NASA CR-165,243

DOE/NASA/0081-2
NASA CR-165243
AiResearch 79-16182, ADD. 1

Advanced Electric Propulsion System Concept for Electric Vehicles

Addendum 1—Voltage Considerations

A. E. Raynard and F. E. Forbes
AiResearch Manufacturing Company of California
The Garrett Corporation

August 1980

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Under Contract DEN 3-81

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Transportation Programs

```
        DISPLAY 29/2/1
      81N31034*#   ISSUE 21   PAGE 2992   CATEGORY 85   RPT#: NASA-CR-165243
      DOE/NASA/0081-2 AIRESEARCH-79-16182-ADD-1   CNT#: DEN3-81 EC-77-A-31-1044
      80/08/00  77 PAGES   UNCLASSIFIED DOCUMENT
UTTL: Advanced electric propulsion system concept for electric vehicles.
      Addendum 1:  Voltage considerations   TLSP: Final Report
AUTH: A/RAYNARD, A. E.;  B/FORBES, F. E.
CORP: AiResearch Mfg. Co., Torrance, Calif.     AVAIL.NTIS   SAP: HC A05/MF A01
MAJS: /*ELECTRIC BATTERIES/*ELECTRIC MOTOR VEHICLES/*ELECTRIC POTENTIAL/*
      FLYWHEELS/*PROPULSION SYSTEM PERFORMANCE
MINS: / ACCELERATION (PHYSICS)/ COMMUTATORS/ DIRECT CURRENT/ LEAD ACID BATTERIES
      / LIFE CYCLE COSTS/ TRACTION
ABA:  A.R.H.
ABS:  The two electric vehicle propulsion systems that best met cost and
```

DOE/NASA/0081-2
NASA CR-165243
AiResearch 79-16182, ADD. 1

Advanced Electric Propulsion System Concept for Electric Vehicles

Addendum 1—Voltage Considerations

A. E. Raynard and F. E. Forbes
AiResearch Manufacturing Company of California
The Garrett Corporation
Torrance, California 90509

August 1980

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135
Under Contract DEN 3-81

for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Office of Transportation Programs
Washington, D.C. 20585
Under Interagency Agreement EC-77-A-31-1044

N81-31034 #

PREFACE

The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (Public Law 94-413) authorized a Federal program of research and development designed to promote electric and hybrid vehicle technologies. In managing the activity created by Public Law 94-413, the Energy Research and Development Administration (ERDA), now the Department of Energy (DOE), established the Electric and Hybrid Vehicle Research, Development, and Demonstration Project in the Division of Transportation Energy Conservation.

Under interagency agreement EC-77-A-31-1044 the National Aeronautics and Space Administration was requested by ERDA (DOE) to undertake the project, and within NASA the Lewis Research Center was assigned responsibility. The study presented in this report is a part of the Lewis Research Center project for propulsion system research and development for electric vehicles.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

SUMMARY

The program for an advanced electric propulsion system concept for electric vehicles was established to evaluate a number of candidate system configurations, from which two systems were selected for conceptual design and preparation of a development plan. The initial tasks were completed and a formal report was published. Additional work was later authorized adding a subsequent task, a voltage optimization study.

Seventeen electric vehicle propulsion systems were originally studied to select the two designs that best met cost and performance goals. In this voltage optimization study, the final two systems were examined to assess the effect of battery-pack voltage on system performance and cost.

The battery-pack voltage tradeoffs were made for a total energy rating of 24 kW-hr at the 3-hr rate in the range of 54 to 540 V. The battery study results reveal that all the factors studied--specific energy on a mass basis, specific energy on a volume basis, and cost--are optimized at the lowest battery-pack voltage considered, 54 V. Battery cost increases by a factor of two up to 350 V, after which it is constant. Specific energy decreases by 20-30% as the voltage increases from 54 to 540 V.

The basic system uses a permanent-magnet motor with electronic commutation supplied by an ac power control unit. In this system the traction motor and power control unit must handle the peak power needed for acceleration. The traction motor can be designed to operate at specific battery voltages within a broad range, with little effect on motor efficiency, weight, or cost. The power control unit characteristics are affected by battery voltage, and the lowest voltages give the lowest efficiency, highest weight, and highest cost.

The flywheel system has a traction motor that is a dc mechanically commutated machine with shunt field control. Because of the flywheel the traction motor and the battery are not subject to extreme peaks of power demand. Design changes in the battery-pack voltage simply result in compensating changes in the motor configuration. At battery-pack voltages below 100 V the motor operating losses increase sharply.

When the battery data is combined with the electrical equipment data, the influence of the battery cost is the overriding factor. The battery-pack cost is minimum at 54 V, and by such a margin that it overbalances the higher electrical equipment costs, giving the lowest total system cost at 54 V. When considering life-cycle cost, the battery cost is even more influential, because the battery must be replaced several times during the life of the system.

The study of system operation, maintenance, and safety did not produce any data that materially influence the selection of system voltage level. Any voltage above 50 V can be hazardous, though the danger may increase with voltage. The hazard is related to current, rather than directly to voltage, but when a person inadvertently becomes part of an electric circuit, the higher the voltage the higher the current.

In all the studies of system performance and cost, the flywheel system was superior to the basic system. This superiority results from lower estimated component cost and the need for only one battery replacement, compared with three battery replacements projected for the basic system, over the life of the propulsion system. In both systems, battery costs were the major factor in system cost, and a battery pack with the minimum voltage of 54 V produced the lowest life-cycle cost. The minimum life-cycle cost was $0.057/km for the basic system with lead-acid batteries and $0.037/km for the flywheel system. With nickel-zinc batteries life-cycle cost was $0.063/km for the basic system and $0.047/km for the flywheel system.

Although the use of a 54-V battery pack appears optimum, there do appear to be some drawbacks to the low-voltage propulsion system. Electrical losses are very high, heavy cables are required for the high currents, and high-current components are necessary throughout the system. The penalties and costs of the propulsion system are outweighed by the economics of the battery pack, but the electrical design problems are considered undesirable by equipment designers even though solutions are feasible.

An increase in battery-pack voltage to 96 V provides a large improvement in electrical system efficiency at a relatively modest increase in system cost. This voltage level, 96 V, is a convenient multiple of a 6-V or 12-V standard battery module. The improvement in electrical system design is considered to be worth the increase in cost; accordingly, the recommended voltage for the battery pack is 96 V.

INTRODUCTION

The program described in the initial report for this contract was initiated to identify and evaluate advanced propulsion system concepts for mid-size electric vehicles. The objective was to identify potentially attractive concepts for advanced propulsion systems that offer considerable performance improvement over existing systems with little or no potential cost penalty. The propulsion system design concepts were to be based on components that could be developed by 1983.

Prior Work

Seventeen electric vehicle propulsion systems were originally studied to select designs that best met cost and performance goals. Two systems were selected for conceptual design and preparation of a development plan. The work was divided into several tasks. The initial technical tasks were completed and a formal report was published. Additional work was authorized by a contract amendment adding a subsequent task, designated Task VII, a voltage optimization study.

Program Objectives

The objective of the program task covered by this report was to determine the optimum battery-pack voltage and the optimum traction motor nominal voltage for several combinations of battery packs and propulsion systems. The task had three subtasks: (1) Battery Tradeoffs, (2) Propulsion System Component Tradeoffs, and (3) Voltage Recommendations.

Program Tasks

The program effort is discussed in this report in terms of the three principal tasks:

Battery tradeoffs.--A study was conducted to predict specific energy, cycle life, and initial cost of the battery as a function of battery-pack voltage. Battery-pack energy content was set at 24 kW-hr, and the voltage range considered was 54 to 540 V. This work was done for two types of batteries, lead-acid and nickel-zinc.

Propulsion system component tradeoffs.--Two systems were evaluated: one a dc powered unit and one using ac power conversion. These two systems were the ones selected for the previous conceptual design study, as described in the final report. Studies were made of the effect on system electrical components as a function of battery-pack voltage.

Voltage recommendations.--Voltage recommendations were based on life-cycle cost analyses as well as on system performance, operational characteristics, and maintenance and safety factors.

VOLTAGE STUDY GUIDELINES

The program guidelines established by the statement of work were structured to provide under the same contract a logical continuation of the work previously done in defining an advanced electric propulsion system concept for electric vehicles.

Battery Tradeoffs

Battery tradeoffs were required in the development of data to predict specific energy, cycle life, and the initial cost of the battery as a function of battery-pack voltage. These tradeoffs involved two types of batteries: lead-acid and nickel-zinc.

The comparisons were to be normalized by establishing a battery pack energy content of 24 kW-hr at the 3-hr rate. The limits of the nominal battery-pack voltage were selected as 54 to 540 V. Battery-pack characteristics were to be related to the goals established by the Department of Energy for 1981 battery development. The goals for a lead-acid battery, designated as those of an improved state-of-the-art (ISOA) battery, are shown in table 1; nickel-zinc battery goals are shown in the same table.

TABLE 1.--BATTERY CHARACTERISTICS GOALS

	Lead-acid (ISOA)	Nickel-zinc
Specific energy, W-hr/kg (at a 3-hr discharge rate and an 8-hr charge rate, 27°F)	40	80
Specific power, W/kg (peak power average for a period of 15 s)	100	150
Cycle life, cycles (4- to 8-hr charge, 2- to 4-hr discharge to 80 percent depth of discharge)	800	500
Cost, $/kW-hr (price paid by automobile manufacturer based on 100 000 units per year)	50	75

The scope of the study was to include investigation of the effect on battery cost of variations in plate thickness and number of plates, along with considerations of module size and packaging. The study was to produce specific data on cycle life as a function of plate thickness as well as data on specific energy, cycle life, and battery cost as a function of battery-pack voltage.

Propulsion System Component Tradeoffs

Component tradeoffs as a function of nominal battery-pack voltage were required for two systems, one employing ac power control and the other with dc power. The two systems previously detailed in the conceptual design study fulfilled this requirement. Their principal features are as follows:

Basic system.--Brushless permanent-magnet motor with electronic commutation, variable frequency inverter, traction continuously variable transmission.

Flywheel system.--Dc shunt motor, step voltage start and field control above base speed, continuously variable transmission, flywheel energy storage unit clutched to motor.

The features to be investigated were those affected by battery-pack voltage: the traction motor, the motor controller, switchgear, and the battery charger. A special situation to be investigated was the need for a voltage boost over the lower end of the battery voltage range if the traction motor could not be driven at nominal battery voltage. Such a need would require extra power handling controls, and could result in a step change in system power loss, weight, and cost.

In addition to component performance, consideration was also required of maintenance and safety problems associated with various voltage levels. These considerations were to include the application of present-day standards developed in such fields as rail tansport, but were also to assume the development of special standards for electric vehicles.

Life-Cycle Cost Tradeoffs

Life-cycle cost tradeoffs were required for both propulsion systems, at different voltage levels and with both lead-acid and nickel-zinc battery packs. The variations in battery performance and system component performance, as determined by battery pack voltage, were used to establish the actual battery pack size needed to achieve rated system performance. The associated component cost and battery pack cost were then established for use in calculating life-cycle cost. Life-cycle cost tradeoffs were based on achieving full system performance and range at each selected voltage level. Final system voltage recommendations are based on the life-cycle cost tradeoffs, with consideration also given to component performance, maintenance, and safety requirements.

BATTERY TRADEOFFS

Battery tradeoffs were made to determine the effect on battery design of using different battery pack voltages while a constant battery-pack energy content was maintained. The selected energy content was 24 kW-hr, which is approximately equal to the amount of energy needed by the two propulsion system configurations selected in the initial study to achieve the 161-km range. Both lead-acid and nickel-zinc batteries were examined.

Lead-Acid Battery Configuration

The battery model used in the initial propulsion system evaluations was developed from data supplied by Eagle-Picher Industries for their battery model EP200AH, which was a prototype developed for the AiResearch Near-Term Electric Vehicle.* The battery tradeoffs for this voltage study were done by Eagle-Picher as well. The lead-acid battery tradeoffs involve a battery of the same design as the EP200AH.

The basic EP200AH battery module is the 6-V unit shown in figure 1. The design goal was ISOA performance; representative data are tabulated in figure 1. Battery construction is tubular-plate, as illustrated in figure 2. The component parts for the unit are shown in figure 3.

The tubular-plate battery design features positive tubular electrodes and grids without antimony content in either the positive or the negative plates. Tubular plates retain the active materials, prevent shedding, and provide long cycle life. Eliminating antimony from the grid design prevents antimony contamination of the negative plate, thereby providing longer wet-life, improved charge retention, and reduced maintenance.

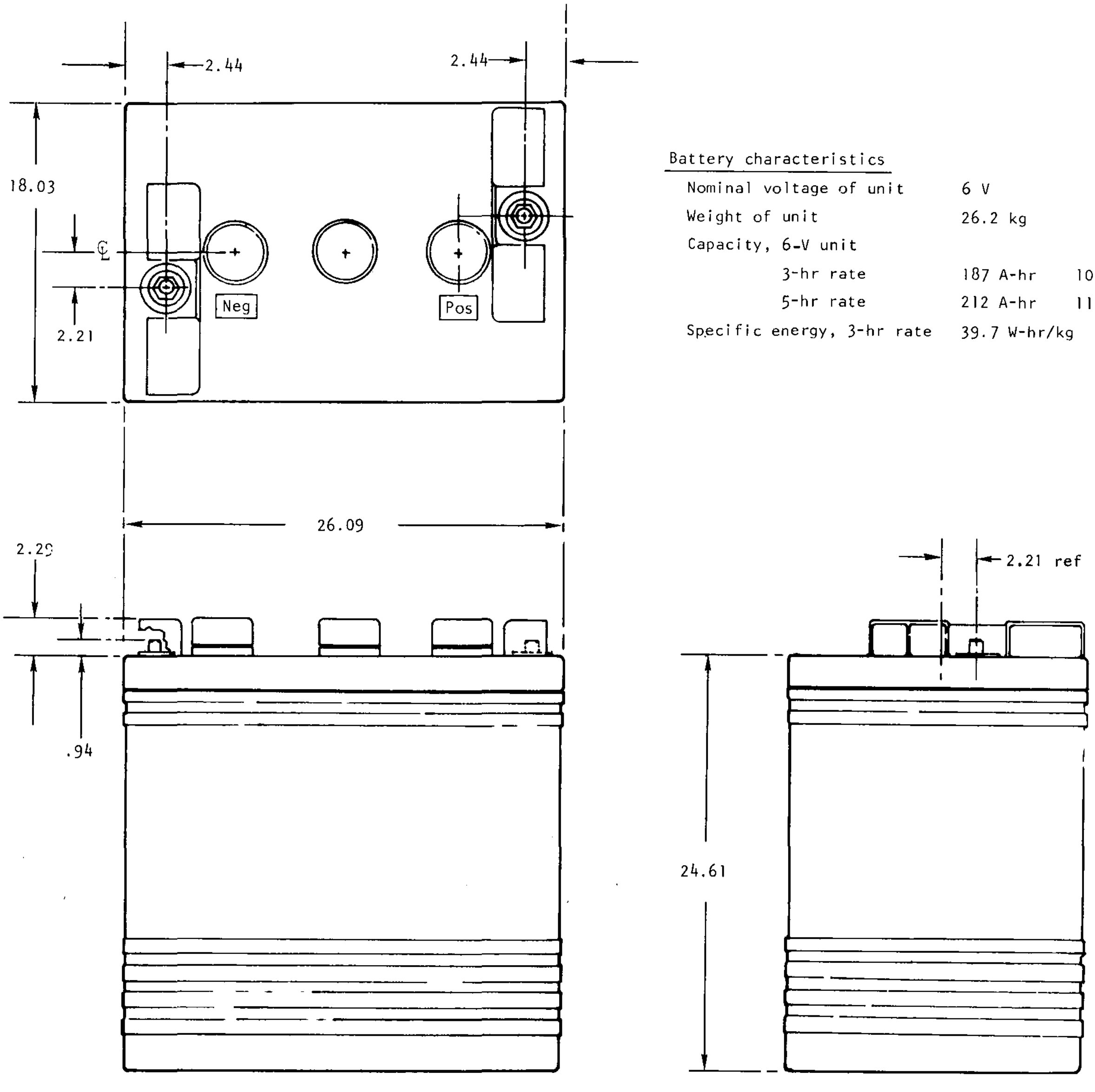
Technical Approach

The basic approach was to use a design model that would yield specific battery pack designs of predicted performance. This task was accomplished by means of a computer program that systematically manipulated a large number of design parameters and selected the acceptable designs.

The basis for each design model was a selected voltage level, which established the number of cells required. Because the total energy content was fixed at 24 kW-hr and the number of cells was set, the task was to determine the amount of active material to be packaged into a limited number of possible configurations. The parameters included tube size, number of plates, and plate height-to-width ratios. Using these parameters, over 15 000 design combinations were investigated.

---

*The Near-Term Electric Vehicle Program was established by the Department of Energy in 1976 to study, design, and fabricate improved electric vehicles. Garrett/AiResearch received a contract to fabricate an electric vehicle; it is scheduled for delivery this year.



Battery characteristics		
Nominal voltage of unit	6 V	
Weight of unit	26.2 kg	
Capacity, 6-V unit		
3-hr rate	187 A-hr	1040 W-hr
5-hr rate	212 A-hr	1185 W-hr
Specific energy, 3-hr rate	39.7 W-hr/kg	

NOTE: Dimensions in cm

A-7002

Figure 1.--Battery outline dimensions and characteristics of EP200AH battery.

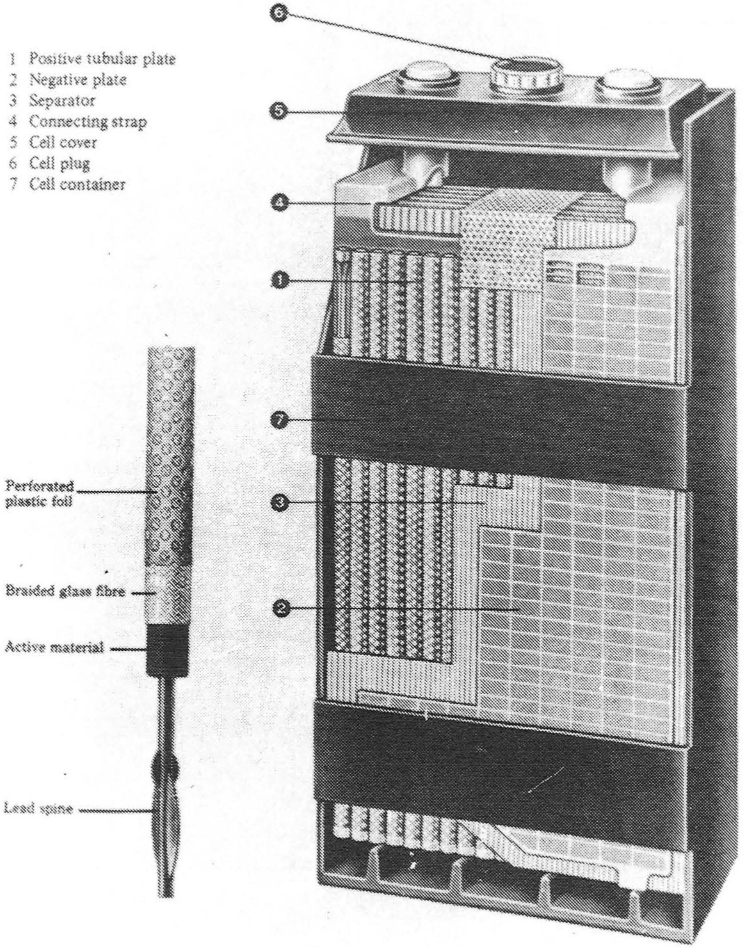
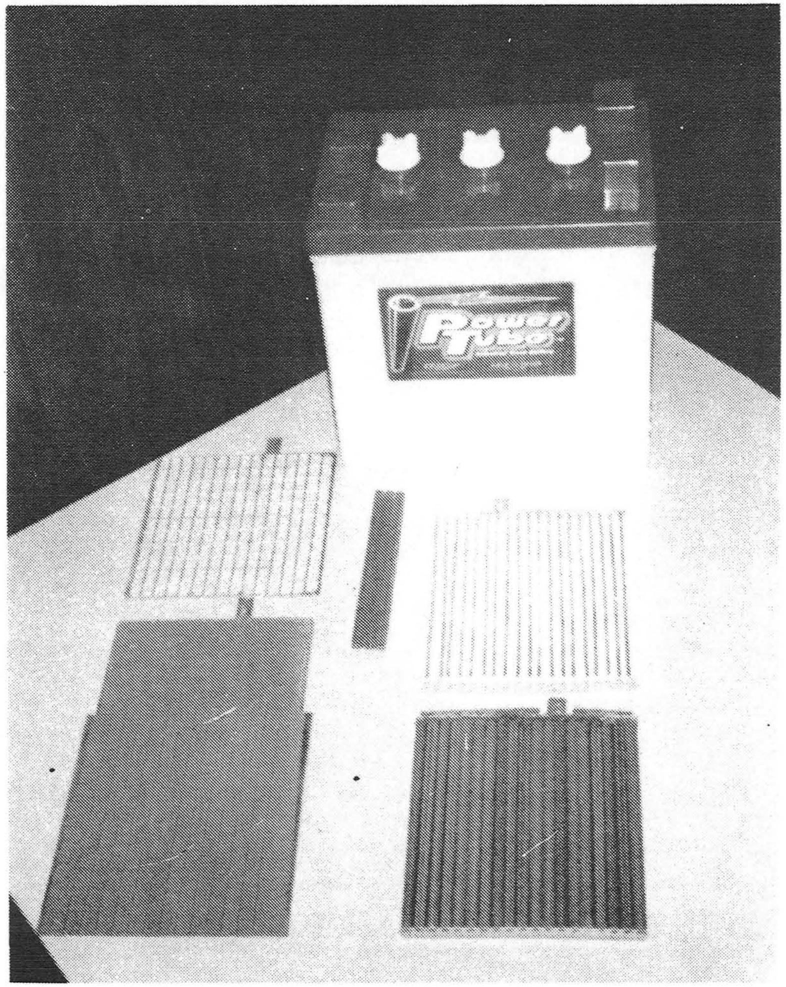


Figure 2.--Tubular-plate battery construction.



F-32781

Figure 3.--Tubular-plate battery components.

A flow chart of the computer program is shown in figure 4. The design combinations were sorted and compared to give tabulations based on each of the principal rating factors: W-hr/kg, W-hr/liter, cycle life, and $/kW-hr. The tabulations included average values of the parameters as well as upper and lower limits. No single battery design being optimum for all rating factors, for each voltage level a separate tabulation was made of several of the designs in the optimum range for all rating factors.

Lead-Acid Battery Characteristics

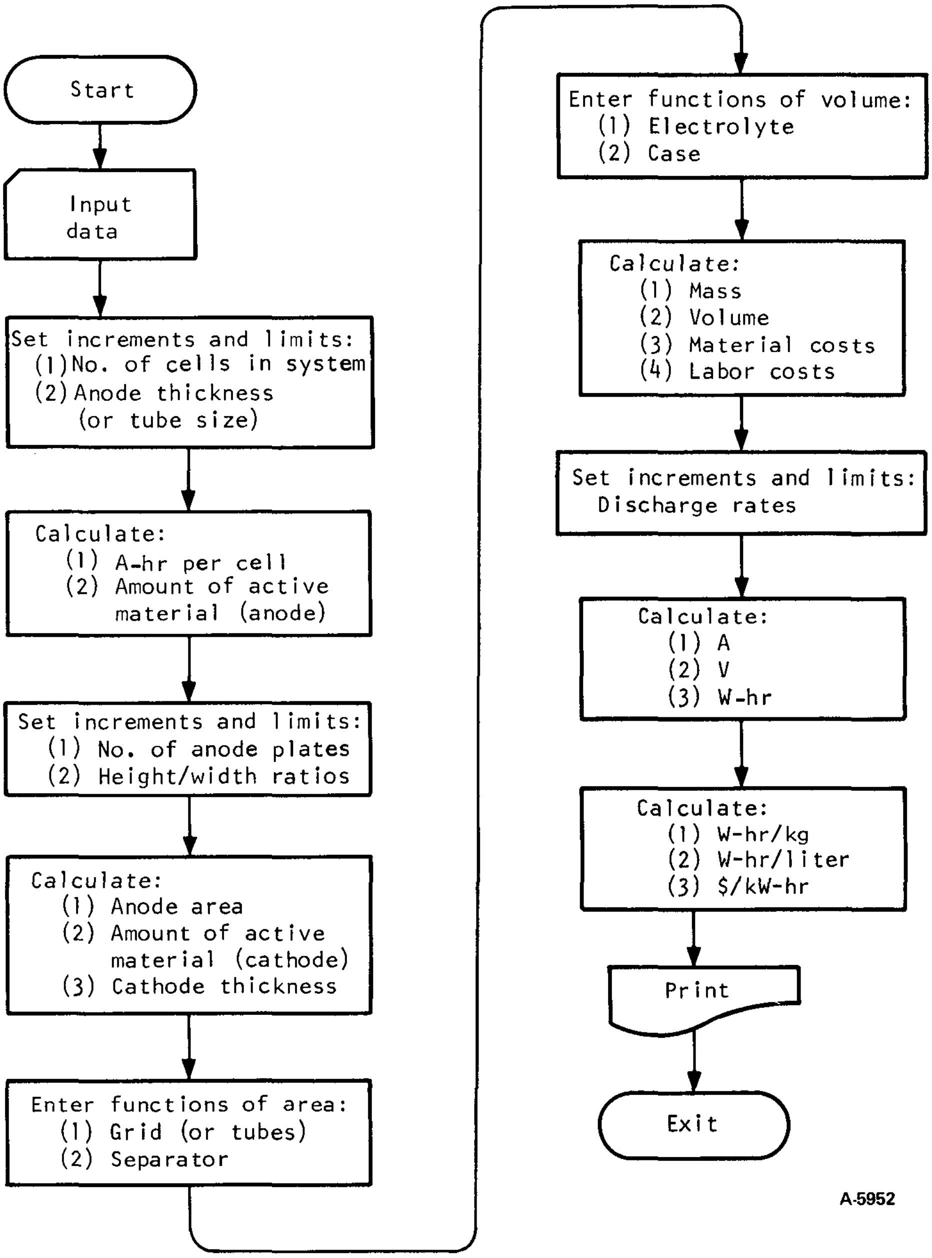
The following characteristics of the lead-acid battery pack were determined by use of the computer design program:

Specific energy (mass).--The effect of battery pack voltage on specific energy on a mass basis (W-hr/kg) is shown in figure 5. Within the range studied, 54 to 540 V, the specific energy decreases as the design voltage is increased. The values shown are average values for all the design configurations considered. The range of values in the design calculations is indicated in figure 6, with the upper limit shown for the 3-hr rate. If, in a particular application, it is desired to maximize specific energy at whatever compromise to other properties, it is possible to obtain ISOA specific energy performance up to 168 V.

Specific energy (volume).--When specific energy is examined on a volume basis (W-hr/liter), the trends are similar to those for specific energy on a mass basis. The data for the 3-hr rate are shown in figure 7, with both the average and the upper limit presented. In general, specific energy decreases as voltage increases, but it should be noted that below 70 V there is no change in specific energy. This effect is probably dependent on the selected plate aspect ratio (the ratio of plate length to width), which was set at 1.1 for packaging convenience.

Cycle life.--The cycle life of a lead-acid battery is primarily limited by consumption of the active material and by corrosion of the positive grid or spine. In this study the cycle-life calculation was based directly on the amount of active material as represented by the positive plate thickness; the calculation is shown in figure 8.

Plate thickness is not related to voltage; the plates for any voltage configuration can be independently varied with only a small effect on specific energy and cost. However, there is a relationship between specific power (W/kg) and plate thickness. Batteries for high discharge rate (high specific power) applications must be designed differently from batteries for moderate or low-rate use. The most obvious difference is that batteries for high-rate service require significantly more plate area in each cell. This is obtained by using a relatively large number of very thin plates. A battery designed in this manner has a very high specific power, but cycle life is sacrificed; thin plates do not perform well in deep-cycling use. An example is the standard automotive battery. This type of battery is capable of supplying very high discharge currents, but can deliver only approximately 100 deep-discharge cycles (ref. 3).



A-5952

Figure 4.--Program logic sequence for battery design.

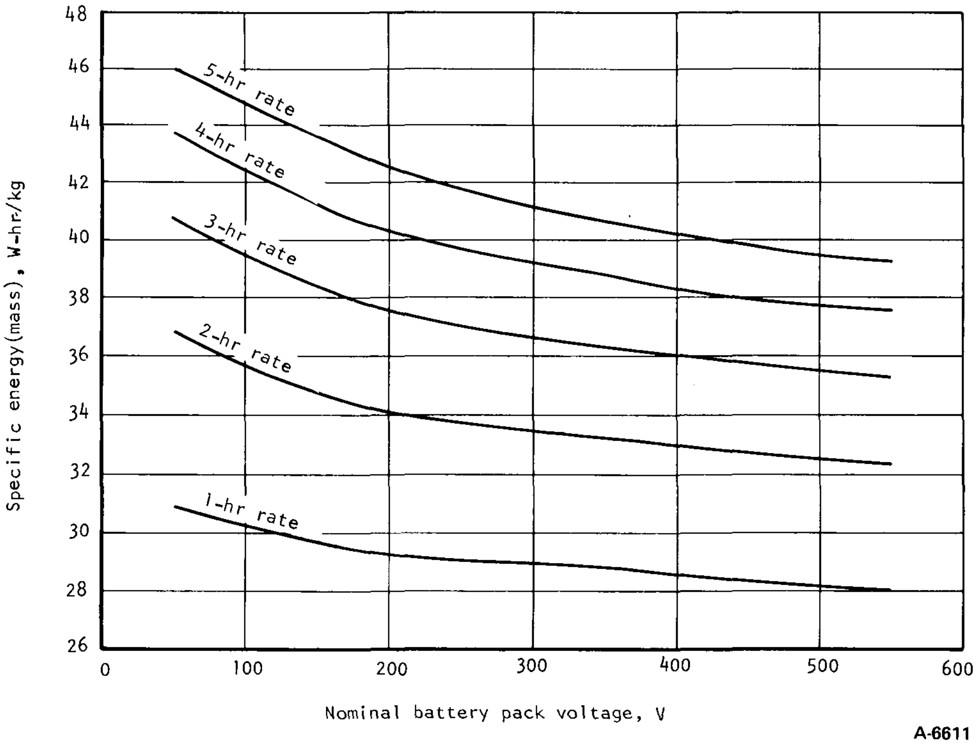


Figure 5.--Specific energy (mass) of lead-acid battery pack.

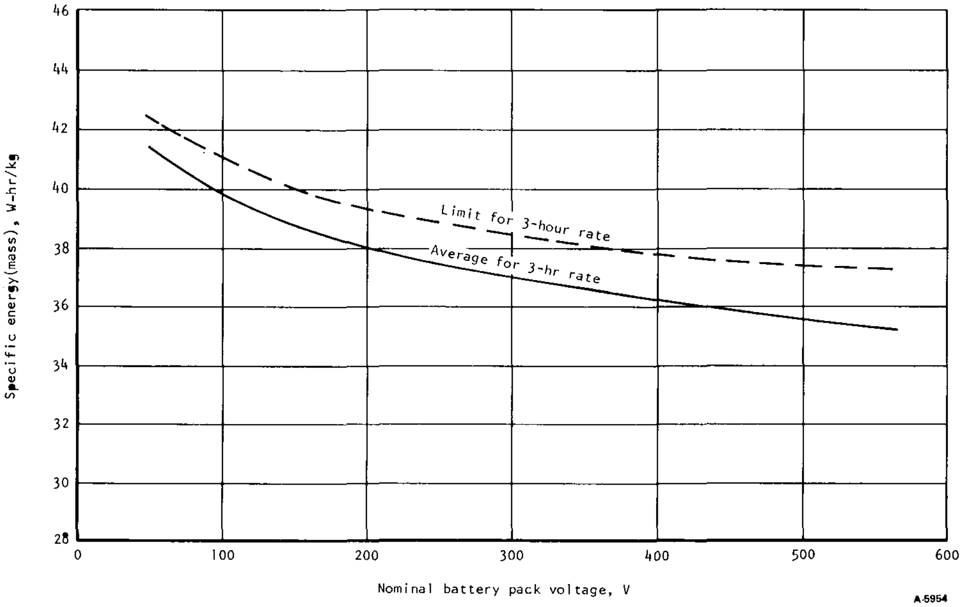


Figure 6.--Range of design for specific energy at the 3-hr rate.

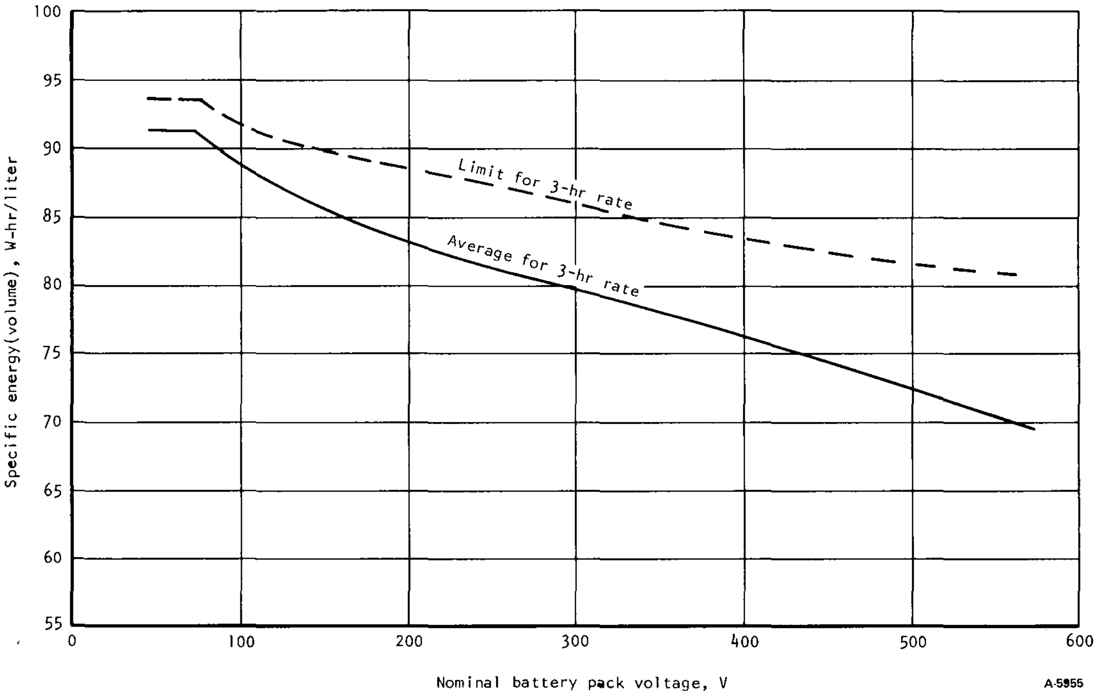


Figure 7.--Specific energy (volume) of lead-acid battery pack.

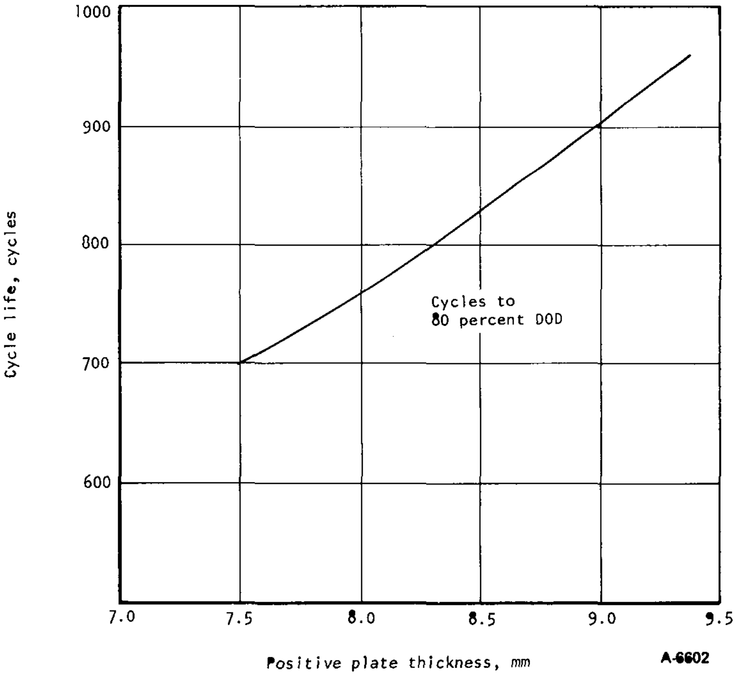


Figure 8.--Cycle life of lead-acid battery vs positive plate thickness.

Cost.--The effect of battery pack voltage on cost is shown in figure 9, which indicates an increase in cost as voltage is increased. Increasing the voltage is accomplished by increasing the number of cells. Material costs increase somewhat as the number of cells increase, but the principal increase is the labor cost of assembling more cells. At voltages over 350 V, the increase in the number of cells is offset by a decrease in the number of plates per cell, so that total cost is nearly constant. The upper line represents the average cost of all designs. The dashed line represents the cost of those units that were lower in cost primarily as a result of compromises in specific energy and in cycle life.

The cost levels indicated, expressed in 1976 dollars, include manufacturing costs that would be experienced in a large-scale operation producing batteries for 100 000 electric vehicles per year. The cost for lead was assumed to be \$0.50/lb. Also, the cost figure is regarded as the acquisition price paid by a vehicle manufacturer and, therefore, would include the profit of the battery manufacturer. These cost levels could be achieved only by a high degree of automation, implying a completely new plant specifically designed for such an operation. The non-recurring cost of such a plant was not included in the battery cost.

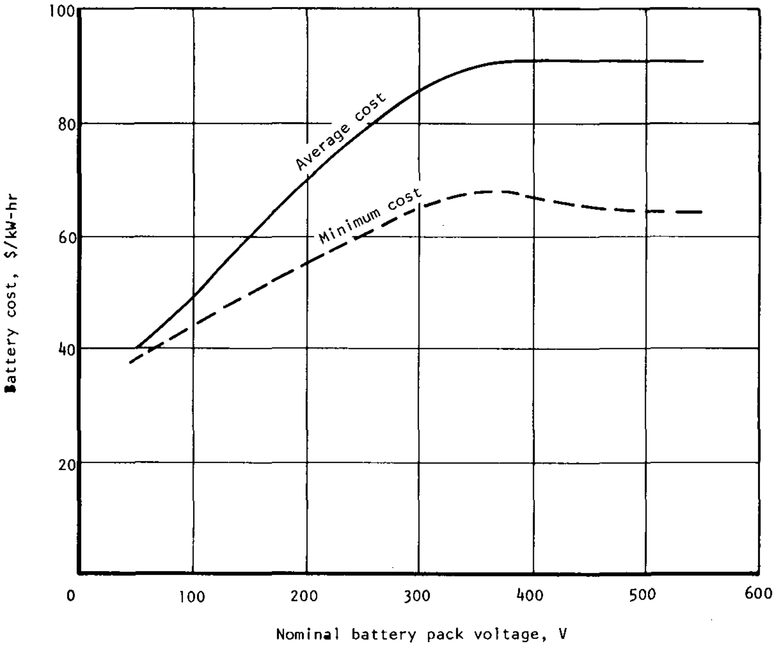


Figure 9.--Cost of lead-acid battery pack in mass production quantities.

Design configurations.--The plots of specific energy and cost tend to indicate that the battery pack should be designed for the minimum nominal voltage. However, some tradeoff is possible between minimum cost and maximum specific energy. This tradeoff is made through the vehicle life-cycle cost computations. The specific battery pack designs used in the life-cycle cost computations were selected by performing a computer scan to produce a printout of a limited number of the best designs in each category of characteristics. These specific designs are listed in table 2. Energy values are based on the 3-hr discharge rate.

TABLE 2.--LEAD-ACID BATTERY PACK DESIGNS

Number of cells	Positive plate thickness, mm	Number of positive plates	Height-to-width ratio	Specific energy, W-hr/kg	Cost factor, $/kW-hr	Cycle life, cycles	Specific energy, W-hr/liter	System voltage, V
27	7.5	10	1.10	42.31	41.43	697	94.93	54.80
27	7.5	7	1.10	42.10	38.93	697	93.28	54.78
27	8.3	6	1.10	41.73	38.09	799	91.95	54.53
27	9.3	6	1.10	41.09	38.32	949	89.96	54.32*
27	9.3	7	1.10	41.40	38.32	949	91.62	54.28
27	9.3	8	1.10	40.89	40.32	949	89.58	54.42
27	7.9	8	1.10	42.05	39.64	746	93.67	54.67
49	7.5	7	1.10	41.27	46.05	697	93.76	95.89
49	7.9	8	1.10	41.18	47.85	746	93.92	95.63
51	7.5	9	1.10	41.11	50.87	697	93.66	99.62
53	8.3	5	1.10	40.15	44.44	799	89.09	102.85
53	8.9	5	1.10	39.76	44.62	886	87.84	102.58*
49	9.3	6	1.10	39.60	45.35	949	87.39	95.25
49	9.3	7	1.10	39.06	47.85	949	85.29	95.52
49	9.3	9	1.10	38.93	51.82	949	85.05	95.62
51	7.5	10	1.10	41.10	52.89	697	93.77	99.64
77	7.9	9	1.10	40.04	63.66	746	91.08	146.35
77	7.9	7	1.10	39.97	57.48	746	90.41	146.34
77	8.3	5	1.10	39.31	52.05	799	87.06	146.23
79	7.9	5	1.10	39.51	52.55	746	87.75	150.05
77	9.3	5	1.10	37.70	53.66	949	80.86	146.27*
77	9.3	6	1.10	38.72	55.37	949	85.52	145.77
77	9.3	7	1.10	38.57	58.65	949	85.09	145.89
77	8.3	9	1.10	39.88	63.73	799	90.62	146.06
109	7.9	5	1.10	38.86	61.81	746	85.97	204.01
105	8.3	4	1.10	38.74	56.55	799	85.04	196.44
107	8.3	4	1.10	38.45	57.41	799	83.84	200.19
105	9.3	4	1.10	37.36	57.92	949	79.85	196.38*
105	9.3	5	1.10	38.12	61.03	949	83.53	196.05
105	9.3	6	1.10	37.76	65.76	949	82.30	196.31
105	7.5	6	1.10	39.18	64.66	697	87.40	197.16
133	7.9	6	1.10	38.69	74.31	746	86.14	247.07
133	8.3	4	1.10	38.31	63.83	799	83.77	246.76
135	7.9	4	1.10	38.40	64.39	746	83.95	250.65
133	9.3	4	1.10	37.38	64.63	949	80.44	246.45*
133	9.3	5	1.10	36.50	71.19	949	77.36	247.04
133	9.3	6	1.10	36.27	76.97	949	76.80	247.22
135	7.5	8	1.10	38.76	86.31	697	86.71	251.09
133	7.9	7	1.10	38.68	79.87	746	86.31	247.12
161	8.3	5	1.10	38.20	77.33	799	84.18	297.05

*Battery pack designs selected for further study.

TABLE 2.--Continued

Number of cells	Positive plate thickness, mm	Number of positive plates	Height-to-width ratio	Specific energy, W-hr/kg	Cost factor, $/kW-hr	Cycle life, cycles	Specific energy, W-hr/liter	System voltage, V
161	7.9	3	1.10	37.75	65.30	746	80.56	297.38
161	8.3	3	1.10	37.35	65.63	799	79.22	297.25*
161	9.3	3	1.10	36.24	66.72	949	75.35	297.07
161	9.3	4	1.10	36.51	72.63	949	77.19	297.08
161	9.3	5	1.10	35.76	80.26	949	74.79	297.59
161	8.3	7	1.10	38.30	90.73	799	85.19	297.06
161	8.9	7	1.10	38.07	90.87	886	84.43	296.67
189	8.3	5	1.10	37.96	85.66	799	83.37	347.36
189	8.3	6	1.10	37.93	93.67	799	83.58	347.42
189	7.9	7	1.10	37.86	101.91	746	83.35	347.87
189	7.5	3	1.10	37.36	71.63	697	78.98	348.15
191	8.9	3	1.10	37.18	71.85	886	79.11	354.23
189	9.3	3	1.10	35.71	73.06	949	73.52	347.55*
189	9.3	4	1.10	36.29	79.73	949	76.49	347.39
189	9.3	5	1.10	35.73	88.35	949	74.82	347.78
217	7.9	5	1.10	37.87	93.97	746	82.92	397.99
217	7.5	5	1.10	37.74	94.31	697	82.22	398.45
219	8.9	2	1.10	36.57	69.67	886	75.22	400.87*
221	9.3	2	1.10	36.49	69.85	949	75.13	404.24
217	7.9	2	1.10	36.62	70.02	746	74.73	398.01
217	9.3	3	1.10	35.69	78.63	949	73.56	397.79
217	9.3	4	1.10	36.62	86.06	949	77.90	397.44
247	9.3	5	1.10	37.25	102.93	949	80.94	451.03
249	9.3	4	1.10	37.18	93.04	949	80.25	454.60
249	8.9	2	1.10	36.45	74.46	886	74.85	454.81*
245	7.9	2	1.10	36.30	74.83	746	73.62	448.44
245	8.3	2	1.10	35.94	75.11	799	72.54	448.32
243	9.3	4	1.10	34.87	94.97	949	71.35	445.06
275	8.3	5	1.10	37.34	111.17	799	81.02	502.04
271	7.9	1	1.10	34.29	74.87	746	62.71	495.06*
275	7.9	1	1.10	34.06	75.81	746	61.97	502.37
271	9.3	3	1.10	34.54	91.17	949	69.50	495.36
273	9.3	1	1.10	33.04	76.26	949	59.65	498.42
273	9.3	2	1.10	35.24	79.88	949	70.56	498.27
273	8.3	5	1.10	37.45	110.45	799	81.47	498.39
271	7.9	4	1.10	37.45	98.59	746	80.78	495.06

*Battery pack design selected for further study.

Nickel-Zinc Battery Configuration

The nickel-zinc battery model used in the voltage study was based on nickel-zinc batteries previously designed by Eagle-Picher Industries. A typical nickel-zinc cell and a four-cell module are shown in figure 10.

The nickel-zinc cell design uses flat plates rather than the tubular plates employed in the lead-acid battery. However, the computerized design procedure for the nickel-zinc battery is nearly the same as that for the lead-acid battery. The principal difference is that in the nickel-zinc design procedure a constant nickel electrode thickness of 2.54 mm was used. It has been found that the nickel electrode thickness is limited by the manufacturing process and not by cell design and that the best design is obtained with the thickest nickel electrode that can be produced.

Nickel-Zinc Battery Characteristics

The following characteristics of the nickel-zinc battery pack were determined by use of the computer design program:

Specific energy (mass).--The effect of battery pack voltage on specific energy on a mass basis (W-hr/kg) is shown in figure 11. Within the range studied, 54 to 540 V, the specific energy decreases as the design voltage is increased. The values shown are average values for all the design configurations considered. The range of values in the design calculations is indicated in figure 12, with the upper limit shown for the 3-hr rate. It was not possible to achieve the 80 W-hr/kg goal for specific energy at the 3-hr rate.

Specific energy (volume).--When specific energy is examined on a volume basis (W-hr/liter), the trends are similar to those for specific energy on a mass basis. The data for the 3-hr rate are shown in figure 13; both average and upper limit data are presented.

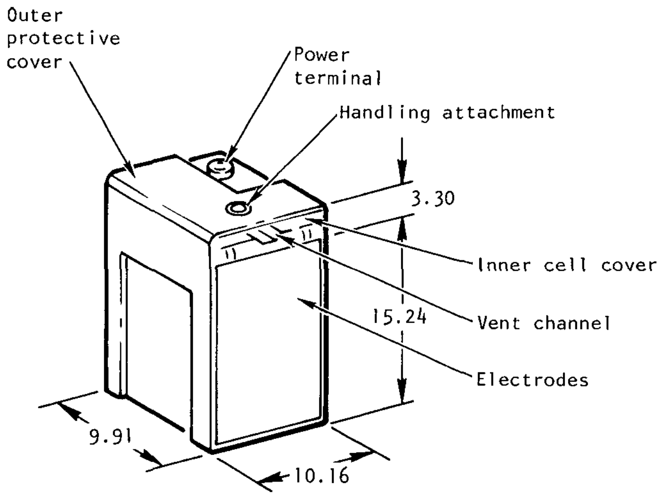
Cycle life.--The cycle life of a nickel-zinc battery is not directly affected by the voltage level of the battery pack. The only effect from changing the number of nickel-zinc cells would be an increased probability of cell imbalance (cells of different capacity) as the number of cells is increased, but this effect is due only to the fact that there are more cells. This probability would also be valid for a lead-acid battery pack as the number of cells is increased.

Limited battery life results from a specific failure within the cell. The two failure modes for the nickel-zinc battery are:

(1) Shorting due to dendrite formation

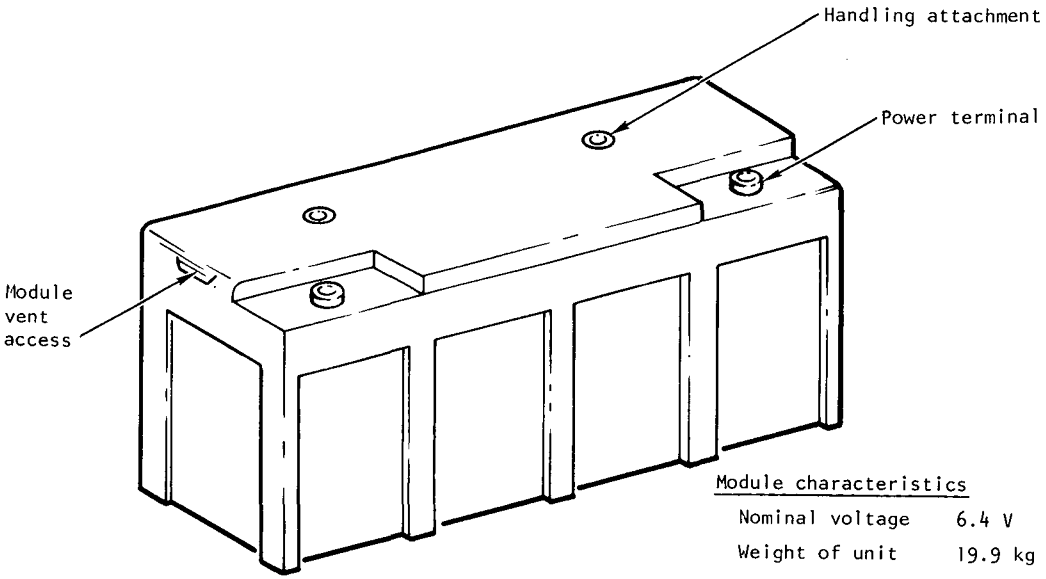
(2) Loss of active material efficiency due to shape-change, a redistribution of plate active materials, that results in a dense plate of less area

These failures occur because the negative plate active material dissolves on discharge and is "re-plated" during charge in each cycle.



Nickel-zinc cell (cutaway)

NOTE: Dimensions in cm



Module characteristics

Nominal voltage	6.4 V
Weight of unit	19.9 kg
Capacity of unit	1.56 kW-hr

Four-cell module

A-7034

Figure 10.--Typical nickel-zinc battery cell and four-cell module.

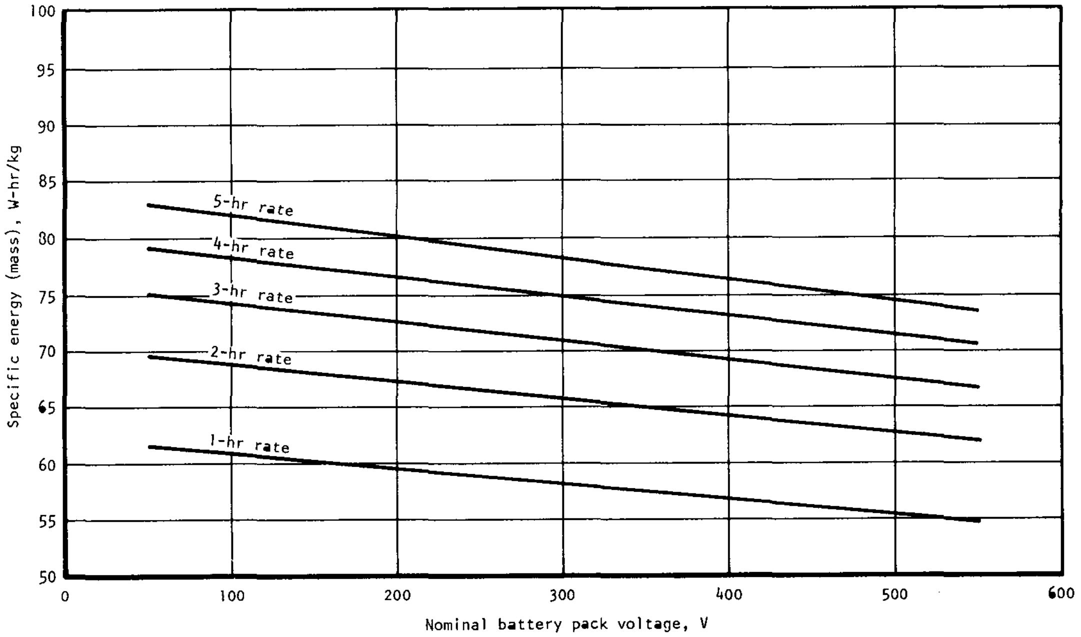


Figure 11.--Specific energy (mass) of nickel-zinc battery pack.

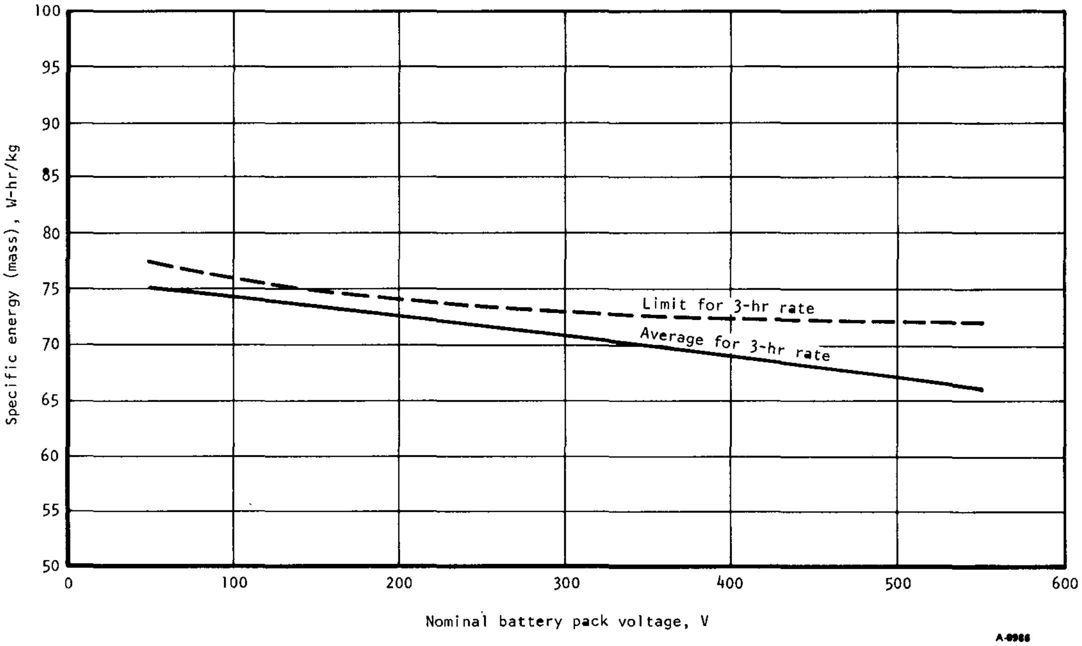


Figure 12.--Range of design values for specific energy of a nickel-zinc battery pack at the 3-hr rate.

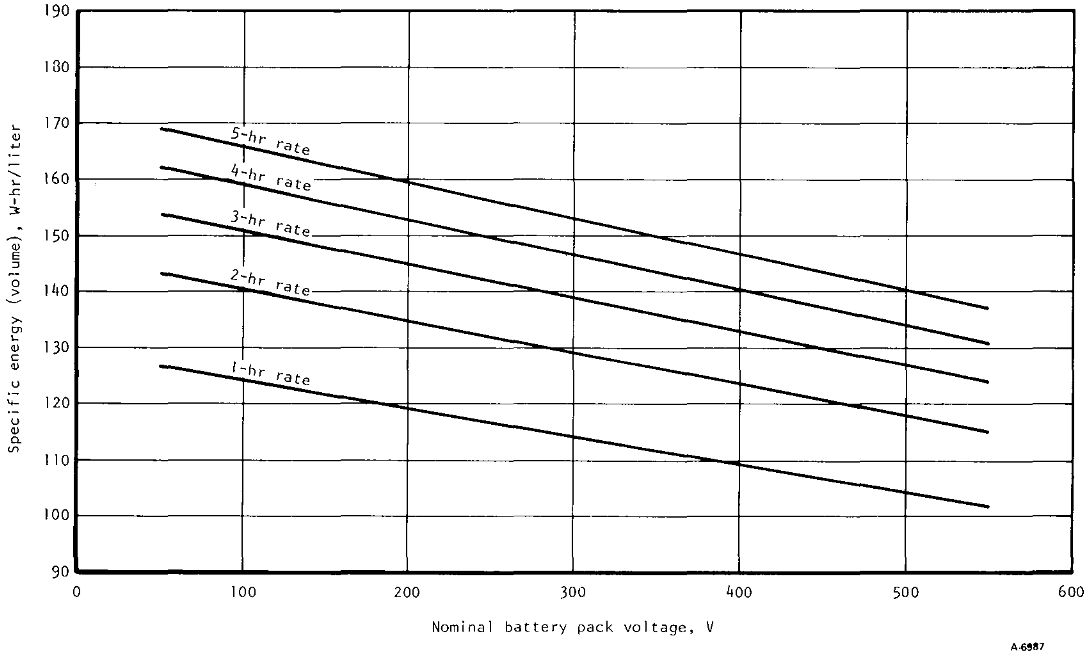


Figure 13.--Specific energy (volume) of a nickel-zinc battery pack.

For current battery designs, the estimated life is 100 cycles at 80 percent depth of discharge (DOD). However, a considerable development effort is being directed at the problem of cycle life, and achievement of the goal of 500 cycles at 80 percent DOD appears reasonable for 1983.

Cost.--The effect of battery pack voltage on cost is shown in figure 14, which shows an increase in cost as voltage is increased. Increasing the voltage is accomplished by increasing the number of cells. Material costs increase somewhat as the number of cells increase, but the principal increase is the labor cost of assembling more cells. At voltages over 350 V, the increase in the number of cells is offset by a decrease in the number of plates per cell, so that total cost is nearly constant. In figure 14 the upper line represents the average cost of all designs. The dashed line represents the cost of those units that were lower in cost primarily as a result of compromises in specific energy through the reduction of the number of plates per cell.

The cost levels indicated, expressed in 1976 dollars, are manufacturing costs that would be experienced in a large-scale operation producing batteries for 100 000 electric vehicles per year. The following costs were assumed for battery raw materials: Nickel at $2.40/lb, nickel nitrate at $0.80/lb, cobalt nitrate at $1.00/lb, and zinc oxide at $0.45/lb. Also, the cost figure is regarded as the acquisition price paid by a vehicle manufacturer and, therefore, would include the profit of the battery manufacturer. These cost levels could be achieved only by a high degree of automation, implying a completely new plant specifically designed for such an operation. The non-recurring cost of such a plant was not included in the battery.

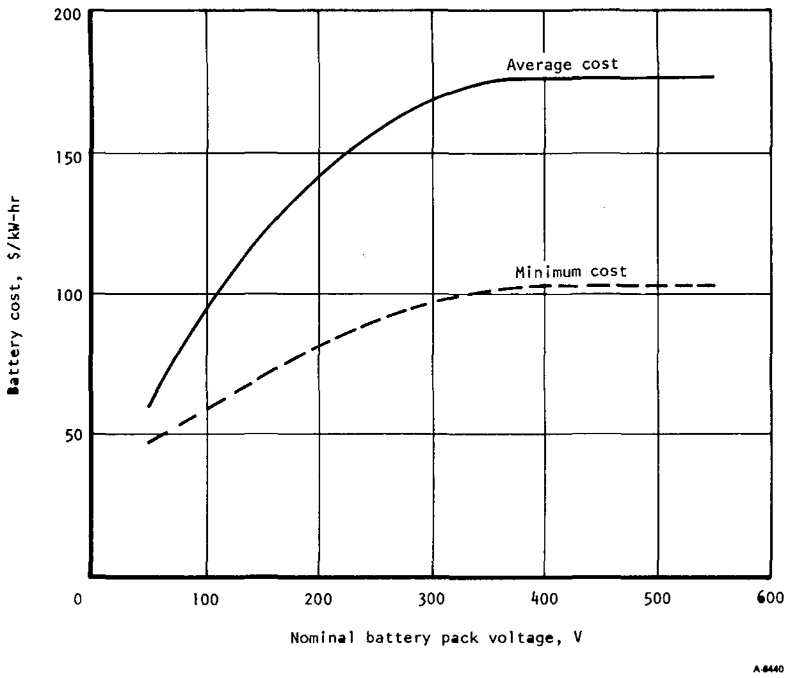


Figure 14.--Cost of nickel-zinc battery pack in mass production quantities.

Design configurations.--The plots of specific energy and cost tend to indicate that the battery pack should be designed for the minimum nominal voltage. However, some tradeoff is possible between minimum cost and maximum specific energy. This tradeoff is made through the vehicle life-cycle cost computations. The specific battery pack designs used in the life-cycle cost computations were selected by performing a computer scan to produce a printout of a limited number of the best designs in each category of characteristics. These specific designs are listed in table 3. Energy values are based on the 3-hr discharge rate.

TABLE 3.--NICKEL-ZINC BATTERY PACK DESIGNS

Number of cells	Number of positive plates	Height-to-width ratio	Specific energy, W-hr/kg	Specific energy, W-hr/liter	Cost factor, $/kW-hr	System voltage, V
32	23	5/4	76.065	157.963	71.934	52.16
32	24	4/4	76.063	158.126	73.735	52.16
32	8	5/4	72.664	144.709	45.692	52.16*
60	21	5/4	74.942	153.630	104.827	97.80
60	23	4/4	74.922	153.781	111.602	97.80
60	23	5/4	74.937	153.734	111.599	97.80
64	7	5/4	71.525	140.420	60.299	104.32*
64	7	6/4	71.515	140.298	60.303	104.32
92	18	5/4	73.882	149.616	130.928	149.95
92	21	4/4	73.852	149.813	146.519	149.95
92	20	4/4	73.870	149.809	141.320	149.95
92	19	4/4	73.876	149.763	136.124	149.95
92	7	5/4	71.126	138.991	74.506	149.95*
92	7	4/4	71.106	139.023	74.507	149.95
120	17	4/4	73.108	146.929	155.854	195.60
120	19	4/4	73.090	147.020	169.413	195.60
120	18	4/4	73.107	147.002	162.631	195.60
120	20	4/4	73.060	146.991	176.198	195.60
124	6	5/4	69.718	134.093	84.004	202.11*
152	17	4/4	72.345	144.324	190.257	247.76
152	18	4/4	72.319	144.320	198.850	247.76
152	16	4/4	72.353	144.264	181.669	247.76
152	6	5/4	69.373	132.948	96.624	247.76*
184	16	5/4	71.690	141.947	214.245	299.91
184	15	4/4	71.688	141.947	203.850	299.91
184	5	5/4	67.735	127.468	101.016	299.91*
212	15	5/4	71.170	140.142	230.760	345.55
212	14	4/4	71.162	140.111	218.785	345.55
212	5	5/4	67.450	126.597	112.042	345.55*
244	12	5/4	70.572	137.858	220.160	397.71
244	13	4/4	70.609	138.198	233.937	397.71
244	4	5/4	65.318	119.750	111.423	397.71*
276	12	4/4	70.090	136.404	245.467	449.88
276	4	5/4	65.070	119.006	122.203	449.88*
304	10	5/4	69.527	134.220	233.294	495.52
308	10	4/4	69.468	134.126	236.006	502.03
304	3	5/4	61.925	109.540	115.445	495.52*

*Battery pack design selected for further study.

PROPULSION SYSTEM COMPONENT TRADEOFFS

Design tradeoffs were made for the electric power components of the two propulsion system configurations. The object was to identify the principal changes required to operate at various battery voltages throughout the range from 54 to 540 V. The study was limited to the electric components that handle the power: the traction motor and the power control unit that controls the motor output. It was assumed that the system controller, a microprocessor that controls system operation in response to drive commands, could be made compatible with any battery-pack voltage at no increase in cost or complexity.

Basic System

The basic system uses a permanent-magnet motor with electronic commutation The power is supplied by a power control unit that uses an inverter to supply 3-phase ac power to the motor. In the basic system the traction motor and the power control unit must be designed to handle the peak power needed for acceleration. The previous design study found that the maximum motor output required was approximately 53.5 kW during the maximum acceleration. Because motor efficiency and controller efficiency may vary with voltage, the design study problem statement was established as follows:

(1) Battery voltage range is from 54 to 540 V.

(2) Maximum power control unit output is 60 kW, and at this load the input voltage from the battery is half the nominal battery-pack voltage.

(3) Maximum motor output required is 54 kW at a maximum speed of 13 000 rpm.

Traction motor.--The traction motor can be matched to a broad range of supply voltages by varying the design of the stator windings. These windings are ribbon conductors that can be made in different widths, thicknesses, and circuit arrangements to maintain nearly constant commutation reactance, and hence constant output. However, certain physical limits on the fabrication of the windings restrict this range to a voltage below 540 V. On the low end of the range, the limit is established by the minimum voltage at maximum load. The battery-pack voltage of 168 V used in the original design study has been adopted as a reasonable limit for nominal battery pack voltage.

At battery-pack voltages below 168 V, a booster will be used to boost battery voltage preceding the inverter. Therefore, the traction motor will be used only within its established design range. Within this range, the design variations in the stator windings will not cause any significant effect on motor size, weight, performance, or cost.

Power control unit.--The complete electronic control unit consists of two main devices: the power control unit for control of motor power and the system controller (a microprocessor) that controls system operation in response to drive commands.

The basic control scheme for the motor includes the following: a chopper that controls the motor current; a silicon-controlled rectifier (SCR) inverter with an auxiliary commutator for commutating the inverter switches during the motor start sequence; and a regenerative switching scheme that returns energy to the battery during braking. A block diagram of the electronic control unit, presented in figure 15, shows the interrelation of the system controller and the power control unit.

The schematic of the power control circuit is presented in figure 16. Electronic symbols are shown for the power handling devices, which are the components affected by system voltage and operating current levels. The low-power logic devices are indicated with block diagrams. This schematic applies where no voltage boost is needed from the battery level. The chopper is used for current control.

When voltage boost is needed, a combined chopper must be employed of the type shown in figure 17. The first section of the chopper is used for voltage control and the second section is used for current control. The use of the voltage control chopper introduces added complexity, cost, and operating losses. This combined chopper is used for nominal battery-pack voltages below 168 V. However, the voltage boost is made to a level of 240 V, so that in the boost configuration the motor is not used at the extreme low limit of its voltage capability.

The operating losses of the power control unit are shown in figure 18. There is an indicated transition in the loss curve between the nonboost voltage of 168 V and the voltage boost level of 240 V. The efficiency of the power control unit at two different load ratings is presented in figure 19. It is apparent that losses mount very rapidly at voltages below 100 V and that optimum operation is at voltages above 300 V.

The estimated weight of the power control unit is shown in figure 20. The corresponding estimated cost is shown in figure 21. This cost is based on the manufacture of a fully developed package at a rate of 100 000 units per year. Costs are in 1976 dollars. System component costs are summarized in Appendix A.

The weight and cost estimates do not include an amount for cables or connectors. These items are discussed in the section on switchgear.

Flywheel System

In making the system component tradeoffs, it was originally anticipated that there would be a lower limiting voltage for the traction motor in each system, and that below this level the motor controller or power converter would have to boost voltage from the battery-pack level to the traction-motor input. Although this low-level boost is required for the basic system with ac power conversion, it is not needed for the flywheel system with dc power. The dc motor can be designed to operate at the lowest system battery voltage, making unnecessary a voltage booster that would mean added system cost and complexity.

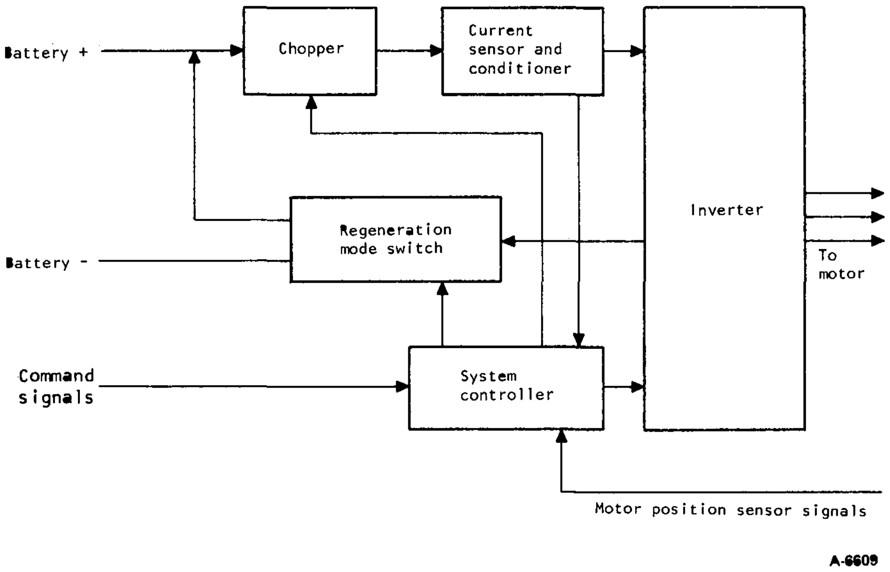


Figure 15.--Electronic control unit block diagram.

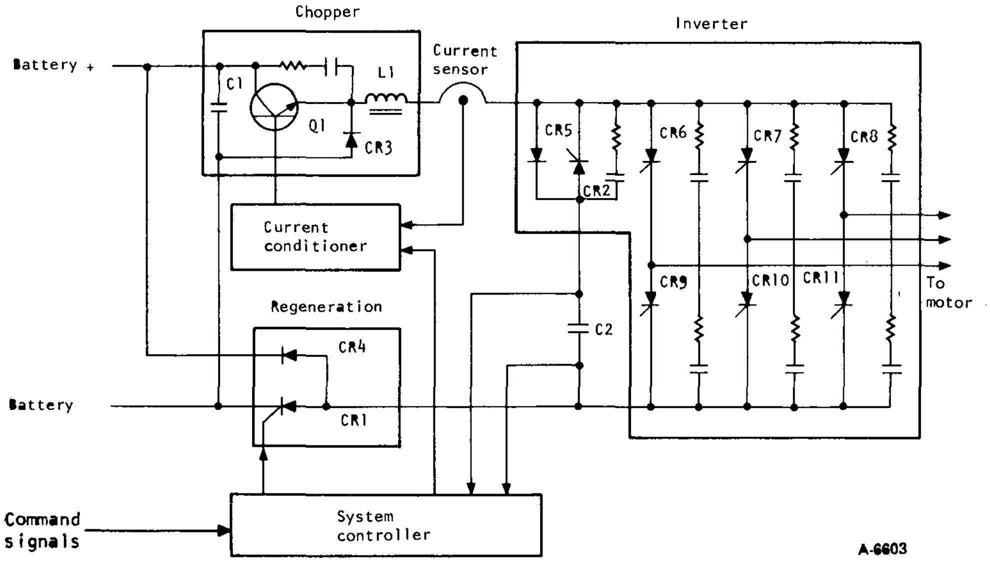
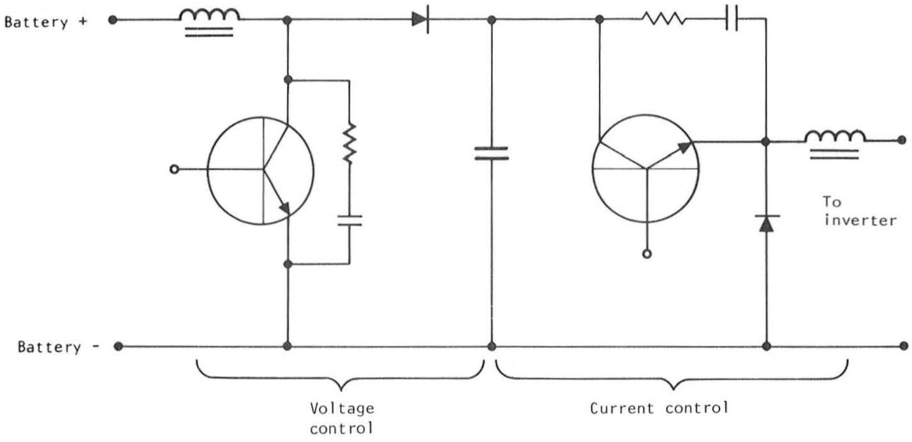
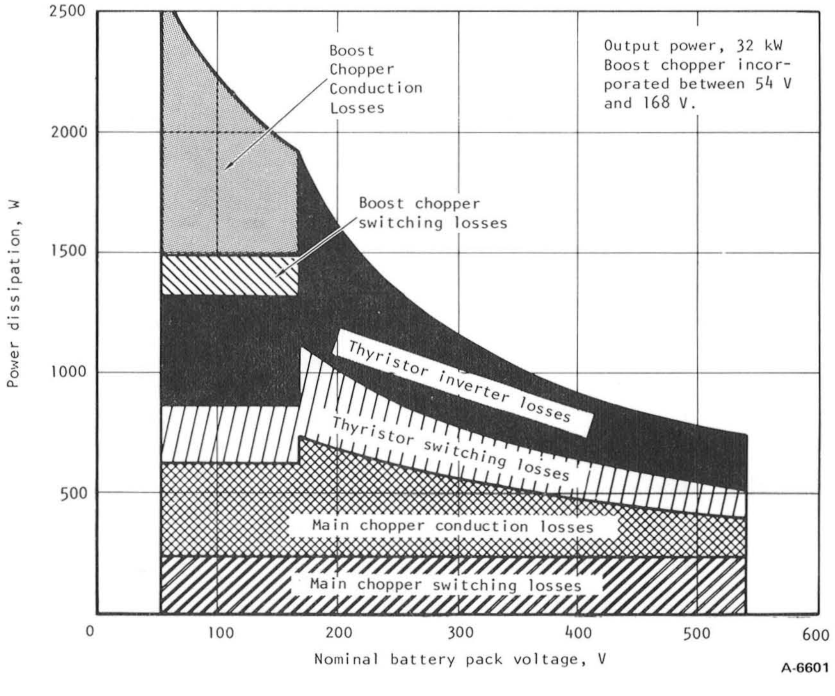


Figure 16.--Power circuit schematic diagram.



A-6607

Figure 17.--Combination chopper schematic diagram.



A-6601

Figure 18.--Power dissipation of power control unit vs battery pack voltage.

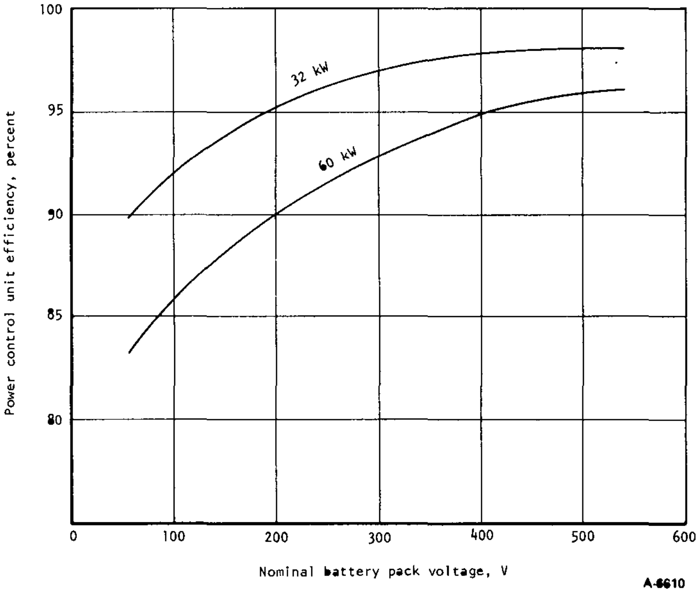


Figure 19.--Power control unit efficiency vs battery pack voltage.

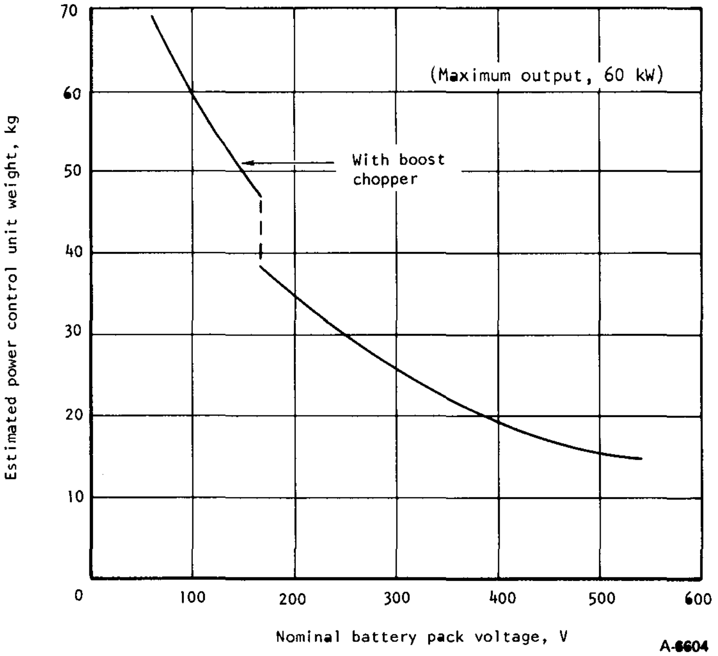


Figure 20.--Estimated power control unit weight vs battery pack voltage.

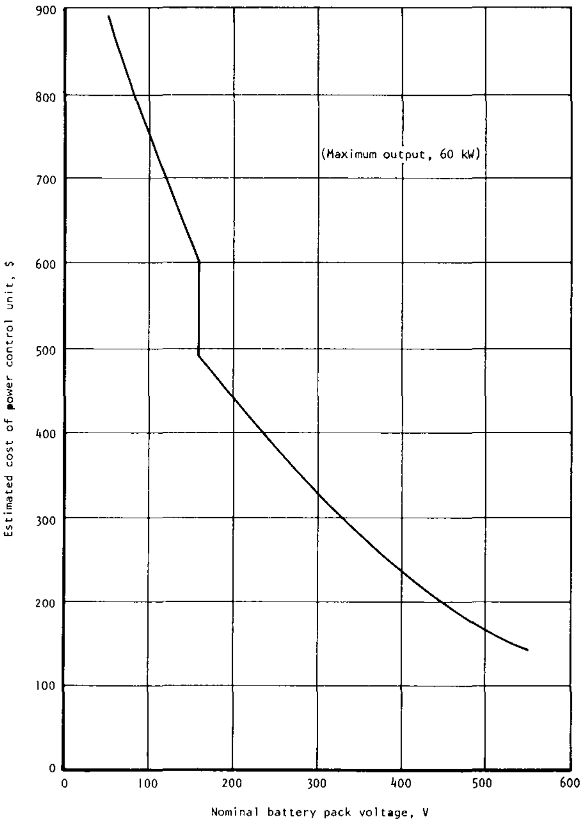


Figure 21.--Estimated power control unit cost vs battery pack voltage.

Traction motor.--The dc mechanically commutated motor with shunt field control was studied with the following basic performance parameters held constant: (1) Rating, 25 kW; (2) Base speed, 4000 rpm; and (3) Maximum speed, 8000 rpm.

Design studies were done for the dc traction motor over the full range of battery-pack voltage. A 4-pole motor design was used from 54 to 350 V, and a 2-pole design above 350 V. Losses are very high at low voltages because of the large currents required to achieve the rated power, as shown in figure 22. The operating efficiency of the motor is shown in figure 23 for both the maximum load of 24 kW and the typical cruising load of 10 kW.

The transition from a 4-pole to a 2-pole motor design is required because of commutation limits. These limits, in turn, are established by the size and spacing of the commutator bars, which are related to motor power and size. For a motor of greater output, the physical size would be greater, and the 4-pole design could be employed up to a greater voltage level. The combination of 400 V and 25 kW output, for instance, is not an optimum combination.

The estimated weight of the motor is shown in figure 24, and the corresponding estimated cost is shown in figure 25. System component costs are summarized in Appendix A.

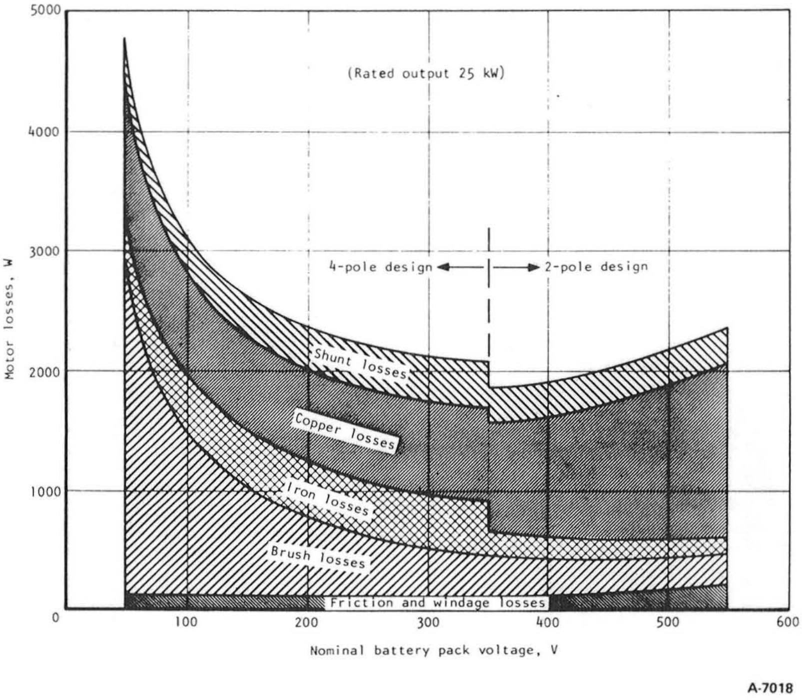


Figure 22.--Operating losses of dc traction motor vs battery pack voltage.

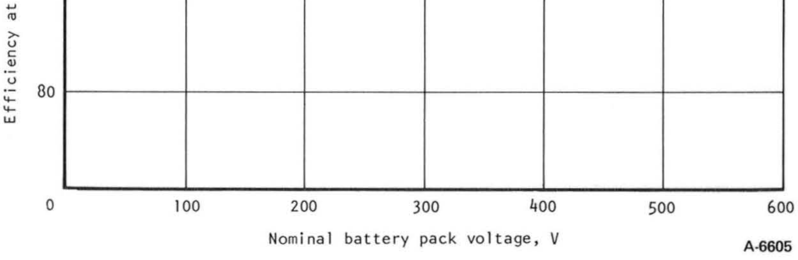


Figure 23.--Dc motor efficiency vs battery pack voltage.

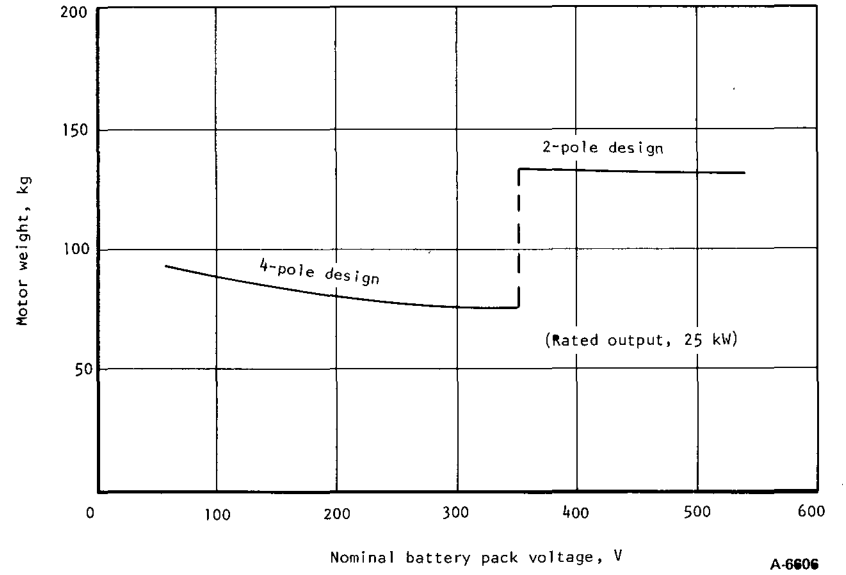


Figure 24.--Estimated dc motor weight vs battery-pack voltage.

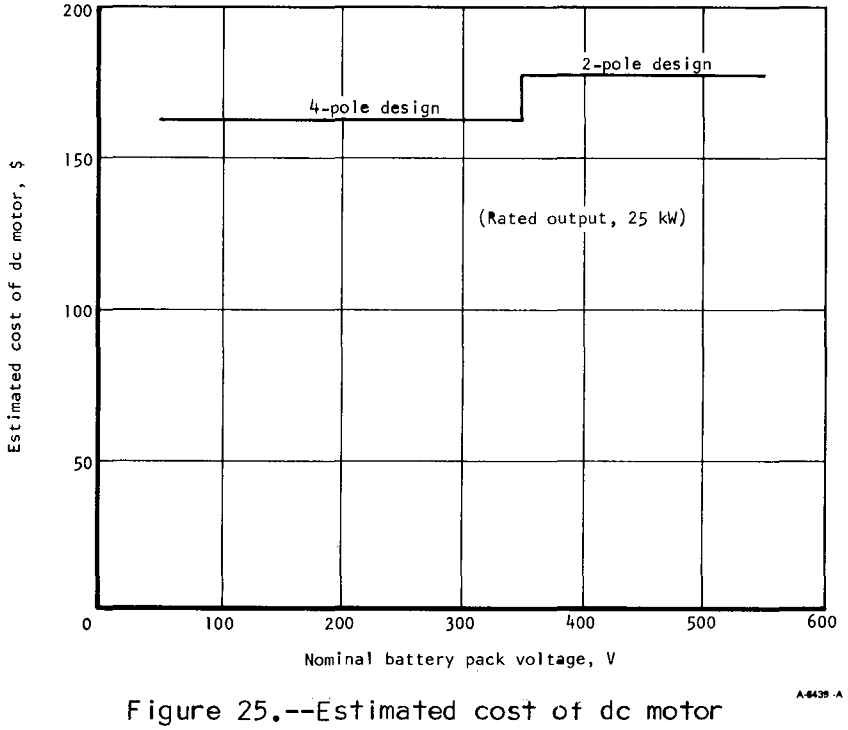


Figure 25.--Estimated cost of dc motor vs battery-pack voltage.

Power control unit.--The power control unit for the dc traction motor (figure 26) is not appreciably affected by the level of battery-pack voltage. The field chopper controls the shunt field current, and hence the shunt load, which, as was shown in figure 22, is nearly constant over the range of battery-pack voltage.

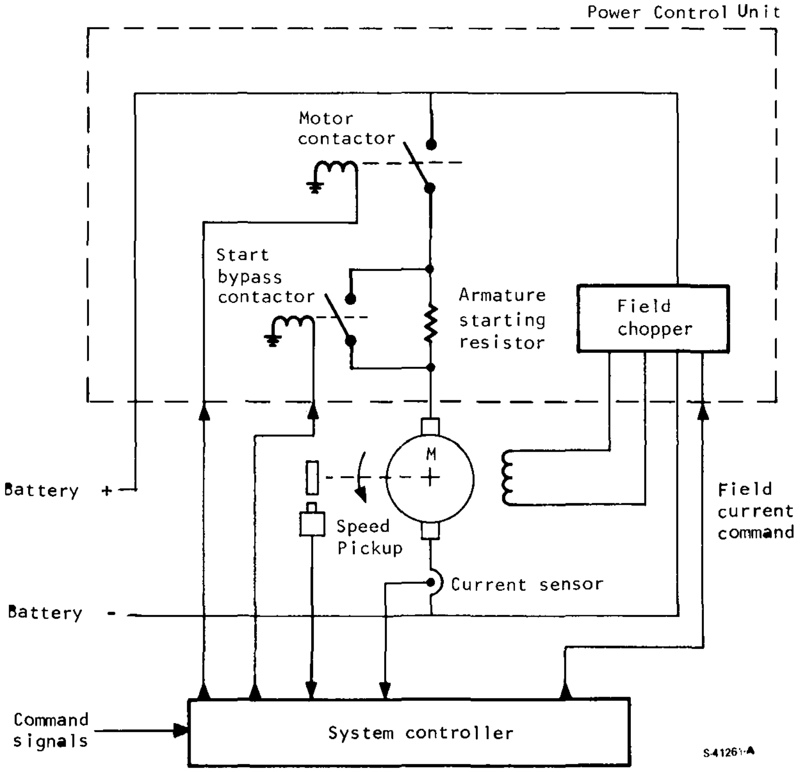


Figure 26.--Power control circuit.

The contactor is a switching device with arc suppresion, typical of devices for automotive service. The starting resistor is a current-limiting device used for only a few seconds during motor starting, then bypassed during normal operation. The bypass is closed by the controller in response to the motor speed and current signals. The effect of voltage on the contactors, cables, and connectors is discussed in the following section under the heading of switchgear.

Switchgear

A survey was made of commercial switchgear to establish the general trend of size and weight by voltage class. Most commercial equipment is designed for stationary service and is much larger and heavier than similar equipment designed specifically for vehicle use.

Two principal design criteria for this type of electric equipment are the creepage and clearance distances (ref. 33). The creepage distance is the shortest distance along an insulating surface between two conductors or between a conductor and ground, over which a current can flow along the surface of the insulation. The clearance distance is the minimum distance in air between two conductors or between a conductor and ground.

In general, the higher the operating voltage of the system the greater must be the spacing between conductive parts. In addition, environmental conditions and the type of service must be considered. For ground transportation equipment, reference 33 defines four classes, as discussed in detail in Appendix B. For automotive applications, Class II was selected as the most appropriate level. This classification is applicable to equipment that is reasonably clean and dry, but that requires some tolerance to the effects of moisture, residual brake and road dust, or to gases produced by switchgear.

When contacts are opened under load, arcing may occur. When switching a load between two live power sources, contact spacing must be great enough so that arcing is extinguished before transfer is completed--especially with reactive loads. Otherwise, arcing across the stationary contacts will short-circuit the power sources and melt or even explode the contacts if the voltage is high enough (ref. 36).

For contacts used in circuits above 250 V, an arc chute is usually provided to extinguish the arc formed as a result of actuating the contacts under load. This provision adds considerably to the size, weight, and cost of high-voltage switchgear. Although other design solutions are possible, they would be equally expensive.

At low voltages with large currents, the magnitude of the current makes large contacts inevitable. This requirement necessitates large and expensive switchgear for the low-voltage system. The large currents would also require the use of large cables and connectors. The connectors are assumed to be included in the switchgear cost. The cables are assumed to be a minor cost item. The design of the propulsion systems is so compact that cable runs are very short. The increase in cable cost at low voltage would be due to an increase in size, but not length. This increase was not considered to be significant in the overall cost.

The estimated cost of switchgear for an electric vehicle is shown in figure 27. There are a number of assumptions in this estimation. Costs are for switchgear designed especially for electric vehicle use, under class II conditions. The devices would be fully developed, and mass-produced in quantities for 100 000 vehicles per year. As are all costs in this study, costs are in 1976 dollars.

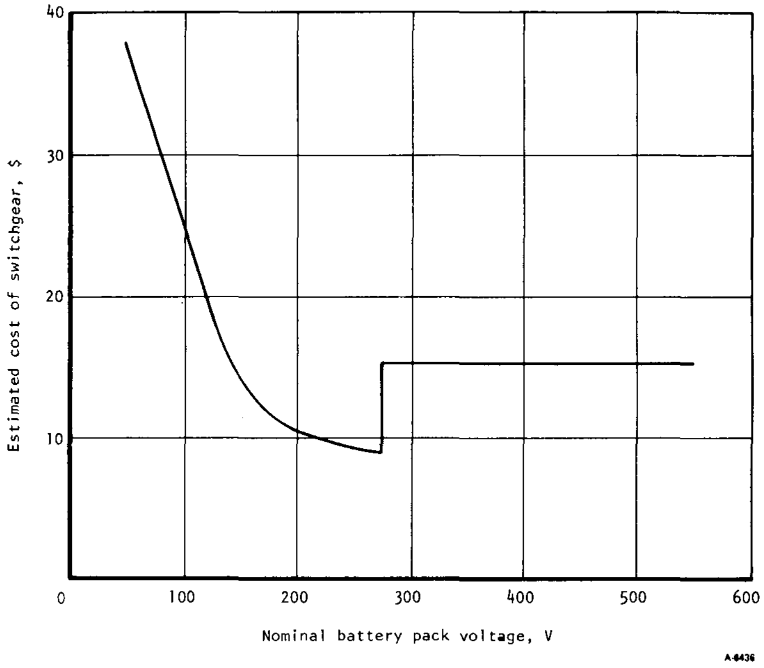


Figure 27.--Estimated cost of switchgear vs battery pack voltage.

Battery Charger

The statement of work required the assumption of a 220-V, 60-Hz, single-phase battery charger. The principal consideration in this study was the effect of battery-pack voltage on the physical specification of the battery charger. If it is possible to construct a lightweight battery charger, it can be incorporated into the vehicle for maximum convenience. However, if heavy transformers or other large components are required, the battery charger must be built as a fixed installation. The battery charger tradeoffs are discussed in Appendix C.

The effect that battery-pack voltage has on the charger is the requirement for a transformer or choke, which may dictate a charger that is too large to be conveniently installed in the vehicle. The cost of a propulsion system battery charger, on the other hand, is primarily a function of the complexity required for the charging cycle, rather than the battery-pack voltage level. The original study of the propulsion system costs did not include a battery charger, and battery charger costs have not been included in the voltage study comparisons.

LIFE-CYCLE COST ANALYSIS

The life-cycle cost analysis was done on the two propulsion systems selected for conceptual design studies using the various battery pack designs described in the battery pack voltage study. The analysis included the varying cost of both the propulsion system and the batteries, and it was found that the battery has the predominant effect: the cost of the battery pack is the major element in the acquisition cost, and battery replacement costs during the vehicle life far outweigh any other operating costs. The most significant cost tradeoffs, therefore, are those affecting battery cost and battery life.

Guidelines for Life-Cycle Cost Calculations

The following guidelines were established by the statement of work for use in the life-cycle cost calculations:

(1) Costs are calculated only for the propulsion system plus the battery; other vehicle costs, insurance, and taxes are not included.

(2) Costs are expressed in 1976 dollars.

(3) Acquisition cost is the sum of the OEM cost (manufacturing cost plus corporate level costs such as general and administrative, required return on investments of facilities and tooling, cost of sales,...) of components plus the cost of assembling the components plus the dealer markup, given as 17 percent. For the battery, total markup is 30 percent. Sales tax is not added to purchase price.

(4) Annual production is 100 000 units.

(5) Operating cost is the sum of maintenance costs plus repair costs plus electricity cost plus battery replacement costs.

(6) Electricity cost is 4 cents/kW-hr from the wall plug.

(7) Vehicle lifetime is 10 yr and 160 900 km.

(8) A constant noninflating dollar is used. No inflation factor is included in the discount rate; it is assumed that personal disposable income tracks inflation. A 2 percent discount rate for personal cars is used because it represents only time preference (opportunity cost).

(9) Cost of financing is not included in this procedure because it is assumed that the discounted present value of the sequence of total payments would approximately equal the original purchase price.

(10) All expenses are assumed to be costed at the end of each year. Year "Zero" is reserved for those costs that must be incurred before the vehicle is operated.

(11) Propulsion system salvage value is given as 2 percent of the purchase price, depleted battery salvage value is 10 percent of the purchase price, and used battery salvage is 50 percent of the purchase price prorated over the remaining life of the battery.

(12) In determining battery life it is assumed the vehicle is driven 16 090 km per year. For convenience in calculation, the distance is accumulated through successive SAE J227a schedule D driving cycles as follows: 400 trips per year of 16.1 km each; 150 trips of 48.3 km each; and 30 trips of 80.5 km each, charging after each trip. The battery cycle life is based on these trip profiles, field environmental effects, and the degradation due to the actual conditions imposed on the battery by the propulsion system and vehicle.

(13) The calculation of life-cycle cost follows the format of the required worksheets.

Purchase Price

The purchase price of each propulsion system variant was found from the manufacturing costs previously presented in the propulsion system design study, to which were added appropriate increases or decreases for voltage-related variations. The battery was treated as a separately acquired item for which the purchase price is the acquisition cost plus a 30 percent markup. The purchase price is the same for the battery required for periodic replacements, and the price was assumed to include installation.

Maintenance and Repair Costs

Maintenance is defined as scheduled action to maintain equipment in good operating condition. Repair is unscheduled action to correct some malfunction. The propulsion system components will require very little maintenance in comparison with such other vehicle components as tires and brakes. The battery will require periodic water level maintenance and the cleaning of terminals. Repair action is difficult to predict, but it appears from reliability considerations that the most probable repair actions will be for the electronic package. Maintenance and repair costs were assumed to be constant, equal to those established in the original propulsion system design study.

Battery Use and Replacement

Battery usage was determined in the previous propulsion system design study; the results for the 168-V system are presented in table 4. The percent of battery life consumed for each trip is based on the battery cycle-life. A battery that is capable of 1000 cycles to a depth of discharge of 70 percent, for example, is assumed to have expended 0.1 percent of its life for each trip that takes it to 70 percent depth of discharge. The battery is replaced when battery life is fully exhausted, based upon the designated driving trip schedule furnished in the guidelines (see item 12).

TABLE 5.--BATTERY CONSUMPTION AND CHARGING FOR A 168-V SYSTEM

Battery use	System		
	Basic system with lead-acid battery	Flywheel system with lead-acid battery	Flywheel system with nickel-zinc battery
Energy consumption for J227a (D) cycle, W-hr	210.7	232.2	208.1
Distance traveled in a J227a (D) cycle, km	1.65	1.64	1.64
Rate of energy consumption, W-hr/km	127.7	141.6	126.9
Battery depletion for a 16.1-km trip (depth of discharge), percent	7.29	7.66	7.96
Battery depletion for a 48.3-km trip (depth of discharge), percent	20.7	23.5	23.9
Battery depletion for a 80.5-km trip (depth of discharge), percent	33.8	39.3	39.0
Battery life, yr	2.5	5.1	3.3
Cost of battery charging per year, dollars	109.62	121.26	108.69

The basic system requires a battery having high specific power to achieve the required acceleration from 0 to 89 km/hr in 15 sec. As discussed in the section on lead-acid battery cycle life, achieving high specific power results in a compromise in cycle life. Therefore, the battery cycle life for lead-acid batteries in the life-cycle cost analysis for the basic system was assumed to be the same as that in the previous propulsion system design study. The data on specific energy and cost from the battery voltage study were used directly in the life-cycle cost analysis of the basic system, but the life was set at 2.50 yr, corresponding to 40 percent consumption per year.

The specific power of the nickel-zinc battery pack for the basic system is high enough to achieve the required acceleration from 0 to 89 km/hr in 15 sec without compromising the cycle life. The cyle life used for the nickel-zinc battery in both the basic system and the flywheel system is assumed to be 500 cycles to an 80 percent depth of discharge as given in Table 1.

For the flywheel system, high specific power is not required because the flywheel supplies peak power demands. The life of the lead-acid battery pack used in the life-cycle cost analysis was found by multiplying the life period (yr) used in the original propulsion system study by the ratio of the cycle life in the battery-pack voltage study to the original cycle life of 800 cycles.

The size of the battery pack required at each voltage level was found by multiplying the energy content for the original 168-V system by the ratio of the original system efficiency to the efficiency predicted for the system at a given voltage level. The battery cost is the product of battery pack energy capacity and the cost factor from Tables 2 and 3. (A sample cost calculation is included in Appendix A.)

Battery charging is based on the calculated ratio of energy consumption per cycle and the corresponding distance covered. Total energy consumption for a designated trip is the product of energy consumption per kilometer and the required trip length in kilometers. This energy is replaced by the battery charger, which is assumed to operate with an overall efficiency of approximately 75 percent. This low efficiency takes account of battery losses and inefficiency during topping-off at a low charge level. Because this number is small and is based on an estimate, no adjustment was made for the differences in energy consumption and battery charger operation at different voltage levels. Energy cost is 4 cents/kW-hr, as given in the guidelines.

Life-Cycle Cost Calculations

Life-cycle cost calculations were done for both the basic system and the flywheel system using the battery-pack designs developed in the battery-pack voltage study. The resulting minimum life-cycle cost with the lead-acid battery pack is presented in figure 28; with the nickel-zinc battery pack, in figure 29. In both figures the curve for the basic system shows a step at 168 V, which is the level at which a change is made to the voltage boost configuration.

Worksheets for various systems and voltage levels are presented in figures 30 through 37. A more detailed cost calculation example is included in Appendix A. All costs are in dollars except the life-cycle cost, which is in $/km.

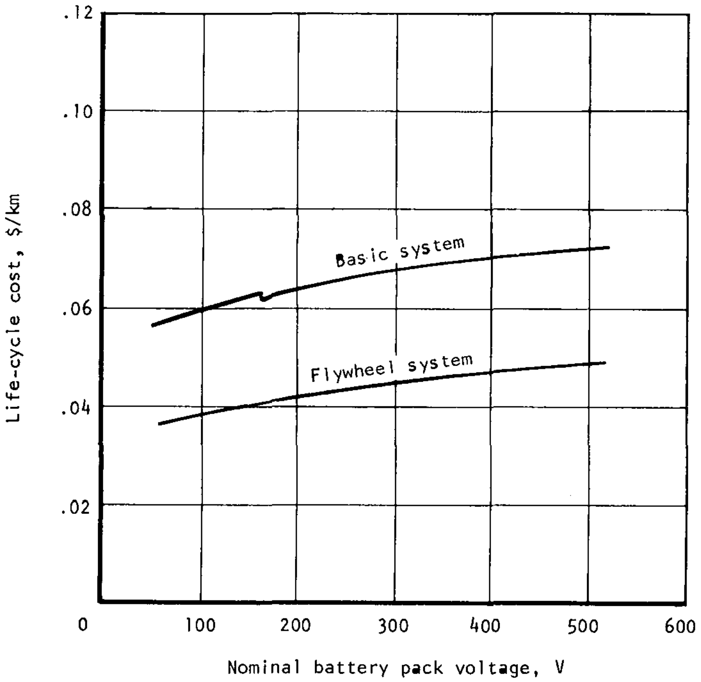


Figure 28.--Life-cycle cost of propulsion systems with lead-acid battery pack.

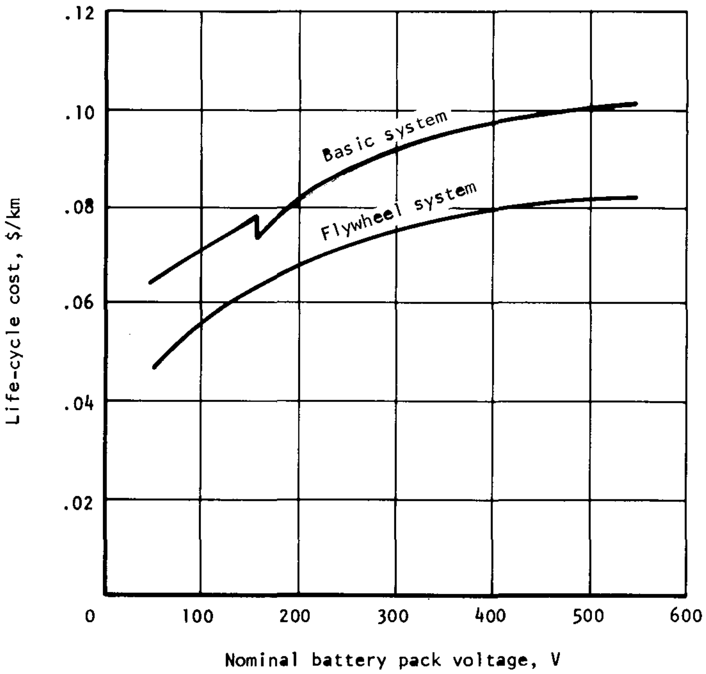


Figure 29.--Life-cycle cost of propulsion systems with nickel-zinc battery pack.

YEAR	"O"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	2886.00										
2 ELECTRICITY		121.26	121.26	121.26	121.26	121.26	121.26	121.26	121.26	121.26	121.26
3 REPAIR + MAINTENANCE		98.00	98.00	116.00	98.00	236.00	66.00	98.00	116.00	98.00	98.00
4 BATTERY REPLACEMENT			0	0	0	0	1360.00	0	0	0	
5 PROPULSION SYSTEM (MINUS)											-30.66
6 BATTERY SALVAGE (MINUS)			0	0	0	0	-136.00	0	0	0	-136.00
7 TOTAL	2886.00	219.26	219.26	237.26	219.26	357.26	1411.26	219.26	237.26	219.26	52.60
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	2886.00	214.87	210.71	223.50	202.60	323.68	1253.20	190.98	202.38	183.52	43.13

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 5934.57

S-40796-A

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0369

Figure 30.--Life-cycle cost in dollars for flywheel system with 54-V lead-acid battery pack.

YEAR	"O"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	4047.00										
2 ELECTRICITY		121.26	121.26	121.26	121.26	121.26	121.26	121.26	121.26	121.26	121.26
3 REPAIR + MAINTENANCE		98.00	98.00	116.00	98.00	236.00	66.00	98.00	116.00	98.00	98.00
4 BATTERY REPLACEMENT			0	0	0	0	2528.00	0	0	0	
5 PROPULSION SYSTEM (MINUS)											-30.42
6 BATTERY SALVAGE (MINUS)			0	0	0	0	-252.80	0	0	0	-252.80
7 TOTAL	4047.00	219.26	219.26	237.26	219.26	357.26	2462.46	219.26	237.26	219.26	-63.96
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	4047.00	214.87	210.71	223.50	202.60	323.68	2186.66	190.98	202.38	183.52	-52.45

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 7933.45

S-40796-A

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0493

Figure 31.--Life-cycle cost in dollars for flywheel system with 498-V lead-acid battery pack.

YEAR	"O"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	4251.00										
2 ELECTRICITY		109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62
3 REPAIR + MAINTENANCE		98.00	98.00	66.00	98.00	98.00	66.00	98.00	66.00	98.00	98.00
4 BATTERY REPLACEMENT			0	1380.00	0	0	1380.00	0	1380.00	0	
5 PROPULSION SYSTEM (MINUS)											-57.42
6 BATTERY SALVAGE (MINUS)			0	-138.00	0	0	-138.00	0	-138.00	0	-138.00
7 TOTAL	4251.00	207.62	207.62	1417.62	207.62	207.62	1417.62	207.62	1417.62	207.62	12.20
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	4251.00	203.47	199.52	1335.40	191.84	188.10	1258.85	180.84	1209.23	173.78	10.00

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 9202.03

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0572

S-40796-A

Figure 32.--Life-cycle cost in dollars for basic system with 54-V lead-acid battery pack.

YEAR	"O"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	3929.00	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2 ELECTRICITY	▨	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62
3 REPAIR + MAINTENANCE	▨	98.00	98.00	66.00	98.00	98.00	66.00	98.00	66.00	98.00	98.00
4 BATTERY REPLACEMENT	▨	▨	0	2504.00	0	0	2504.00	0	2504.00	0	▨
5 PROPULSION SYSTEM (MINUS)	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	-31.04
6 BATTERY SALVAGE (MINUS)	▨	▨	0	-250.40	0	0	-250.40	0	-250.40	0	-250.40
7 TOTAL	3929.00	207.62	207.62	2429.22	207.62	207.62	2429.22	207.62	2429.22	207.62	-73.82
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	3929.00	203.47	199.52	2288.33	191.84	188.10	2157.15	180.84	2072.12	173.78	-60.53

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 11 523.62

S-40796-A

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0716

Figure 33.--Life-cycle cost in dollars for basic system with 495-V lead-acid battery pack.

YEAR	"0"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	3149.00	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
2 ELECTRICITY	▨	108.69	108.69	108.69	108.69	108.69	108.69	108.69	108.69	108.69	108.69
3 REPAIR + MAINTENANCE	▨	98.00	98.00	116.00	66.00	236.00	98.00	66.00	116.00	98.00	66.00
4 BATTERY REPLACEMENT	▨	▨	0	0	1622.00	0	0	1622.00	0	0	▨
5 PROPULSION SYSTEM (MINUS)	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	-30.66
6 BATTERY SALVAGE (MINUS)	▨	▨	0	0	-162.20	0	0	-162.20	0	0	-162.20
7 TOTAL	3149.00	206.69	206.69	224.69	1634.49	344.69	206.69	1634.49	224.69	206.69	-18.17
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	3149.00	202.56	198.63	211.66	1510.27	312.29	183.54	1423.64	191.66	173.00	-14.90

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 7541.35

S-40796-A

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0469

Figure 34.--Life-cycle cost in dollars for flywheel system with 52-V nickel-zinc battery pack.

YEAR	"0"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	5325.00										
2 ELECTRICITY		108.69	108.69	108.69	108.69	108.69	108.69	108.69	108.69	108.69	108.69
3 REPAIR + MAINTENANCE		98.00	98.00	116.00	66.00	236.00	98.00	66.00	116.00	98.00	66.00
4 BATTERY REPLACEMENT			0	0	3806.00	0	0	3806.00	0	0	
5 PROPULSION SYSTEM (MINUS)											-30.42
6 BATTERY SALVAGE (MINUS)			0	0	-380.60	0	0	-380.60	0	0	-380.60
7 TOTAL	5325.00	206.69	206.69	224.69	3600.09	344.69	206.69	3600.09	224.69	206.69	-236.33
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	5325.00	202.56	198.63	211.66	3326.48	312.29	183.54	3135.68	191.66	173.00	-193.79

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 13 066.71

S-40796-A

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0812

Figure 35.--Life-cycle cost in dollars for flywheel system with 496-V nickel zinc battery pack

YEAR	"0"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	4526.00										
2 ELECTRICITY		109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62
3 REPAIR + MAINTENANCE		98.00	98.00	66.00	98.00	98.00	66.00	98.00	66.00	98.00	98.00
4 BATTERY REPLACEMENT			0	1655.00	0	0	1655.00	0	1655.00	0	
5 PROPULSION SYSTEM (MINUS)											-57.42
6 BATTERY SALVAGE (MINUS)			0	-165.50	0	0	-165.50	0	-165.50	0	-165.50
7 TOTAL	4526.00	207.62	207.62	1665.12	207.62	207.62	1665.12	207.62	1665.12	207.62	-15.30
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	4526.00	203.55	199.56	1569.08	191.81	188.05	1478.58	180.75	1421.16	173.73	-12.55

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 10 119.72

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0629

S-40796-A

Figure 36.— Life-cycle cost in dollars for basic system with 52-V nickel-zinc battery pack.

YEAR	"O"	1	2	3	4	5	6	7	8	9	10
1 PURCHASE PRICE	5285.00										
2 ELECTRICITY		109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62	109.62
3 REPAIR + MAINTENANCE		98.00	98.00	66.00	98.00	98.00	66.00	98.00	66.00	98.00	98.00
4 BATTERY REPLACEMENT			0	3860.00	0	0	3860.00	0	3860.00	0	
5 PROPULSION SYSTEM (MINUS)											-31.04
6 BATTERY SALVAGE (MINUS)			0	-386.00	0	0	-386.00	0	-386.00	0	-386.00
7 TOTAL	5285.00	207.62	207.62	3649.62	207.62	207.62	3649.62	207.62	3649.62	207.62	-209.42
8 DISCOUNT FACTOR	1.000	0.980	0.961	0.942	0.924	0.906	0.888	0.871	0.853	0.837	0.820
9 PRESENT VALUE (7 x 8)	5285.00	203.47	199.52	3437.94	191.84	188.10	3240.86	180.84	3113.13	173.78	-171.72

10 PRESENT VALUE OF LIFE CYCLE COST (SUM OF 9) = 16 042.76

S-40796-A

11 PRESENT VALUE OF LIFE CYCLE PER KILOMETER DRIVEN (10/TOTAL KM) = 0.0997

Figure 37.-- Life-cycle cost in dollars for basic system with 496-V nickel-zinc battery pack.

OPERATION, MAINTENANCE, AND SAFETY CONSIDERATIONS

Each selected voltage level of the battery pack imposes its own requirement for operation and maintenance of the propulsion system. Similarly, each voltage requires selective evaluation of special problems of safety that are voltage related, particularly high voltage. However, no attempt was made to study all aspects of operation and maintenance or of vehicle safety, but rather to determine what tradeoffs there were with regard to the selection of battery-pack voltage.

System Operation

The effects of battery-pack voltage on system operation were discussed above in the section dealing with system components. In general, propulsion system electrical efficiency is lower at low voltages (see figs. 19 and 23), requiring a compensating increase in battery-pack energy content. This requirement for more energy is offset to some extent by the greater specific energy of the low-voltage battery pack. The variation with voltage in system battery weight is shown in figure 38; the lead-acid battery packs are represented by the upper pair of lines, and the nickel-zinc battery packs by the lower pair.

The weight variation is small, but system weight does increase slightly with an increase in voltage. The increase in size and weight of the battery pack slightly degrades system performance, the effect being greater for the basic system than for the flywheel system. Compared to performance at the designed 168 V, the estimated reduction in range with a 500-V battery pack is 2 percent for the basic system and 0.5 percent for the flywheel system.

System Maintenance

The effects of battery-pack voltage on system maintenance are primarily associated with the fact that, for a given power requirement, the lower the voltage level the greater the current. Large currents require large cables, large electrical contacts, massive connectors, and large commutator brushes. Such equipment usually requires more maintenance than equipment associated with low currents, and the large devices required for the high currents can be difficult to handle and service. However, these problems are not of major importance, for there are many types of high-current devices routinely in service in both transit vehicles and stationary systems.

For the battery pack, the required voltage is achieved by assembling many cells in series. Although these cells are of identical construction, there will be some difference in individual capacity. As the battery pack is repeatedly charged and discharged, the cells can become unequally charged. This imbalance within the battery pack limits the total energy available and degrades system performance. Consequently, special effort must be devoted to maintaining a fully balanced charge. The greater number of cells makes this effort proportionally greater for a high-voltage system than for one of low voltage.

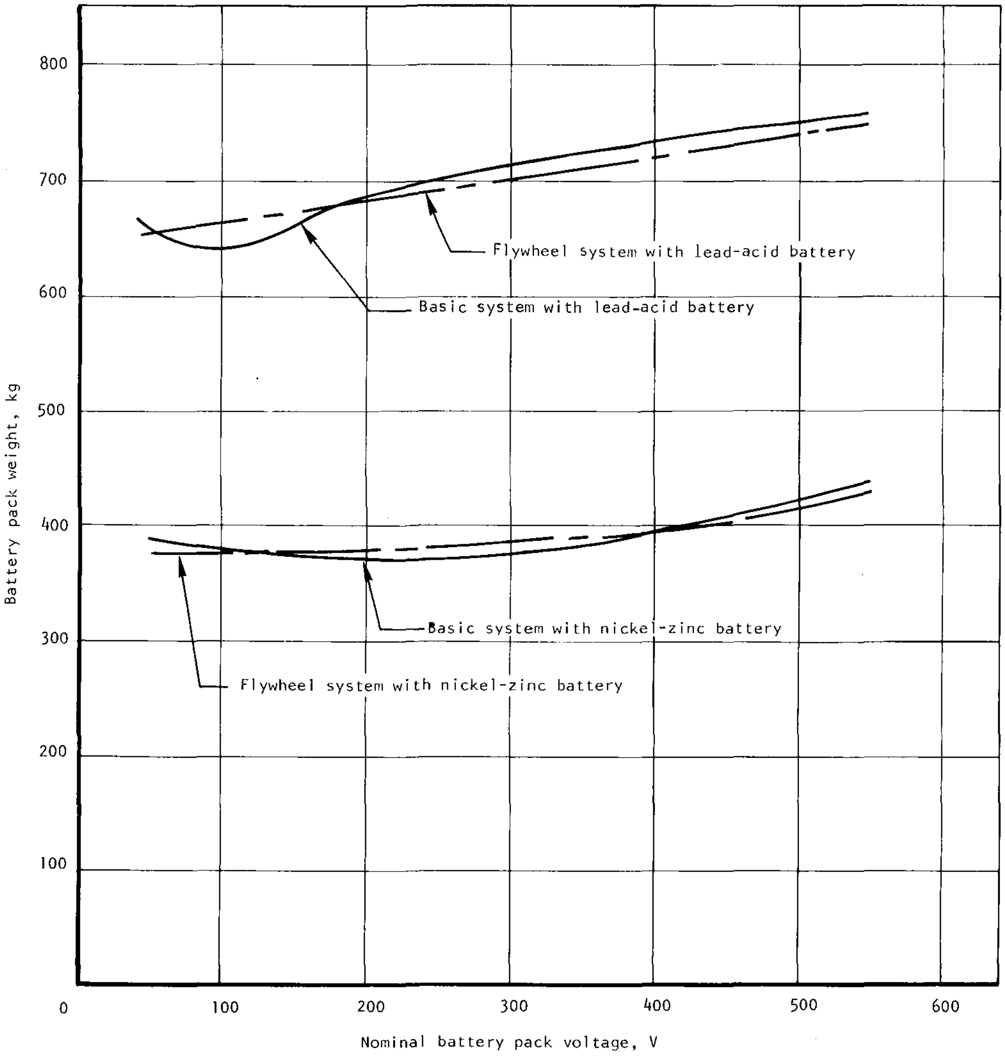


Figure 38.--Effect of voltage on battery-pack weight.

The hazards of working on a high-voltage system are greater than those for a low-voltage system, as is discussed in the following section. These greater hazards increase the difficulty and expense of maintenance to some degree, requiring more elaborate safety procedures, special training of personnel, and special tools and equipment.

System Safety

No definite correlation was found between battery-pack voltage and system safety requirements. As noted in Appendix D, any voltage above 50 V can produce a lethal shock if a person becomes part of the electrical circuit. The resulting hazard is proportional to the current that passes through the body, rather than to the voltage. However, for a given impedance of a human body, the higher the voltage the higher the current. Therefore, the hazard of injury due to electrical shock may be considered greater at high voltage than at low voltage even though the likelihood of actually receiving a shock may be low.

In addition to direct personal injury from shock, other hazards that could be voltage-related are: damage to the propulsion system and loss of system function. There are many design criteria and safety provisions that are specified for electrical systems and are based on the system operating voltage level. If these specifications are followed in the design, the result should be an electrical system that is equally safe at any voltage.

DISCUSSION OF RESULTS

The general trend in voltage levels for electric propulsion systems has been toward higher voltages (ref. 1). This trend has favorably affected the design of propulsion system electrical equipment, as was indicated in this study. The optimum voltage of the electrical system appears to be above 250 V for either an ac system or a dc system. The study was directed toward two specific propulsion systems, but the trends should apply to other configurations with similar equipment.

The study results for the 24 kw-hr battery pack reveal that all the factors studied--specific energy on a mass basis, specific energy on a volume basis, and cost--are optimized at the lowest battery pack voltage considered, 54 V. Battery cost increases by a factor of two up to 350V, after which it is constant. Specific energy decreases by 20-30% as the voltage increases from 54 to 540V. Under these circumstances the incentive is to operate at 54 V.

When the battery data is combined with the electrical equipment data, the influence of the battery cost is the overriding factor. The battery-pack cost is minimum at 54 V, and by such a margin that it overbalances the higher electrical equipment costs, giving the lowest total system cost at 54 V. When considering life cycle cost, the battery cost is even more influential, because the battery must be replaced several times during the life of the system.

The study of system operation, maintenance, and safety did not produce any data that materially influence the selection of system voltage level. Any voltage above 50 V can be hazardous, though the danger may increase with voltage. The hazard is related to current, rather than directly to voltage, but when a person inadvertently becomes part of an electric circuit, the higher the voltage the higher the current.

In all the studies of system performance and cost, the flywheel system was superior to the basic system. This superiority results from lower estimated component cost and the need for only one battery replacement, compared with three battery replacements projected for the basic system, over life of the propulsion system.

The study of the propulsion system battery charger showed that charger cost was primarily a function of the complexity of the required charging cycle. Battery-pack voltage affected the requirement for a transformer or a choke, which may dictate the ability of the charger to be installed in the vehicle. For an onboard charger, battery pack voltage should be within the limits of 54 to 108V for charger input of 115V, 60 Hz or 150 to 250V for charger input of 220 V, 60 Hz.

VOLTAGE RECOMMENDATIONS

Although the use of a 54-V battery pack appears optimum, there do appear to be some drawbacks to the low-voltage propulsion system. Electrical losses are very high, heavy cables are required for the high currents, and high-current components are necessary throughout the system. The penalties and costs of the propulsion system are outweighed by the economics of the battery pack, but the electrical design problems are considered undesirable by equipment designers even though solutions are feasible.

An increase in battery-pack voltage to 96 V provides a large improvement in electrical system efficiency at a relatively modest increase in system cost. This voltage level, 96 V, is a convenient multiple of a 6-V or 12-V standard battery module. The improvement in electrical system design is considered to be worth the increase in cost; accordingly, the recommended voltage for the battery pack is 96 V.

APPENDIX A

SUMMARY OF COST CALCULATIONS

The voltage study separately examined the effects of battery-pack voltage on the cost of the battery pack and the propulsion system components. This information was then combined with propulsion system costs previously established for the basic system and the flywheel system (using a battery-pack voltage of 168 V) to arrive at the new system costs at other voltage levels.

Component Costs

The manufacturing costs of system components were estimated for use in the original system comparisons, and modified for variable battery pack voltages. These are presented in tables A1 and A2.

Manufacturing cost was defined as the cost of direct labor, materials, and tooling, and includes the cost of acquiring small parts to fabricate and assemble the major components. Manufacturing cost does not include any corporate level costs, overhead, cost of sales, etc. The cost estimates for the indicated components are based on anticipated production of 100 000 vehicles a year, with production commencing after completion of development. Costs of standard items available for automotive service are derived from reference 21. Costs of other mass-produced parts are found in reference 22, and electronic parts are covered in reference 23, though the data base is not the same in each case. Some information was also available for the Near-Term Electric Vehicle program (ref. 3).

TABLE A1--ESTIMATED COMPONENT COSTS FOR THE BASIC SYSTEM (1976 DOLLARS)

	Battery Pack Voltage					
Component	50	100	200	300	400	500
Motor/generator	290	290	290	290	290	290
Electronics	887	750	445	330	238	170
Transmission/differential	233	233	233	233	233	233
Switchgear	35	24	10	15	15	15
Miscellaneous	18	18	18	18	18	18
Total Manufacturing Cost	1463	1315	996	886	794	726

TABLE A2--ESTIMATED COMPONENT COSTS FOR THE FLYWHEEL SYSTEM (1976 DOLLARS)

Component	Battery Pack Voltage					
	50	100	200	300	400	500
Motor/generator	162	162	162	162	178	178
Electronics	75	75	75	75	75	75
Transmission/differential	233	233	233	233	233	233
Flywheel	225	225	225	225	225	225
Switchgear	35	24	10	15	15	15
Miscellaneous	48	48	48	48	48	48
Total Manufacturing Cost	778	767	753	758	774	774

The effect of battery-pack voltage on component costs is limited to the motor/generator, electronics and switchgear. The incremental effect on system cost can be found by comparing component costs at any voltage level with those for the 168-V systems.

Battery Cost

To calculate battery cost, the battery energy requirements must first be defined. The requirements for a 168-V system were established in the original study; these are presented in table A3.

For the basic system, the power control unit is the only component that changes in operating characteristics with battery-pack voltage. The efficiency of the controller was presented in figure 19. At the rated output of 32 kW, the efficiency is 94 percent at 168 V and 90 percent at 54 V. The required battery pack energy at 54 V is estimated by applying the efficiency ratio to the energy given for the battery pack at 168 V; thus:

$$\text{Energy at 54 V} = 26\,680(94/90) = 27\,866 \text{ W-hr}$$

TABLE A3.--BATTERY REQUIREMENTS
FOR A 168-V SYSTEM

Performance requirement	Basic system	Flywheel system
Weight of battery pack to meet range of 161 km with SAE J227a schedule D cycle, kg	671	567
Weight of battery pack to meet range of 209 km at constant 72 km/hr, kg	584	667
Weight of battery pack to meet acceleration of 0 to 89 km/hr in 15 s, kg	671	567
Required battery pack weight to meet all requirements, kg	671	667
Energy content of required battery pack at the 3-hr rate, W-hr	26 680	26 520
Cost of required battery pack, $	1342	1334

Using the data presented in table 2, a portion of which is shown below, a specific battery design is selected for a trial calculation.

Number of cells	Positive plate thickness, mm	Number of positive plates	Height-to-width ratio	Specific energy, W-hr/kg	Cost factor, $/kW-hr	Cycle life, cycles	Specific energy, W-hr/liter	System voltage, V
27	7.5	10	1.10	42.31	41.43	697	94.93	54.80
27	7.5	7	1.10	42.10	38.93	697	93.28	54.78
27	8.3	6	1.10	41.73	38.09	799	91.95	54.53
27	9.3	6	1.10	41.09	38.32	949	89.96	54.32
27	9.3	7	1.10	41.40	38.32	949	91.62	54.28
27	9.3	8	1.10	40.89	40.32	949	89.58	54.42
27	7.9	8	1.10	42.05	39.64	746	93.67	54.67
49	7.5	7	1.10	41.27	46.05	697	93.76	95.89
49	7.9	8		[illegible]	47.85	746	93.92	95.63
51	7.5				[illegible]	697	93.66	99.62
53	[illegible]				[illegible]	799	89.09	102.85
[illegible]						[illegible]	87.84	102.58

Selected design

In some cases, several battery designs had to be tried to find the one that yielded the lowest life-cycle cost. In this case, for a nominal battery pack voltage of 54.5 V, the principal factors are:

Specific energy = 41.73 W-hr/kg

Cost factor = $38.09/kW-hr

The resulting battery pack weight is:

Weight = (27 866 W-hr)/(41.73 W-hr/kg) = 668 kg

The corresponding cost is:

Cost = (27.866 kW-hr)($38.09/kW-hr) = $1061

Comparing these values with those in table A3 reveals that the cost of the battery pack is $281 less, while the weight is only 3 kg lighter. Because there is so little change in weight, no adjustment of the battery energy content was made for change in vehicle weight.

System Purchase Price

The purchase price of each propulsion system may be found from the manufacturing costs presented above in tables A1 and A2, to which must be added the appropriate business costs. The battery is treated as a separately acquired item for which the purchase price is the acquisition cost plus a 30 percent markup. The costs are tabulated in table A4 for the basic and the flywheel systems with lead-acid batteries at a voltage of 168 V. The battery purchase price is also the replacement price of the battery required for periodic replacements, and the price is assumed to include installation.

Propulsion system component costs and the battery cost for systems at different voltage levels are found in the manner described in the preceding paragraphs. The total purchase price of each system is then found by the procedure shown in table A4.

TABLE A4.--PURCHASE PRICE OF PROPULSION SYSTEMS WITH 168-V LEAD-ACID BATTERY PACK (1976 DOLLARS)

Cost item	Basic system	Flywheel system
Manufacturing cost of propulsion system	1046	755
Manufacturing overhead (22%)	230	166
Cost of sales	1276	921
General and administrative (25%)	319	230
Cost of propulsion system	1595	1151
Return on investment (10%)	160	115
Wholesale price	1755	1266
Dealer markup (17%)	298	215
Purchase price of propulsion system	2053	1481
Battery cost	1342	1334
Battery markup (30%)	403	400
Battery purchase price	1745	1734
Total purchase price	3798	3215

APPENDIX B

SWITCHGEAR CONSIDERATIONS

A survey was made of commercial switchgear to establish the general trend of size and weight by voltage class. Most commercial equipment is designed for stationary service and is much larger and heavier than similar equipment designed specifically for vehicle use. Weight and volume for equipment rated at 60 kW is shown in figure B1, and typical costs for single items of equipment are shown in figure B2.

Two principal design criteria for heavy duty electrical equipment are the creepage and clearance distances (ref. 33). The creepage distance is the shortest distance along an insulating surface between two conductors or between a conductor and ground, over which a current can flow along the surface of the insulation. The clearance distance is the minimum distance in air between two conductors or between a conductor and ground.

Adequate creepage distance prevents or limits leakage currents. Leakage current flows only through conductive contaminants on an insulator surface. If the insulator can be kept clean and dry, creepage distance need not be greater than the clearance. But insulators subject to surface contamination require creepage distances exceeding the clearance. Creepage depends on the amount and nature of the contaminants and on insulator material characteristics (ref. 34).

The direct path of an electrical arc through the air during flashover is the clearance distance. To provide voltage-transient protection, the clearance through air between two conductive parts must be greater than that called for by the working voltage. But peak expected transient voltage must be known in order to specify clearance.

Voltage ratings are generally established according to either breakdown voltage or terminal spacing. Breakdown voltage is determined by a high-potential test in which the voltage difference between adjacent terminals is increased until current flashes between terminals or between a terminal and ground. The operating voltage rating is then established as a fraction of the breakdown voltage. Most terminal block manufacturers, for example, use one-third breakdown potential as the operating-voltage rating for blocks rated below 600 V (ref. 35).

In general, the higher the operating voltage of the system the greater must be the spacing between conductive parts. In addition, environmental conditions and the type of service must be considered. For ground transportation equipment, reference 33 defines four classes:

Class I.--This classification is applicable to equipment that is clean and dry and that may reasonably be expected to remain so. For example:

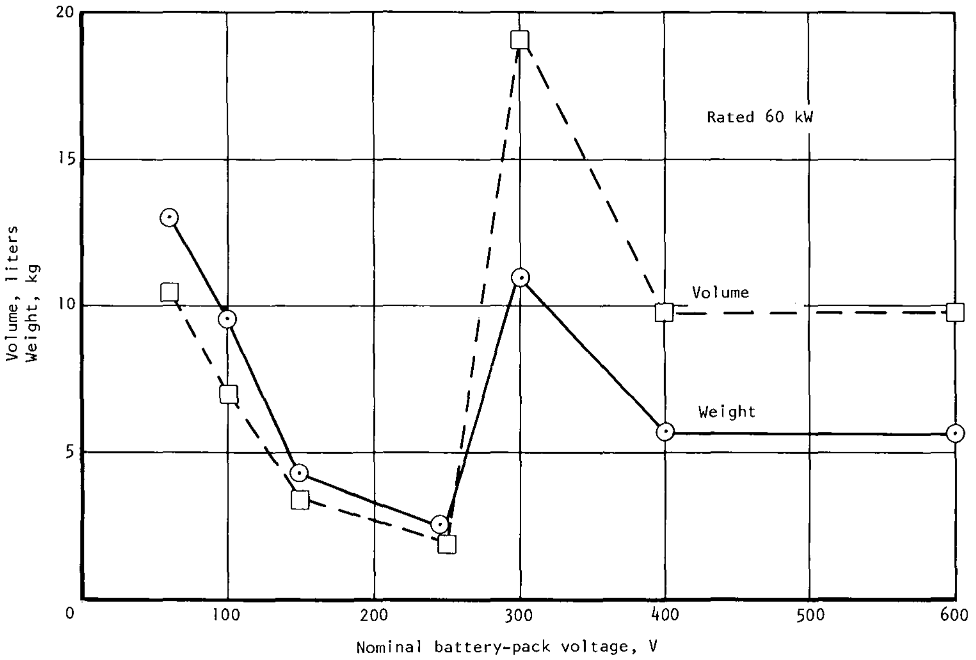


Figure B1.--Commercial switchgear weight and size vs battery pack voltage.

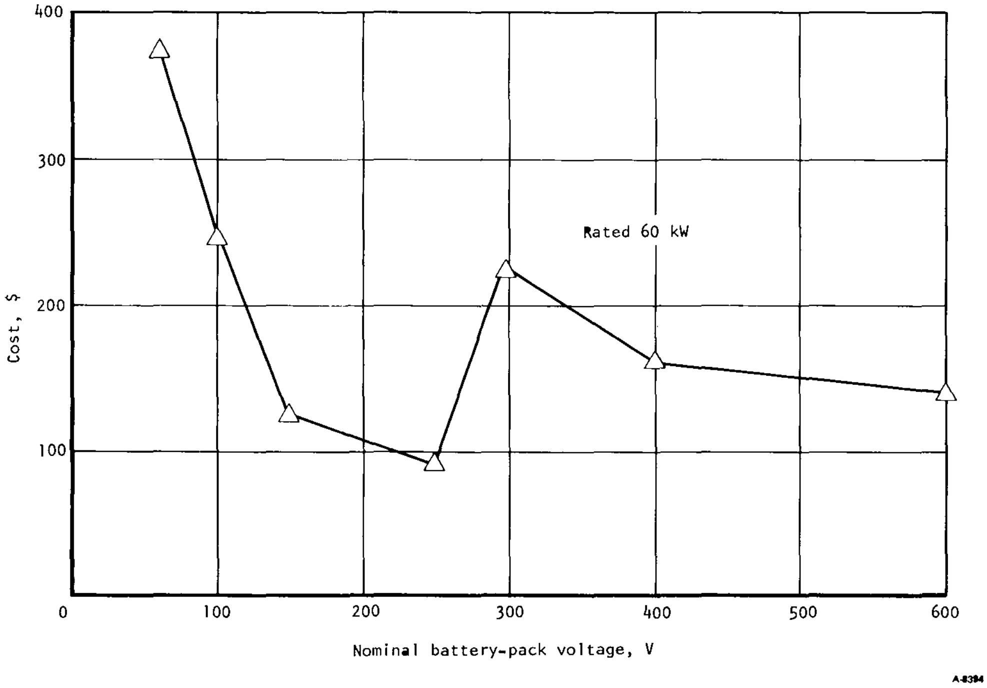


Figure B2.--Commercial switchgear cost vs battery pack voltage.

(1) Equipment that is housed in NEMA type 4 enclosures or that is otherwise protected to an equivalent degree

(2) Convection-cooled electronic control equipment located inside the vehicle, protected against dirt, moisture, and the intrusions of contamination incidental to interior vehicle cleaning

Equipment so housed, but which includes components that during normal operation produce gases or other contaminants, e.g., unsealed contactors or brush-type motors, are considered to belong to class II.

<u>Class II</u>.--This classification is applicable to equipment that is reasonably clean and dry, but that requires an increased tolerance to the effects. of moisture, residual brake and road dust, or to gases produced by switchgear; for example:

(1) Control equipment mounted under the vehicle, housed in well-gasketed enclosures cooled by filtered air drawn from inside the vehicle or from a clean exterior location

(2) External terminal posts well protected by tape or tight-fitting boots

<u>Class III</u>.--This classification is applicable to equipment that is exposed to the atmosphere but that is not subjected to extremely adverse conditions; for example:

(1) Brake resistors

(2) Properly louvered equipment enclosures, without forced-air cooling, mounted under the vehicle or on the roof

(3) Controllers of switched resistor propulsion systems

<u>Class IV</u>.--This classification is applicable to equipment operating under especially adverse conditions for which the spacings given for classes I, II, and III may be inadequate. Such equipment must be subjected to individual analysis to establish the required clearance and creepage distances. Examples of such equipment are:

(1) Wood third-rail shoe beams, where low resistance to tracking, high levels of contamination, flammability, and arcing combine to form a worst case

(2) Equipment enclosures in which considerable contamination can be expected to accumulate; for example, enclosures blown with air taken from under the car (or low sides) in which one or more of the following conditions prevails: poor filter efficiency, lack of positive pressure, horizontal insulating surfaces facing up, etc.

Minimum spacings have been established (ref. 33) for clearance and creepage distances, and typical values are shown in table B1. There are, however, a number of exceptions and limitations to the normal design requirements for which special procedures are required. The spacings specified in table B1 do not apply in the following cases:

(1) In the presence of ionized gas, where considerably larger distances may be required

(2) Inside encapsulated assemblies, where considerably smaller distances may be adequate

(3) To printed circuit cards with governing voltages less than 150 V

(4) To spacings between open contacts of switchgear

This last case introduces important considerations. When a pair of contacts is installed in an electrical circuit, the contact design depends on the type of load. Contacts are designated dry if their switching action does not start or stop current flow. However, dry contacts may carry current after they close and before they open. If initial contact interface resistance is high, appreciable voltage may appear across closed contacts when some other part of the circuit is closed. This resistance may decrease sharply or change very little, depending on contact surface condition.

TABLE B1.--MINIMUM SPACINGS BETWEEN CONDUCTORS IN TRANSPORTATION EQUIPMENT

Governing voltage, V	Clearance in air (strike), mm			Creepage distance , mm		
	Class I	Class II	Class III	Class I	Class II	Class III
0 to 50	3.2	4.8	6.4	3.2	6.4	9.5
51 to 150	3.2	6.4	9.5	6.4	12.7	17.4
151 to 249	6.4	9.5	12.7	9.5	17.4	31.8
250 to 400	12.0	19.0	25.0	13.0	30.0	60.0
400 to 550	12.0	19.0	29.0	16.0	35.0	60.0

When contacts are opened under load, arcing may occur. When switching a load between two live power sources, contact spacing must be great enough so that arcing is extinguished before transfer is completed--especially with reactive loads. Otherwise, arcing across the stationary contacts will short-circuit the power sources and melt or even explode the contacts if the voltage is high enough (ref. 36).

Contact arcing is the major cause of relay failure. Once a dc arc is established across stationary contacts, it persists until the contacts are destroyed. Below 400 Hz the arc extinguishes as voltage passes through zero. At higher frequences, however, voltage can again increase and restrike the arc before the contact gap is deionized (ref. 36).

Arcing results from several conditions. Contact-to-contact or contact-to-case arcing can occur, for example, in hermetically sealed relays when repeated switching builds up ionization in the captive atmosphere.

Arcing caused by exceeding contact ratings is avoided simply by selecting a relay with adequate spacing and insulation between poles for the switching application. However, eliminating arcing caused by switching inductive dc loads is more complex. The traditional solution is to provide a discharge path across the inductance (ref. 36).

For contacts used in circuits above 250 V, an arc chute is usually provided to extinguish the arc formed as a result of actuating the contacts under load. This provision adds considerably to the size, weight, and cost of high-voltage switchgear, as can be seen in figures B1 and B2.

At low voltages with large currents, the magnitude of the current makes large contacts inevitable. This requirement necessitates large and expensive switchgear for the low-voltage system.

The estimated cost of switchgear for electric vehicle use under class II conditions is assumed to bear a similar relation to voltage as commercial switchgear. However, unit cost would be very much lower, because the devices would be fully developed, and mass-produced in quantities for 100 000 vehicles per year.

APPENDIX C

BATTERY CHARGER CONSIDERATIONS

The statement of work established the requirement for a 220-V, 60-Hz, single-phase battery charger. No requirement was established as to the size, weight, or efficiency of the charger. The principal consideration in this study was the effect of battery-pack voltage on the physical specification of the battery charger. If it is possible to construct a lightweight battery charger, it can be incorporated into the vehicle for maximum convenience. However, if heavy transformers or other large components are required, the battery charger must be built as a fixed installation.

Charging duty.--The charging duty for the battery charger has not been specified. However, the usual requirement is 8 hr charging for an 80-percent-depleted battery. If an energy input of approximately 24 kW-hr is required in the 8-hr period, then the average charge rate is 3000 W. With a nominal charging voltage of 220 V, the average current is 13.6 A, which is well within the rating of a typical 220-V service. Most charging procedures use an initial high-charge rate that tapers to a lower rate as the battery reaches full charge (ref. 37).

Charging potential.--The typical simplified battery charger employs a rectifier, usually a full-wave rectifier, which produces a voltage characteristic as shown in figure C1.

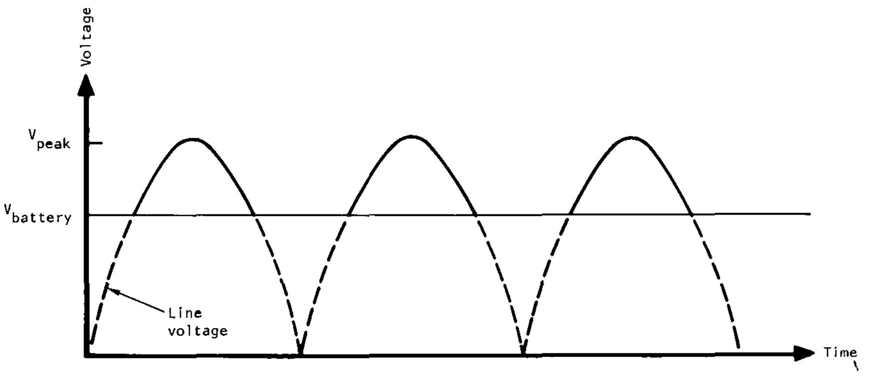


Figure C1.--Typical rectifier waveform.

It is apparent that the potential for charging is the difference between the line voltage and the battery voltage, which occurs for only a portion of the total cycle. When this difference is small, or if the battery voltage actually exceeds the peak voltage, then a transformer must be used to obtain a higher supply voltage. When the difference is large, as is the case with low battery voltage, a step-down transformer, choke, or other device may be required to prevent excessive currents due to the large charging potential. The need for line voltage conditioning is likely to require equipment too heavy for an onboard vehicle battery charger.

When the line voltage is within a reasonable range compared with the battery voltage, then a number of techniques can be used to moderate the voltage peaks and produce a smooth charging current. The voltage of the battery charger must be sufficiently above the battery voltage to induce the charging current, as is indicated in figure C2.

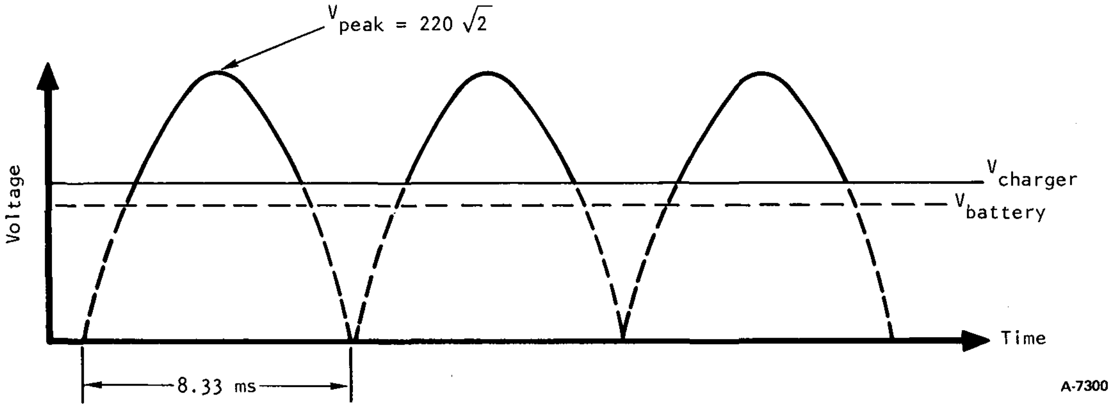


Figure C2.--Battery charger voltage conditions.

Rectifier circuit.--A typical schematic diagram for a battery charger employing a rectifier is shown in figure C3. This charger operates on the basic scheme of a fullwave rectifier driving current through an inductor.

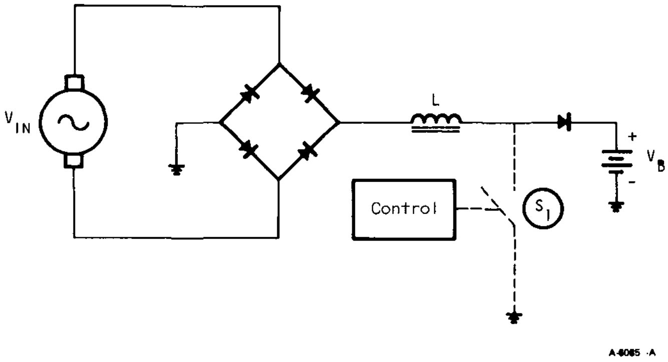
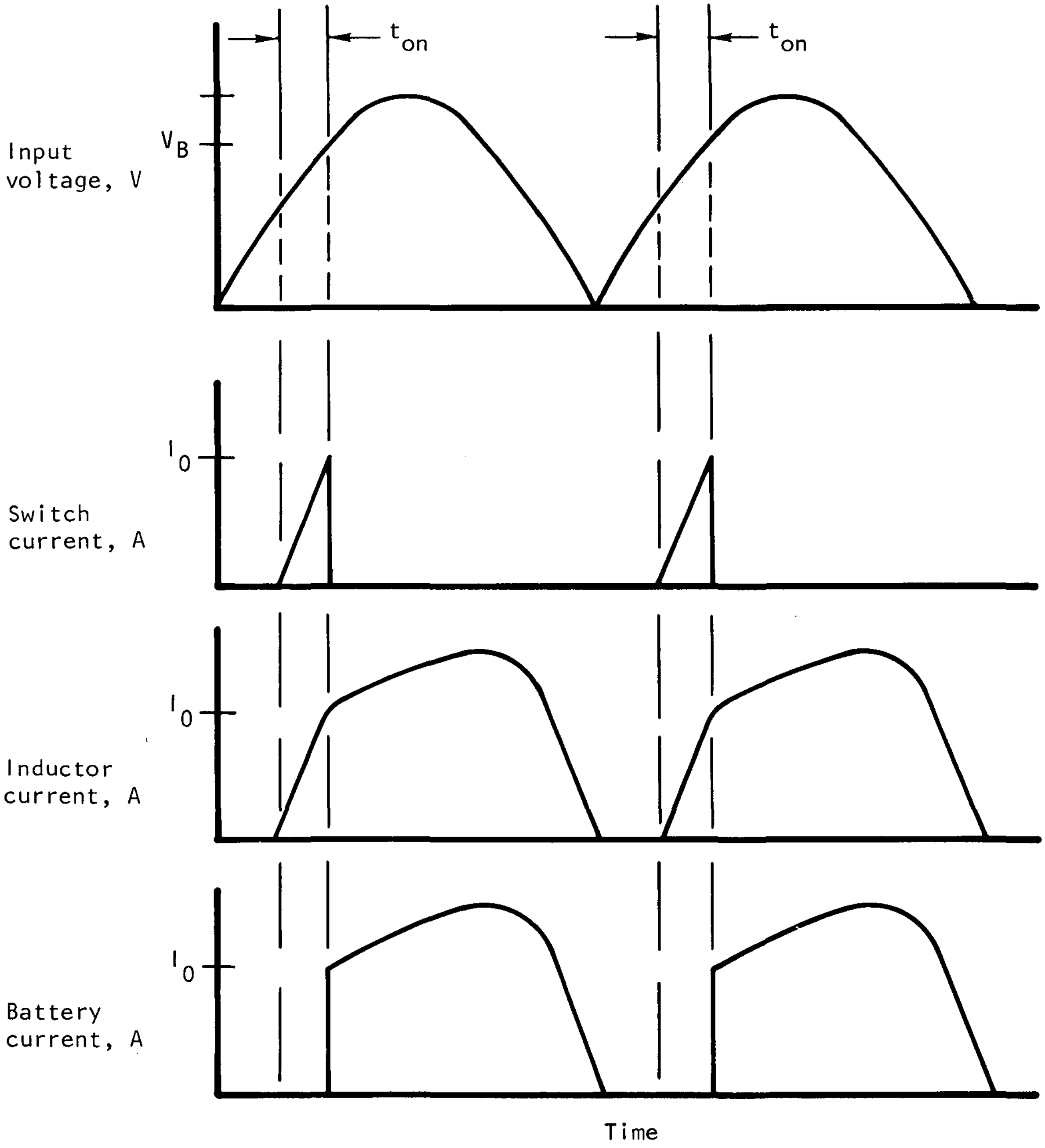


Figure C3.--Typical battery charger schematic.

The use of the inductor smooths the current, and the control can be used to vary the effect of the inductor as charging requirements vary over the charging cycle. The basic voltage and current waveforms of figure C4 show how the current control is accomplished by adjusting the amount of time the switch is on, t_{on}. When the switch is turned on, the voltage across the inductor is increased from $V_{IN}-V_B$ to V_{IN}. The increased voltage gives an increase in inductor current. When the switch is again turned off, the inductor current establishes the initial battery current I_o.



A-7302

Figure C4.--Charger voltage and current waveforms.

Charging mode.--A typical tapered charge procedure is illustrated in figure C5. The limiting voltage where tapering is initiated may be set by a limiting battery temperature or gassing rate. The final charge maintenance level insures that the weakest cells are fully charged.

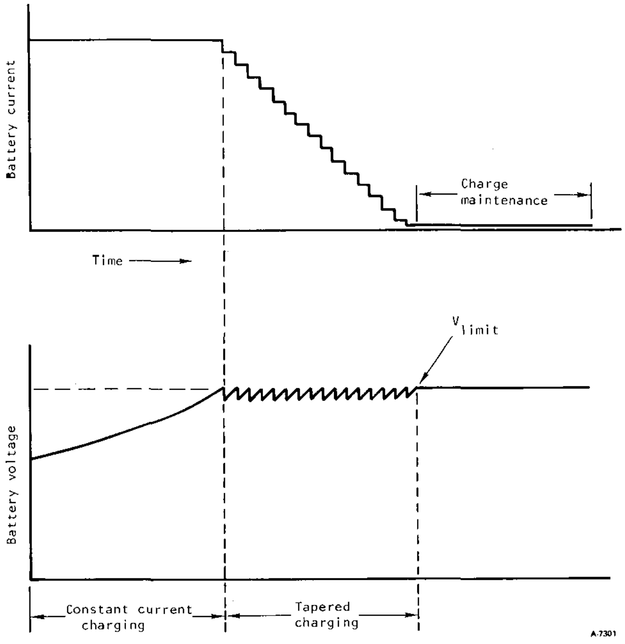


Figure C5.--Typical battery charging schedule.

This tapered charge procedure implies the use of a rather sophisticated logic device to control the rate, as well as sensors to measure the battery voltage and temperature. The charger cost will increase with the degree of sophistication, and presents a tradeoff of operator needs vs equipment cost.

Voltage tradeoff.--The cost of a propulsion system battery charger is primarily a function of the complexity required for the charging cycle, rather than the battery-pack voltage level. The effect that battery-pack voltage has on the charger is the requirement for a transformer or choke, which may dictate a charger that is too large to be conveniently installed in the vehicle. For a 220-V, 60-Hz input to the charger when an onboard charger is desired, the battery-pack voltage range should be within the approximate limits of 150 to 250 V. If the input voltage to the charger were 115 V, 60 Hz, then the battery-pack range could be 54 to 108 V for an onboard charger.

APPENDIX D

SYSTEM SAFETY CONSIDERATIONS

Although safety in electrical systems is generally thought of in terms of shock hazard and although shock is a major consideration, an electrical system can present several types of hazard:

(1) Direct personal injury
(2) Damage to the system
(3) Loss of system function

All of these hazards are somewhat greater for a high-voltage system than for a low-voltage system (50 V compared to 500 V). There is sufficient information available to design a system with adequate safeguards against mechanical and electrical malfunction; there is, however, no way to completely insure a system against the consequences of human error. Safeguards are possible, but since accidents can happen, consideration should be given to the possible effects of electrical shock.

Effects of electrical shock.--When the human body becomes part of an electrical circuit, the resulting current flow is governed by the voltage of the source and the total impedance of the system. Generally, the impedance of the human body is large compared with the impedance of the other parts of the system. At low frequencies the impedance of the body is essentially resistive, with a typical value of approximately 1000 ohms (ref. 28).

The effects of a current on the body depend upon the magnitude, the duration, and the path of the current flow. A current of about 50 mA passing through the body for several seconds can, under some conditions, be fatal (ref. 29). Sizeable shocks can be harmless when confined to a body extremity, such as the hand; however, when the body is grounded so that a current passes through the heart, ventricular fibrillation can be induced, resulting in death from very small currents (ref. 30).

At low voltages the resistance at the point of contact is the chief current-limiting factor. Dry skin can have a resistance as high as 300 000 ohms/sq cm, but when the skin is wet, the resistance may drop to 1 percent of this value. Contacts where the skin is broken exhibit even lower resistance. At 240 V and above, a shock current can puncture the skin and cause a deep localized burn. In such cases the skin resistance is eliminated, and the internal impedance of the body is the major current-limiting factor (ref. 30).

Although death is the most dramatic and tragic consequence of electrical shock, serious physical effects may result from sublethal currents as low as 5 mA. Low currents can cause muscle contractions that produce direct injury or can lead to secondary accidents. A summary of the effects of electric currents on humans is presented in table D1 (ref. 31). Higher currents are required with direct current than with alternating current to produce the same result.

TABLE D1.--EFFECTS OF ELECTRIC CURRENT ON HUMANS

Effect	Current in milliamperes			
	Direct		60 cycles	
	Men	Women	Men	Women
Slight sensation on hand	1	0.6	0.4	0.3
Perception threshold	5.2	3.5	1.1	0.7
Shock--not painful, muscular control not lost	9	6	1.8	1.2
Shock--painful, muscular control not lost	62	41	9	6
Shock--painful, let-go threshold	76	51	16	10.5
Shock-painful and severe, muscular contractions, breathing difficult	90	60	23	15
Shock--possible ventricular fibrillation effect from 3-sec shocks	500	500	100	100

A significant current level is the "let-go" current. If a subject holds an electrode in his hand and the current is gradually increased, the sensations progress through the stages listed in table D1 until there comes a time when the subject cannot let go of the electrode. The maximum current a subject can tolerate and at which he can still release the conductor by using the muscles directly stimulated by the current is called his let-go current. It has been found that the let-go current is nearly independent of the size and shape of the electrode (ref. 32). As may be seen in table D1, the threshold let-go current is 76 mA for men and 51 mA for women (with dc current).

Shock potential.--For the range of system voltage considered in this study, it is clear that there is some danger from electrical shock at the higher voltages. If we use a value of 1000 ohms for the resistance of the human body

(R) and a current of 50 mA as a dangerous level (I), then the resulting voltage that could produce this current is:

$$V = IR$$
$$= (50 \times 10^{-3})(1000) = 50 \text{ V}$$

This calculation shows that there is serious shock hazard at even the lowest voltage level considered for the battery pack.

Shock protection.-- A number of provisions can be made to limit the exposure of personnel to shock hazard:

(1) The propulsion system ground should not be connected to the vehicle chassis.

(2) All live conductors should be guarded by exclosures.

(3) Interlocks should be installed on enclosures and panels to insure power is turned off before access is permitted.

(4) Any electrical equipment that can be controlled remotely should have all control points located within sight of the equipment or, if this is impracticable, there should be positive disconnect means readily available to forestall the energizing or operation of the equipment. Master control switches for the operation of the system should be of the key type to prevent accidental starting.

(5) A ground fault interrupter (GFI) should be used with a trip value at 5 mA or less.

A number of established codes cover the design and a manufacture of electrical equipment. Many of their provisions are concerned with personnel safety. Some of these codes are listed here with a brief explanation of their general coverage:

(1) National Electrical Manufacturers Association (NEMA). These standards cover electrical power equipment, including standard ratings, performance, testing, manufacturing, and marking. Some of the major types of equipment covered are transformers, motors, switchgear, circuit breakers, power storage capacitors, arresters, generators, fuses, and power rectifiers.

(2) Electronic Industries Association (EIA) (formerly RETMA). These standards cover electronic type electrical equipment and components such as electron tubes, printed circuits, television and radio receiving and transmitting equipment, sound equipment, and microwave and radar systems. Included are performance standards and standard ratings, sizes, and test procedures.

(3) The Insulated Power Cable Engineers Association (IPCEA). These standards cover insulated power, control, and communication cable. Included are standards for conductors, insulation, outer jackets, cable testing, and current-carrying capacity.

(4) American National Standards Institute (ANSI) (formerly ASA). ANSI is the national clearinghouse and coordinating agency for voluntary standards in the United States. It is a federation of 122 trade associations and professional societies and has more than 2000 company members. ANSI standards are numbered with a letter prefix that determines the field of coverage; i.e., "A" -- Civil Engineering and Construction, "B" -- Mechanical Engineering, "C" -- Electrical Engineering, etc. Under Section "C" are listed electrical standards, a large part (but not necessarily all) of which are from and a part of other technical organization and trade association standards such as NEMA, EIA, IEEE, IPCEA, NEC, and others.

(5) Institute of Electrical and Electronic Engineers, Inc. (IEEE) These standards consist of technical reports, testing procedures, establishing of basic service conditions, and ratings for electrical components and equipment generally used in the generation, distribution, and utilization of electric power.

(6) Federal Specifications, General Services Administration. These are specifications for items commonly used by the Federal Government and include electrical components such as insulated conductors, electron tubes, light bulbs, receptacles, etc.

(7) Federal Communications Commission (FCC). Part 18 of these regulations, titled: "Industrial, Scientific, Medical Service," covers the rules and regulations for the use and operation of an apparatus that emits radio frequency energy within the radio spectrum, thereby constituting a possible source of interference.

(8) National Electric Code (NEC). This code covers electrical conductors and equipment installed within or on public and private buildings and other premises. The code has nine chapters titled I, General; II, Wiring Design and Protection; III, Wiring Methods and Materials; IV, Equipment for General Use; V, Special Occupancies; VI, Special Equipment; VII, Special Conditions; VIII, Communications Systems; and IX - Tables and Examples. This code would cover the installation of a battery charger.

(9) Occupational Safety and Health Act (OSHA) has many sections that relate to electrical equipment, with Subpart S being the basic section.

REFERENCES

1. Mighdol, P., W. F. Hahn: Preliminary Power Train Design for a State-of-the-Art Electric Vehicle. Booz, Allen & Hamilton, Report No. DOE/NASA/0595-78/1, September 1978.

2. Ross, J. A., G. A. Wooldridge: Preliminary Power Train Design for a State-of-the-Art Electric Vehicle. Rohr Industries, Report No. DOE/NASA/0592-78/1, September 1978.

3. U. S. Department of Energy: Near-Term Electric Vehicle Program. Report No. SAN/1213-02, SAN/1294-02, August 1978.

4. Rowlette, J., C. Leising: Electric Vehicle Battery Test Report. Jet Propulsion Laboratory Report No. 5030-286, December 1978.

5. Frank, H. A., A. M. Philips: Evaluation of Battery Models for Prediction of Electric Vehicle Range. Jet Propulsion Laboratory, Publication 77-29, August 1, 1977.

6. U. S. Department of Energy: Electric and Hybrid Vehicle Program. 3rd EHV Program Contractors' Meeting, Presentation Aids, June 25, 1979.

7. Shepherd, C. M.: Design of Primary and Secondary Cells, II An Equation Describing Battery Discharge: Journal of the Electromechanical Society. July 1965.

8. Klein, M., D. Dube: Design and Cost Study of Nickel-Zinc Batteries for Electric Vehicle. Energy Research Corp. Report No. ANL-K-76-3541-1, October 1, 1976.

9. Yardney Electric Corp: Design and Cost Study Zinc/Nickel Oxide Battery for Electric Vehicle Propulsion. Report No. ANL-K-76-3543-1, October 1976.

10. Cataldo, R. L.: Response of Lead-Acid Batteries to Chopper-Controlled Discharge: Preliminary Results. NASA Lewis Research Center, NASA TM-73834, February 1978.

11. Dudley, D. W.: Gear Handbook, McGraw-Hill Book Co., 1962.

12. AiResearch Manufacturing Company: Automobile Gas Turbine Optimization Study for the Environmental Protection Agency, Report AT-6100-R7, July 10, 1972.

13. Hewko, L. O.: Roller Traction Drive for Extremely Quiet Power Transmission: Journal of Hydronautics. Vol. 2. No. 3, July 1968.

14. Morris, R.: Variable-Speed Belt Drives, Automatic Transmission of the Future: Machine Design. Vol. 48, No. 19, August 12, 1976.

15. Huntley, P.: Design Factors of Hydro-Mechanical Transmissions of Passenger Cars. Proceedings of the Fourth International Symposium on Automotive Propulsion Systems, NATO/CCMS N. 61, Vol. II, April 18, 1977.

16. Klein, E. A., G. A. Norris: Hydrostatics Tackle Tough New Jobs: Machine Design. Vol. 49, No. 19, August 25, 1977.

17. Behrin, E. et al: Energy Storage Systems for Automobile Propulsion. Volumes 1 and 2, Lawrence Livermore Laboratories, Report UCRL-52303, December 15, 1978.

18. U. S. Department of Energy: Proceedings of the 1978 Mechanical and Magnetic Energy Storage Contractors' Review Meeting. CONF-781046, October 24, 1978.

19. Towgood, D. A.: An Advanced Vehicular Flywheel System for the ERDA Electric Powered Passenger Vehicle: DOE Flywheel Technology Symposium Abstracts, October 5-7, 1977.

20. Satchwell, D. L.: An Advanced Energy Storage Unit for a U.S. Postal Service Delivery Vehicle: DOE Flywheel Technology Symposium Abstracts, October 5-7, 1977.

21. Rath and Strong, Inc.: Estimated Weights and Manufacturing Costs of Automobiles: Fuel Economy Goals Beyond 1980. Report to U. S. Department of Transportation, Transportation Systems Center.

22. The Aerospace Corporation: Hybrid Heat Engine/Electric Systems Study. Report No. TOR-059 (6769-01) -2, June 1, 1971.

23. AiResearch Manufacturing Company of California: Study of Heat Engine/Flywheel Hybrid Propulsion Configuration with Electrical Transmission System. ALO-41/1, April 1978.

24. Marello, L: Optimizing the Engine-Transmission System by Means of an Electronically Controlled Gearbox. Proceedings of the Fourth International Symposium on Automative Propulsion Systems, NATO/CCMS N. 61, Vol. II, page 610, April 18, 1977.

25. Loewenthal, S. H. et al: Performance of a Nasvytis Multiroller Traction Drive. NASA Technical Paper 1378, AVRADCOM Technical Report 78-36, November 1978.

26. Kruse, R. E., T. A. Huls: Development of the Federal Urban Driving Schedule: Society of Automotive Engineers, Paper 730553, 1973.

27. Simanaitis, D. J.: Emission Test Cycles Around the World: Automotive Engineering. Vol. 85, No. 8, August 1977.

28. Hamilton, D. E.: A Review of Grounding Practices for Mine Power Systems: AIEE Conference Paper. April 13, 1960.

29. Heinemann Electric Company: Ground Fault, and How to Protect Against Its Varied Threats. Heinemann Ideafile No. 5, 1972.

30. Dalziel, C. F.: Electric Shock Hazard. IEEE Spectrum, February 1972.

31. National Safety Council: Accident Prevention Manual for Industrial Operations. Sixth ed., 1975.

32. Dalziel, C. F.; Ogden, E.; and Abbott, C. E.: Effect of Frequency on Let-Go Currents. Trans. AIEE, vol. 62, December 1943.

33. AiResearch Manufacturing Company: Design Guidelines for Electrical Clearance and Creepage Distances in Ground Transportation Equipment. Report No. 77-13641, March 2, 1977.

34. Carlisle, B. H.: Space Saving in Electrical Packaging: Machine Design. Vol. 51, No. 18, August 9, 1979.

35. Van der Elson, R. J.: Terminal Block Ratings: Machine Design. Vol. 49, No. 7, April 7, 1977.

36. Leonard, M.: Avoiding Mistakes with Relays: Machine Design. Vol. 47, No. 13, July 24, 1975.

37. Smithrick, J. J.: Rapid, Efficient Charging of Lead-Acid and Nickel-Zinc Traction Cells. NASA Technical Paper TM-78901, August 20, 1978.

1. Report No. NASA CR-165243	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle

ADVANCED ELECTRIC PROPULSION SYSTEM
CONCEPT FOR ELECTRIC VEHICLES
ADDENDUM 1 - VOLTAGE CONSIDERATIONS

5. Report Date
August 1980

6. Performing Organization Code
70210

7. Author(s)

A. E. Raynard and F. E. Forbes

8. Performing Organization Report No.
79-16182, Add. 1

9. Performing Organization Name and Address

AiResearch Manufacturing Company of California
A Division of The Garrett Corporation
2525 W. 190th Street, Torrance, California 90509

10. Work Unit No.

11. Contract or Grant No.
DEN 3-81

12. Sponsoring Agency Name and Address

U.S. Department of Energy
Office of Transportation Programs
Washington, D.C. 20585

13. Type of Report and Period Covered
Contractor Report

14. Sponsoring Agency Code
DOE/NASA/0081-2

15. Supplementary Notes

Addendum 1 to Final Report. Prepared under Interagency Agreement EC-77-A-31-1044. Project Manager, R. Schuh, Electric and Hybrid Vehicle Project Office, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

Seventeen electric vehicle propulsion systems were originally studied to select two designs that best met cost and performance goals. Both systems have now been examined to assess the effect of battery pack voltage on system performance and cost. A voltage range of 54 to 540 V was considered for a typical battery pack capacity of 24 kW-hr. The highest battery specific energy (W-hr/kg) and the lowest cost ($/kW-hr) were obtained at the minimum voltage level.

The flywheel system traction motor is a dc, mechanically commutated machine with shunt field control, and due to the flywheel the traction motor and the battery are not subject to extreme peaks of power demand. Design changes in the battery pack voltage simply result in compensating changes in the motor configuration.

The basic system uses a permanent-magnet motor with electronic commutation supplied by an ac power control unit. In this system the traction motor and power control unit must handle the peak power needed for acceleration. The traction motor can be designed to operate at specific battery voltages within a broad range, with little effect on motor efficiency, weight, or cost. The power control unit characteristics are effected by battery voltage, and the lowest voltages give the lowest efficiency, highest weight, and highest cost.

In both systems battery costs were the major factor in system voltage selection, and a battery pack with the minimum voltage of 54 V produced the lowest life-cycle cost. The minimum life-cycle cost for the basic system with lead-acid batteries was $0.057/km and for the flywheel system was $0.037/km.

17. Key Words (Suggested by Author(s))

Electric vehicle, battery-powered vehicle, electric propulsion system, traction motor, CVT, flywheel energy storage

18. Distribution Statement

Unclassified -- unlimited
STAR Category 85
DOE Category UC-96

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 75	22. Price*

*For sale by the National Technical Information Service, Springfield, Virginia 22161

☆ U.S. GOVERNMENT PRINTING OFFICE: 1981 -757-052/3204