously described in this report is recommended. Because these converters are well-known, their development would be straightforward.

The final recommendation is that the BC/SCI be specialized for specific batteries, which includes using the appropriate power section and software modifications for a specific battery. The batteries should be promising candidates for electric vehicles. The battery and BC/SCI subsystem could then be optimized together.

## SECTION VI

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## APPENDIX A

## FUNCTIONAL REQUIREMENTS

### DEFINITIONS

The Power Section is that part of the Battery Charger through which energy from the power source flows to the battery. The Sensors are in the section of the BC/SCI which obtains data pertaining to battery and vehicle parameters. The Control Module determines the State of Charge and the Charging Sequence. The Display Panel indicates the status of the vehicle and batteries to the operator. The Control Panel allows the operator to make inputs to the system. Figure A-1 is a block diagram of a concept of a BC/SCI, and is included herein only to clarify the Functional Requirements.

1. Application

   The advanced BATTERY CHARGER and STATE OF CHARGE INDICATOR (BC/SCI) SHALL be capable of integration into new electrically powered vehicles at the time of manufacture, or retrofitted into existing vehicles after delivery. The BC/SCI SHALL be capable of being produced in large quantitites on a competitive basis.

2. Flexibility

   The BC/SCI SHALL be designed for operation in electrically powered passenger vehicles such as subcompact automobiles, light trucks and small vans with a system voltage ranging from 50 to 200 volts; and should incorporate sufficient flexibility to facilitate modification for operation in vehicles using near term batteries of nickel/iron or nickel/zinc construction. The BC/SCI should be of modular construction to simplify maintenance and facilitate modification for use in larger vehicles such as trucks and buses.

3. Power Section

   The Power Section SHALL include components which conditions the power as described in Paragraph (Par.) 12 and to deliver the power according to instructions received from the Control Module so as to achieve the desired charging sequence. Components in the Power Section may include magnetics with variable taps and voltage and current regulating devices with suitable interfacing equipment.

4. Control Module

   The Control Module SHALL include data conditioning capability to utilize the data from the Sensors and, in accordance with instructions from the Control Panel, provide the signals

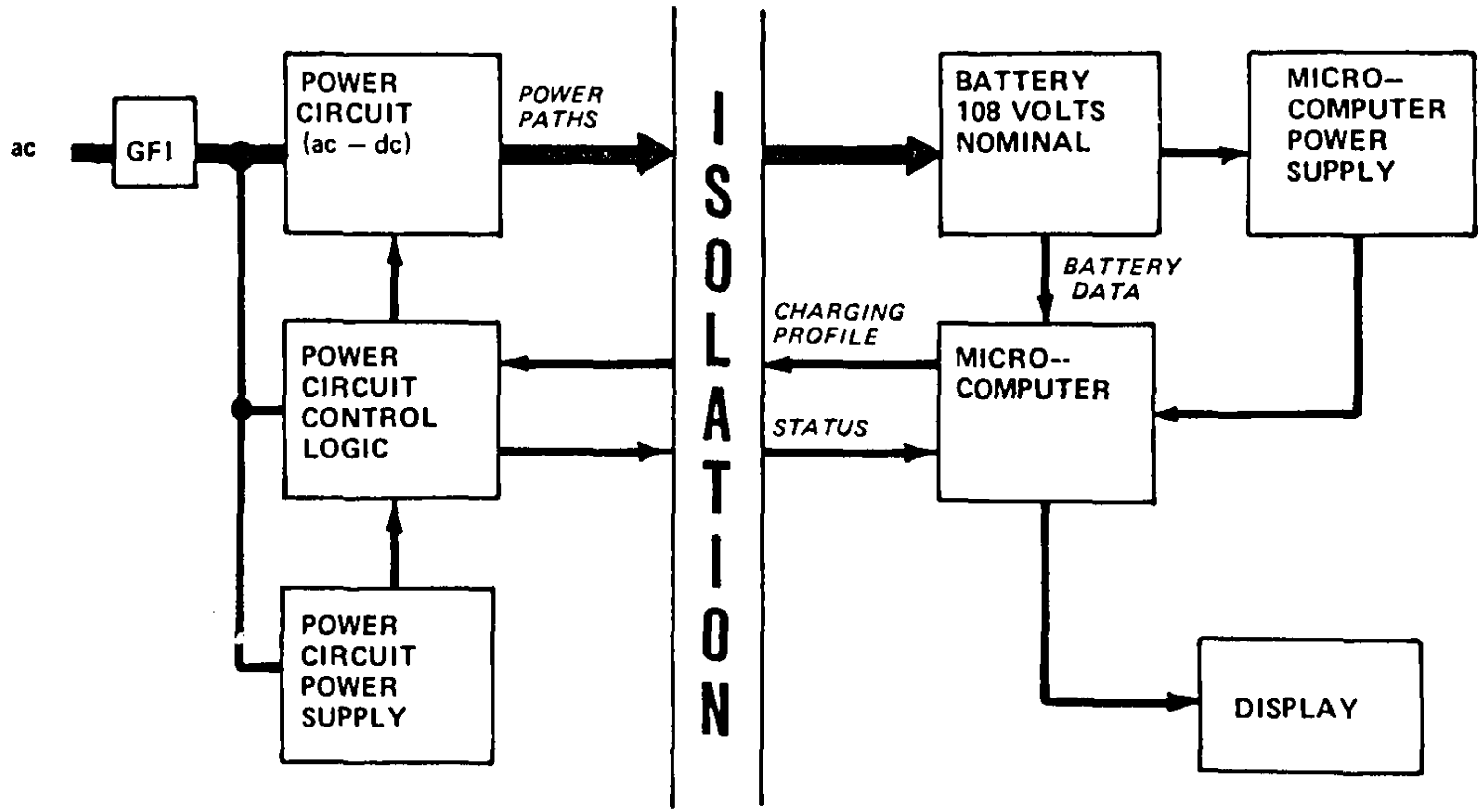


Figure A-1. Battery Charger/State-of-Charge Indicator required by the Power Section to control the voltages and currents needed to achieve the desired charging curves. The Control Module SHALL provide signals to the Display Panel so that the correct displays are available to the vehicle operator. The Control Module SHALL be capable of determining when the battery needs such equalization charge or watering, when the Charger is on, and if the currents, voltages, or temperatures are in excess of anticipated levels during the charge cycle.

5. Sensors

The Sensors for the BC/SCI are an integral part of the system, and SHALL be provided with the system. The Sensors may be attached to the batteries, interconnecting cables, or vehicle, but SHALL not require modification of the batteries for attachment, except that probes may be inserted into the batteries through the filler openings. Sensors may be attached to the vehicle drive shaft, wheels, or speedometer cable to attain data required by the State of Charge indicator. Sensors SHALL include signal conditioning equipment as required to provide proper data to the Control Module. Cabling between the Sensors and the Control Module may include shielding, multiplexing, or fiber optics to minimize weight, cost or susceptability to signal degradation due to high levels of ElectroMagnetic Interference (EMI), and SHALL incorporate connectors to facilitate a change of batteries. Sensors attached to the battery pack SHALL be accurate enough so that the BC/SCI will function within the tolerance limits established in Par. 7.

6. Control Panel

The Control Panel SHALL include provisions for operator control of input power, Par. 12, and alternate charging sequences, Par. 16. The Control Panel should also have an operator request for miles remaining, Par. 7. The controls for the BC/SCI may be incorporated into a single control panel or they may be packaged separately.

7. Display Panel

The Display Panel for the State of Charge Indicator SHALL include a presentation as to the level of energy remaining in the battery pack with a tolerance of +0% to -10% (i.e.: The battery may still have up to 10% of its energy remaining when the meter reads zero), taking into account the temperature and condition of the batteries, but not including vehicle parameters. The charge indication SHALL be based on the assumption that the remaining energy will be extracted at constant power until the cut-off voltage is reached. The level of battery energy SHALL be continuously displayed in increments of 10% with the 100% indication being attained only after an equalization charge with a new battery.

A display should be provided which combines parameters from the battery and vehicle to indicate the distance (in miles or kilometers) remaining if the driving mode used during the short period of operation just prior to operator request is continued.

The Battery Charger Display Panel SHALL include indications of "Charger On", "Need for equalizing charge", "Need for Battery watering", and a warning signal if currents, voltage, or temperatures exceed anticipated levels during the charge cycle.

The Display Panel for the BC/SCI may be combined into a single Display Panel.

8. Fast Charge Interface

The Battery Charger SHALL include the flexibility to facilitate modification to operate with and provide control signals to a separate, off board, fast charger. (i.e.: A charger capable of delivering over 25 kW power.)

9. Environment

The BC/SCI SHALL be capable of operation in an environment from -30°F to +150°F and from 0% to 100% humidity, and SHALL be able to withstand the vibration levels anticipated for electric vehicles of the types specified in Par. 2.

10. Reliability

The BC/SCI SHALL be designed to provide a minimum of three years of service with no routine maintenance. The system SHALL incorporate internal fault diagnostic capabilities consistent with Par. 4 and Par. 7. The BC/SCI SHALL be designed for a service life of ten years.

11. Safety

The BC/SCI SHALL provide safeguards against operation of the vehicle while the battery charger is connected to a power receptacle and against accidental contact with live circuits. Isolation from the power source and ground fault protection SHALL be incorporated into the design.

12. Input Power

The Battery Charger SHALL be capable of operation from a "standard" 105-120 Vrms, 60 Hz, 20 Amp power receptacle. The Battery Charger shall operate from this source with an input power of 1 kW. The input current SHALL be as large as possible without inadvertent tripping of circuit breakers. The Battery Charger may also operate from this source on an operator initiated alternate charge sequence with maximum current input limited to 10 Amperes.

The Battery Charger SHALL also be capable of operation from a power receptacle of higher rating, with the input current limited to 25 Amps, in an operator initiated quicker than normal charge sequence. This higher charging rate is independent of the fast charging rate specified in Par. 8.

13. EFFICIENCY

The Power Section SHALL be capable of operation with power efficiency (Power Output/Power Input) of no less than 95% when operating at maximum currents specified in Par. 12 (90% when operating at an input power of 1 kW). The energy efficiency (Energy Output/Energy Input) over the entire charging cycle SHALL be at least 90%).

The power factor SHALL be 0.94 or better at full load.

14. Weight

The total weight of the BC/SCI, including sensors but not including interconnecting cables, should be less than 35 lb.

15. Noise Spectrum

The Battery Charger SHALL generate no more than 100 mA and 100 mV of line conducted noise over a frequency range between 120 Hz and 10 MHz.

The BC/SCI SHALL be capable of operating in any EMI environment experienced in an operating electric vehicle as defined in Par. 2.

16. Charging Profiles

The BC/SCI SHALL be designed to function with any type of lead/acid storage batteries. Battery life, maintenance, efficiency, and charge time SHALL be considered in determining the normal charging profile the Battery Charger will follow when the input power is limited by the "standard" power receptacle, Par. 12. The Battery Charger SHALL also be capable of quicker than normal charging and equalization charging. The BC/SCI should also have sufficient flexibility to facilitate modification to operate with near term nickel/iron or nickel/zinc batteries.

17. Packaging

The BC/SCI SHALL be designed such that, in its production form, it can be readily integrated into any vehicle described in Par. 2, with controls and displays peculiar to the BC/SCI easily accessible to the vehicle operator. The deliverable breadboard BC/SCI specified in the Statement of Work SHALL be packaged such that it can be mounted in a subcompact vehicle (to be defined) for evaluation. The BC/SCI should be of modular construction.

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