55
12-11-78

Ch. 838

ENERGY

COO-2966-1

COST ANALYSIS OF 50 KWH ZINC-CHLORINE BATTERIES
FOR MOBILE APPLICATIONS

By
H. Catherino
G. L. Henriksen
C. C. Whittlesey
C. J. Warde
P. Carr
P. C. Symons

January 1978

Work Performed Under Contract No. EY-76-C-02-2966

Energy Development Associates
Madison Heights, Michigan

U. S. DEPARTMENT OF ENERGY

Division of Energy Storage Systems

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOI-1AKTH0200

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$5.25
Microfiche \$3.00

COST ANALYSIS OF
50 KWH ZINC-CHLORINE BATTERIES FOR
MOBILE APPLICATIONS

H. Catherino	Research Associate
G. L. Henriksen	Group Leader
C. C. Whittlesey	Senior Design Engineer
C. J. Warde	Manager, Battery Development
P. Carr	Manager, Vehicle Batteries
P. C. Symons	Chief Scientist

Energy Development Associates
1100 W. Whitcomb Avenue
Madison Heights, Michigan 48071
A Gulf + Western Company

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

January 1978

Prepared For
The Department of Energy
Under Contract No. EY-76-C-02-2966

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

Foreword

This cost and design study is part of a combined study of zinc-chlorine battery costs for utility and vehicular applications. There are significant differences between the batteries for the two applications, but the many similarities allow many parts of a cost and design study to be done only once. Funding for this cost study on zinc-chlorine batteries was provided jointly by EDA and DoE, while a parallel study on zinc-chlorine batteries for peak-shaving was funded by EDA as part of a joint EDA-EPRI program. The parallel effort on peak-shaving batteries allowed a more comprehensive analysis of portions of the vehicular battery study.

Acknowledgments

This work was supported jointly by Energy Development Associates and the Battery Branch (Kurt W. Klunder, Chief), Division of Energy Storage Systems, Department of Energy. This support is gratefully acknowledged. The contributions from the EDA-EPRI program (Dr. James R. Birk, Project Manager) Advanced Battery Development, Electric Power Research Institute, are also gratefully acknowledged.

TABLE OF CONTENTS

<u>Section No.</u>		<u>Page No.</u>
	ABSTRACT	1
1	INTRODUCTION	2
2	ENGINEERING SPECIFICATIONS	
	Introduction	5
	Electrochemical Design Points	5
	Mass Flow and System Operation	7
	Energy Balances	9
	Projected Chemical Weights and Volumes	14
	Discussion	14
3	DESIGN DESCRIPTION	
	Design Criteria	17
	Module Concept	17
4	COSTING	
	Introduction	28
	Materials	28
	Process Description	30
	The Manufacturing Facility	34
	Investment, Indirect and Overhead Costs	42
	Manufacturing Cost and Selling Price	48
5	DISCUSSION	
	Introduction	51
	Observation	51
	Components and Equipment Development	52
	Influence of Porous Graphite Cost on Selling Price	52
	Vehicle Cost Estimate	53
	Battery Charger	54
	The Future	54
6	REFERENCES	56

ABSTRACT

An analysis of the costs comprising the projected selling price of a 50 kWh zinc-chlorine battery for mobile applications was performed. This analysis is predicated on a battery whose engineering and design specifications are well crystallized. Such a design has been proposed and a process plan conceived. This, in turn, led to a simulated manufacturing plan. This analysis showed that no critical resources or complex manufacturing operations are required. The projected cost presumes a production level of 25,000 batteries per year. In that context, a selling price was estimated, in mid-1977 dollars, to be \$1645 per battery or \$33/kWh. This price excludes the battery charger for which an added \$400 (\$8/kWh) is considered reasonable.

Section 1

INTRODUCTION

Zinc-chlorine batteries have an intermediate energy density and are potentially of low cost. Intermediate energy density batteries are those with energy densities in the range of 30 to 50 Wh/lb. In the near term, the lead acid battery and its evolutionary variants will prevail in the electric vehicle market. The expected energy densities are 10-18 Wh/lb. The intermediate systems are characterized by employing batteries that are in a relatively advanced state of development. Included are nickel-zinc, nickel-iron and zinc-chlorine batteries. In the far term, batteries having energy densities of 70-100 Wh/lb are projected.

For a four passenger electric vehicle range of about 100 miles under urban driving conditions, a rechargeable battery of up to 50 kWh and greater than 30 Wh/lb is required. In order that the vehicle can safely and conveniently operate with other (non-electric) traffic, acceleration and grade-climbing require batteries with power densities in excess of 30 W/lb. Electric vehicle sales, and thus petroleum conservation, will come about only if electric vehicles are economically comparable with gasoline vehicles. Therefore, batteries will have to be sold at a price of \$30-50/kWh and must have an energy efficiency in excess of 50%. In addition, a useful vehicle life of 100,000 miles will be necessary. This leads to a battery life requirement of about 1,000 deep cycles and 10 years. Also, critical resources cannot be used in the materials of construction of the battery.

The identification of an optimum battery for use in electric vehicles depends on user satisfaction from performance and economic standpoints. Performance can be translated into quantitative measures by specifying the vehicle range and energy requirements necessary to achieve user needs. An important boundary condition is that no battery powered vehicle, near or far term, is considered capable of intercity driving. The reason for this is that intercity driving would require a fast recharge - not as yet possible within a reasonable time - or a battery exchange while en route. As a consequence, an electric vehicle, to be acceptable, must satisfy the consumer driving needs for intracity commuting. In the light of this boundary condition together with the data resulting from a survey by the Federal Highway Administration on the travel distance distribution of automobile trips, a basis exists for estimating driver needs from a probabilistic standpoint. A recent study attempted this using a Monte Carlo Simulation for the purpose of redistributing

the annual data into daily driving requirements. A measure of usefulness listed as a percent of days of the year that the electric vehicle could meet the driving requirements was used as the figure of merit. The results were:

System	Practical Daily Mileage Range	% of Days of Year that System is Useful
Near-term	43	83
Intermediate-term	85	95
Far-term	170	98

This study showed that the increased capabilities of the far-term battery does not significantly improve the utility of the vehicle over the intermediate-term battery. Economics will therefore determine the usefulness of batteries within both these categories.

This quoted study places intermediate-term batteries in a very favorable light relative to the other batteries. The zinc-chlorine battery is, as a result, not just an interim candidate system anticipating the higher energy density system but, instead, an ultimate electric vehicle power source in its own right. Specifically, the zinc-chlorine battery is capable of greater than 50% overall efficiency and an attractive selling price (vide infra). It can provide a service life of 1000 cycles during a ten year period. Zinc-chlorine batteries can meet these goals for the following reasons:

- The system uses no critical resources and, as a consequence, uses inexpensive and readily available active materials.
- The system is well-behaved and allows the use of potentially inexpensive electrodes with high voltaic efficiency.
- The system can be made to operate close to ambient temperature.
- Operating zinc-chlorine batteries with inactive substrates for zinc electrodes and with periodic complete discharge leads to no loss of capacity on cycling.
- The coulombic efficiency of the system can be maximized by suitable arrangements to control the dissolved chlorine concentration in charge and discharge. This obviates the need for expensive and potentially life-limiting separators.

Chlorine hydrate, as the chlorine-storage means, offers some advantages over other chlorine storage methods².

- The system can be operated very close to ambient pressure, thus obviating the use of chlorine compressors and conferring greater safety on the system.

- Chlorine hydrate appears to offer cost advantages since the complex uses water at virtually zero cost.
- The enthalpy of formation of chlorine hydrate is sufficiently large so as to provide significant battery cooling in discharge.
- It is unnecessary to dry the chlorine before hydrate formation which leads to capital cost, operating cost, operational reliability and safety advantages.
- Since chlorine hydrate is a solid, having a large heat of formation, tank rupture does not lead to massive chlorine gas leakage.
- Storing the halogen external to the electrochemical cell prevents activated stand losses by direct reaction of chlorine with zinc.

For these reasons the zinc-chlorine battery is a realistic candidate for a commercial electric vehicle.

Section 2

ENGINEERING SPECIFICATIONS

INTRODUCTION

Design of battery systems for electric vehicle applications are guided by the vehicle performance criteria and the resulting battery design goals established to meet these criteria. The performance goals for commercial zinc-chlorine electric vehicle batteries include:

- Delivered energy density of 45 Wh/lb
- Sustained specific power of 35 W/lb
- Overall energy efficiency of >50%

In order for a battery system to be accepted into this market it must meet or exceed the minimum requirements in these areas. These design goals have been utilized in this study to develop the design points and engineering specifications for a commercial zinc-chlorine vehicle battery system of the 50 kWh size.

ELECTROCHEMICAL DESIGN POINTS

The electrochemical design points for a commercial zinc-chlorine battery are listed in Table I. The charge current density of 27 mA/cm^2 corresponds to a charge current of 74 amperes for eight hours duration. The corresponding discharge currents are 110 amperes (40 mA/cm^2) at the four-hour (C/4) discharge rate and 400 amperes (160 mA/cm^2) at the one-hour (C/1) discharge rate. The four-hour rate corresponds to the nominal power demands for open highway cruising while the one-hour rate corresponds to the high power demands during acceleration or maintaining speed up a grade. The four-hour discharge capacity compared to the charge capacity reflects a net round-trip usable coulombic efficiency of 74.3%. The projected charge and discharge voltages of 2.2 V/cell (133 volts/battery) and 1.95 V/cell (117 volts/battery) at the four-hour rate, represent a projected voltaic efficiency of 87.8%. The resulting electrochemical energy efficiency is therefore projected to be 65.2%. The 4% unusable capacity is an average over a number of incomplete discharge cycles between complete discharge cycles. An incomplete discharge cycle is defined as a cycle where a portion of the usable capacity is still present in the battery at the point where the discharge process is terminated and the charge process is initiated.

Table I

COMMERCIAL VEHICLE BATTERY
DESIGN POINTS

I. Time (hours)	
Charge	8
Discharge (C/4)	4
(C/1)	1
II. Current Density (mA/cm ²)	
Charge	27 (74 amps)
Discharge (C/4)	40 (110 amps)
(C/1)	160 (440 amps)
III. Voltage (volts/cell)	
Charge	2.22 (133 volts)
Discharge (C/4)	1.95 (117 volts)
(C/1)	1.50 (90 volts)
Voltaic Efficiency (C/4) (%)	87.8
IV. Coulombic Efficiency (%)	
Charge	87.0
Discharge (C/4)	90.0
Gross Round Trip	78.3
Unusable Capacity	4.0
Net Round Trip	74.3
V. Electrochemical Energy Efficiency (%)	65.2
VI. Delivered Electrochemical Energy (kWh) (excluding auxiliary equipment)	
(C/4)	51.5
(~C/1)	42.5
VII. Net Delivered Energy (kWh) (@C/4) (including auxiliary requirements)	50.4
VIII. Delivered Power (kW) (@C/1)	39.6
IX. Battery Weight (lbs)	1101
X. Battery Volume (cubic feet)	13.5
XI. Energy Density (@C/4)	
Wh/lb	45.7
Wh/cu. in.	2.2

A complete discharge cycle is one where the battery is completely discharged (stripped of all metallic zinc) prior to initiation of the charge process. The unusable capacity on the first incomplete discharge cycle will be 1.5-2.0% and will increase through subsequent incomplete discharge cycles due to asymmetrical current distribution between charge and discharge and edge effects. Complete discharge cycles restore the battery to its original state and are performed intermittently to achieve this leveling. The net usable d.c. energy delivered to the propulsion motor control for this commercial zinc-chlorine battery is projected to be 50.36 kWh at the four-hour discharge rate. The projected weight of the battery is 1,101 pounds which results in an energy density of 45.7 Wh/lb (100.9 Wh/kg) of battery.

MASS FLOWS AND SYSTEM OPERATION

Figure 1 is an operational schematic of the battery. Operation of the battery will be controlled by a single pressure sensor located in the stack. Pressure differential is maintained between the stack and the store using a gas pump to transfer gas from the stack to the store via line (5). Electrolyte return and pressure relief of the store is accomplished via line (7). Absolute pressure control is accomplished during charge by controlling the rate of chlorine hydrate formation and during discharge by controlling the rate of chlorine hydrate decomposition. The hydrate formation rate on charge is controlled by the rate of heat removal from the store, which is controlled by the flow of coolant through the hydrate formation heat exchanger (HX1). The hydrate decomposition rate on discharge is controlled by the rate of transfer of electrolyte from stack to store via line (2).

During the charge mode, the main electrolyte pump (P-1) feeds dechlorinated electrolyte to the chlorine electrodes in the stack via line (1). Electrolyte overflows from the cells of the stack, collects in separate return lines, and returns by gravity to the sump. The chlorine gas generated during charge is pumped from the stack, via line (5), by the gas pump (P-2) where it is mixed with chilled electrolyte from line (3) to form chlorine hydrate. The electrolyte is chilled in HX1 just prior to mixing with the chlorine gas. Electrolyte transfer from the stack to the store is accomplished via one leg of line (2). Valve V1 is locked closed during charge to prevent interchange of unchilled electrolyte. The store is held at a reduced pressure during charge by controlling the rate of hydrate formation as previously described. The gas pump (P-2) establishes the pressure differential between the store and the stack, while electrolyte return and pressure relief of the store is accomplished via line (7). The reduced pressure established on the stack accomplishes dechlorination of the electrolyte during charge. The temperature of the stack and sump are permitted to float during charge and a steady state achieved near 9°C in the stack for a 0°C store temperature.

During the discharge mode the electrolyte pump (P-1) feeds chlorinated electrolyte to the chlorine electrodes in the stack via line (1). Again, electrolyte overflows the stack and returns by gravity to the sump through

LEGEND

P-1	ELECTROLYTE PUMP		CALIBRATED RESTRICTOR
P-2	CHLORINE GAS PUMP		LIQUID FILLED LINES
V-1	DISCHARGE VALVE — PRESSURE CONTROL WITH OVERRIDE		GAS FILLED LINES
V-2	CHARGE VALVE — PRESSURE CONTROL		STREAM IDENTIFICATION
HX-1	CHARGE HEAT EXCHANGER — CHILLER		
HX-2	SUMP HEAT EXCHANGER — FOR TEMP. REGULATION — AIR COOLED		

Figure 1. Operational Schematic of the Vehicle Battery.

separate return lines. Chlorination of the electrolyte is accomplished by injecting gaseous chlorine into the electrolyte on the high pressure side of the main electrolyte pump (P-1) via line (7). Chlorine gas is formed in the store by decomposition of chlorine hydrate. Flow of the warm electrolyte from the stack to the store via line (2) accomplishes decomposition of the hydrate. Control of the electrolyte interchange rate, via valve V1, controls the rate of chlorine gas formation and provides the absolute pressure control on discharge. The gas pump (P-2) is again used to establish the differential pressure between the store and the stack. Return of electrolyte from the store to the stack is accomplished via line (7). Temperature control of the stack and sump will be accomplished in HX2, an air cooled heat exchanger.

ENERGY BALANCES

The electrochemical energy balance for the battery stack is summarized in Table II. The various electrochemical energy losses are derived from the voltaic and coulombic efficiencies of Table I. A total of 24.15 kWh of energy is projected to be lost per cycle due to inefficiencies occurring in the battery stack during charge and discharge. Almost 68% of the lost energy is due to coulombic inefficiency - the major loss occurring during charge when the concentration of dissolved chlorine is high. The ratio of the usable delivered d.c. energy to the d.c. energy input results in a projected electrochemical energy efficiency of 65.2%.

The energy balance for the battery module is presented in Figure 2. The a.c. requirement for refrigeration is projected to be 6.96 kWh during the eight-hour charge. The rectification efficiency is assumed to be 98%. After rectification the auxiliaries are projected to require a total of 3.44 kWh of d.c. energy during charge. The d.c. energy requirements for auxiliaries during a four-hour discharge are projected to total 1.22 kWh. The total energy requirement for auxiliaries (including the a.c. refrigeration requirement on charge) are projected to be 11.62 kWh. The net usable d.c. energy output is projected to be 50.36 kWh. The ratio of the usable delivered d.c. energy to the a.c. energy input projects a usable delivered energy efficiency of 55.3%.

Table III is a heat balance summary for the battery. Table IIIa summarizes the various heat gains and losses in the stack and store during the eight-hour charge. The temperature of the battery stack is allowed to float and establish dynamic equilibrium so there is no net heat gain or loss in the battery stack during charge. Assuming a C.O.P. of 3.0 for the refrigeration equipment, the work required to remove the 20.89 kWh of heat from the store to form and store the chlorine hydrate during charge will be 6.96 kWh.

Table IIIb summarizes the projected heat gains and losses in the stack and store during a four-hour discharge. The projected net heat gain in the stack during discharge is 8.77 kWh. Cooling of the stack will be required to maintain temperature control. The heat requirement for decomposing chlorine hydrate in the store during discharge is projected to be 10.76 kWh.

Table II

ELECTROCHEMICAL ENERGY BALANCE SUMMARY

	<u>Capacity (Ah)</u>	<u>Energy (kWh)</u>
I. Charge		
A. Input to battery	35,601	79.03
B. Losses		
(1) Coulombic	4,628	10.27
(2) Voltaic		3.10
II. Stored in battery	30,973	65.66
III. Discharge		
A. Losses		
(1) Coulombic	3,097	6.04
(2) Voltaic		4.74
B. Unusable	1,424	3.30
C. Usable delivered from battery	26,452	51.58

Figure 2.

Table IIIa

HEAT BALANCE SUMMARY FOR 8-HOUR CHARGE

I. Stack

A. kWh

Charged 79.03 kWh

Stored 65.66 kWh

B. Heat gains

Electrochemical inefficiency 13.37 kWh

Pump Heats

electrolyte pump (100%) 2.04 kWh

gas pump (70%) 0.84 kWh

Environment to battery 1.00 kWh

TOTAL 17.25 kWh

C. Heat losses

 $\Delta H - \Delta G$ (13.7 kCal/mole) 9.17 kWh

Battery to store 0.54 kWh

Through electrolyte interchange 7.54 kWh

TOTAL 17.25 kWh

D. No net heat gain or loss

II. Store

A. Heat gains

Formation of hydrate (577 moles x
18.6 kCal/mole) 12.45 kWh

Through electrolyte interchange 7.54 kWh

Pump heat (gas pump) (30%) 0.36 kWh

Battery to store 0.54 kWh

TOTAL 20.89 kWh

B. Work to remove heat at

C.O.P. of 3.0 6.96 kWh

Table IIIb

HEAT BALANCE SUMMARY FOR 4-HOUR DISCHARGE

I. Stack	
A. kWh	
Stored	65.66 kWh
Unused	3.30 kWh
Removed on discharge	62.36 kWh
Delivered on discharge	51.58 kWh
B. Heat gains	
Electrochemical inefficiency	10.78 kWh
Pump heats	
electrolyte pump (100%)	1.02 kWh
gas pump (70%)	0.07 kWh
$\Delta H - \Delta G$ (13.7 kCal/mole)	<u>8.74 kWh</u>
TOTAL	20.61 kWh
C. Heat losses	
Battery to store	1.08 kWh
Through electrolyte interchange	<u>10.76 kWh</u>
TOTAL	11.84 kWh
D. Net heat gain	8.77 kWh
II. Store	
A. Heat to decompose hydrate	
(550 moles x 18.6 kCal/mole)	11.87 kWh
B. Heat gains	
Pump heat (gas pump) (30%)	0.08 kWh
Battery to store	<u>1.08 kWh</u>
TOTAL	1.11 kWh
C. Additional heat required through electrolyte interchange	10.76 kWh

This heat will be transferred from the stack to the store by electrolyte interchange between the two compartments.

PROJECTED CHEMICAL WEIGHTS AND VOLUMES

Table IV summarizes the chemical weights and volumes in the battery. At the beginning of charge the battery contains 240.3 liters of electrolyte weighing 310 kg. During the eight-hour charge 40.9 kg of chlorine gas will be transferred to the store and transformed into 124 kg of chlorine hydrate. Simultaneously, 37.8 kg of metallic zinc will be deposited and stored in the stack. At the end of charge the chlorine hydrate occupies 100.8 liters in the store, and the electrolyte volume is reduced to 134.1 liters. The total volume of all products is 240.2 liters. The net volume change from complete discharge to complete charge is -0.1 liter. The final store fluid is 26 $\frac{w}{g}$ chlorine. The volumes of the stack, sump, and store are 6.5 ft³, 0.84 ft³, and 5.45 ft³, respectively. These volumes for the sump and store allow for the auxiliary components.³ The case adds another 0.71 ft³ to give a total package volume of 13.5 ft³.

The projected 1101 lb weight of the battery is estimated from the electrolyte weight of 683.4 lb, the stack weight of 210 lb, and an assumed weight for the auxiliaries and the case of 207.6 lb. The weight-to-volume ratio projects a packaged battery density of 81.6 lb/ft³.

DISCUSSION

Assuming the projected weight, volume, and performance specifications are achieved the performance design goals for a commercial zinc-chlorine electric vehicle battery will be met. Table V compares the projected specifications with the previously presented goals.

The projected specifications reflect improvements in electrochemical and auxiliary component efficiencies, as well as minimization of weights and volumes. The electrochemical design points reflect only marginal improvements over existing large zinc-chlorine systems. The major effort will be applied to weight and volume minimization and auxiliary component efficiency optimization. The weight and volume minimization includes development of a high density chlorine hydrate store.

Table IV

COMMERCIAL VEHICLE BATTERY WEIGHTS AND VOLUMES

ZnCl ₂ decomposed	78.8 kg
Zinc stored	37.8 kg
Chlorine stored	40.9 kg
8 H ₂ O	83.1 kg
Cl ₂ ·8H ₂ O	124.0 kg

Starting electrolyte:

Weight	310.0 kg
Volume (ρ=1.29 kg/liter)	240.3 liters

End of charge:

Total electrolyte:

Weight	148.2 kg
Volume (ρ=1.10 kg/liter)	134.1 liters

Zinc stored:

Weight	37.8 kg
Volume (ρ=7.14 kg/liter)	5.3 liters

Cl₂·8H₂O stored:

Weight	124.0 kg
Volume (ρ=1.23 kg/liter)	100.8 liters

Total volume of all components	240.2 liters
--------------------------------	--------------

Summary:

Stack Volume (total)	6.50 cubic feet
Sump Volume (total)	0.84 cubic feet
Store Volume (total)	5.45 cubic feet
Packing Volume	0.71 cubic feet
Total Battery Volume	13.5 cubic feet
Projected Battery Weight	1101 pounds

Table V

	<u>Projected Specifications</u>	<u>Goals</u>
Delivered Energy Density (Wh/lb)	45.7	45.0
Sustained Specific Power (W/lb)	36.0	35.0
Overall Energy Efficiency (%)	55.3	>50.0

Section 3

DESIGN DESCRIPTION

DESIGN CRITERIA

The design presented in this study envisions a rechargeable zinc-chlorine battery intended for use as the primary source of motive power in a highway vehicle. To be suitable for this service a battery must meet a number of specific criteria. These are summarized in the following table.

Table VI

PRIMARY DESIGN CRITERIA

● Stored Energy Density	45 Wh/lb
● Specific Power - sustained	35 W/lb
● Peak Specific Power - 2 second duration	45 W/lb
● Battery Selling Price - excluding charging equipment	~\$35/kWh
● Overall Roundtrip Efficiency	>50%
● Battery life equals 100,000 vehicle miles	
● Meet all safety and environmental requirements	

These are, of course derived from vehicle mission and performance requirements as well as economic, energy conservation and environmental factors. Meeting these specifications requires a light weight battery that will operate very efficiently and can be produced in volume at a marketable price. These needs, together with the electrochemical design parameters set forth in the preceding Engineering Specification section, provide a second set of criteria that will exert a controlling influence on the design of the electric vehicle battery. These secondary criteria are summarized in Table VII.

MODULE CONCEPT

The design conceived to best meet all these criteria has been evolving at EDA for several years. The concept presented here is that of a self-contained

Table VII

SECONDARY DESIGN CRITERIA

- Battery output to be 50 kWh at C/4 rate
- Electrochemical energy efficiency of 65%
- Chlorine desorption from electrolyte during charge by reduction of stack pressure
- Battery case to operate at less than atmospheric pressure as safety precaution
- Total weight of 1100 lbs
- Use of electrolyte rather than water in hydrate store
- Configuration appropriate to vehicle installation
- Non-serviceable factory-sealed unit
- Use of ordinary, readily-available materials of construction and common mass-production processes

completely sealed battery module operating at a nominal 120 volts d.c. with a capacity of 50 kWh. The term "module" here refers to this integrated battery package as carried on board the vehicle. Separate from this module is a "charging package" containing the auxiliary equipment necessary to recharge the battery. This unit is not normally carried aboard the vehicle. Most likely this will be a stationary, plug-in package containing a regulated d.c. power supply and a source of refrigerated coolant to chill the hydrate store. As the design for this package is not yet developed it is not further discussed in this report.

The following paragraphs describe the salient design features of the battery module as they relate to manufacturing and costs. Figure 3 illustrates the general arrangement of the major components. It can be seen that the module is divided into an upper and lower section separated by a shelf-like member called a chassis structure. The upper section houses the battery stack while the lower section contains the sump and store compartments and most of the auxiliary equipment. The case for each section seals to the edges of this dividing structure.

Many configurations are, of course, possible for any such group of components. The arrangement proposed in this design was chosen to facilitate the installation of the package into a highway vehicle. To achieve a low center of gravity and to protect the battery from external impact it is desirable to locate the unit down between the frame rails. While little is known today of the general arrangement eventually to be developed for the unique electric vehicle of the future, certainly it will be rectangular in plan supported

Figure 3. Exploded drawing of proposed vehicle battery. Note the stack supported in upper portion by the chassis structure while the store, pumps, and auxiliaries are mounted to underside in sump.

by four wheels. It will most likely have a supporting frame with separate body. For the present, the flat stack and store arrangement presented here seems most likely to fit easily into a vehicle developed especially for battery power.

Battery Stack

The battery stack, being the energy storage unit, is the fundamental part of the package. Here, the anode and cathode electrodes are paired in the comb-type bipolar arrangement depicted in Figure 4. The basic unit

Figure 4. Illustrating comb-type bipolar arrangement of basic electrodes in zinc-chlorine battery.

cell is composed of 20 positive or chlorine electrodes and 21 negative or zinc electrodes. This nominal 2 volt cell is rated at 0.84 kWh d.c. Each electrode is made of graphite and has an active surface area, per face, of 69 square centimeters. Two flat plates of porous graphite with a chamber between make up one chlorine electrode. A single flat plate of fine grain graphite is used for the zinc electrode. These electrodes are approximately 2.5 by 4.5 inch rectangles .05 inches thick. These unit cells are assembled together, ten in series, via the bipolar array to form a submodule of the stack. This is a fundamental separate electric and hydraulic unit. Six submodules arranged side by side and electrically connected in series make up the battery stack.

Electrodes

It can be determined from the above that there are 3660 individual electrode plates in each module. Currently, the chlorine electrode plates are detailed for wafer-cutting from saw-sized blocks of porous graphite. The "as cut" surface is suitable and a generous tolerance of $\pm .002$ inches is allowed for ease of manufacturing. The zinc electrode will be produced by the same methods with the same open tolerances from fine-grained graphite. Sharp corners on the top and bottom edges of these electrodes will be rounded. No other secondary operations are required. The total graphite content for all the electrode plates in one module is 2135 cubic inches (1-1/4 cubic feet).

To complete a chlorine electrode, two porous flat graphite plates are mounted in a frame assembly. This frame is illustrated in Figure 5. It is designed as four snap-together precision-molded pieces serving several important functions. Firstly, it holds the two electrode plates apart and seals the edges so as to form a hydraulic chamber between them. Electrolyte is supplied to this chamber through a flow-regulating passage molded into the frame. The sealer strip completes the enclosing of this supply passage that leads from a socket at the bottom to an inlet nozzle near the top. Vents molded in each upper corner of the frame prevent any entrapped gases from accumulating inside the cavity. In addition to these hydraulic functions, the frame also isolates the electrodes electrically and provides the required positioning and structural support to the graphite. An important detail of the sealer strip section is the compliant lip that insures consistent and accurate masking of the mating zinc electrode face even with appropriate production assembly tolerances. The snap-on cap, identical top and bottom, is ribbed to provide stiffness and yet minimize any restriction to upward exit flow of electrolyte. The frame assembles so that one vertical edge of the two graphite plates is exposed for later electrical contact.

At this point it might be well to describe a companion piece - the zinc mask. This separate plastic extrusion is assembled into the stack at a later stage but it serves much the same function as the sealer strip portion of the frame. The zinc mask mounts to the vertical edge of each zinc electrode after submodule assembly. It serves to position the zinc electrode midway between adjoining chlorine electrodes. This mask also has flexible edges to act as accurately positioned screens for the adjacent electrode faces. These masks define the active area of each electrode and are important in controlling dendrites and other edge effects. The frames and masks of one unit-cell contain eleven cubic inches of injection molded plastic. For a complete 50 kWh module these parts require 660 cubic inches of material.

Following preparation of the electrodes, the next step in stack build-up is to construct the comb assembly. An intercell bus bar 4 x 9 x .25 inches made from a fine grained graphite is employed here to serve two fundamental functions. Slots gang-sawed into each face of the bar receive chlorine electrodes on one side and zinc electrodes on the other side. Thus, it

Figure 5. Exploded drawing of chlorine electrode frame components. Note the flexible lip on each side of sealer strip. All parts snap together.

provides a common electrical connection for all electrodes of one type in a cell and a series connection to the opposite type in an adjoining cell. Also the intercell bus, acting as a partition across the electrolyte tray, hydraulically separates one unit cell from the other. These points are illustrated in Figure 6.

Submodule

The electrolyte tray mentioned above organizes ten unit cells into a basic submodule of the stack. Nine identical comb assemblies, inter-meshed one with another, and a unique half-comb at each end, are included in the 8.3 kWh 20 volt submodule. In this design, the surrounding tray is assembled from sections which are made of two nesting injection molded parts. Each section is formed to provide passages for the management of electrolyte flow to and from the unit cell and to provide accurate location, support, and sealing for each separate comb assembly. Figure 7 illustrates one of these tray sections. Ten such units designed to snap together, with two special end sections, form the complete electrolyte tray for each submodule.

The assembly of this submodule is planned sequentially, beginning with an end section and half-comb of chlorine electrodes. Next will be added a typical tray section and then a typical comb assembly - sliding the zinc electrode set into the previously placed chlorine set. Then another tray section will be added and so on.

As each section of tray is brought into place a series of up-standing nozzles molded in a recessed portion of the tray bottom are engaged into the feeder passage sockets of the chlorine electrode frames. By this means, electrolyte is uniformly distributed from the manifold chamber of the tray into each chlorine electrode pack. The exit flow from each unit cell is collected in a basin and drained by gravity through a series of channels under the tray bottom. The completed submodule has a manifold inlet port and an outlet port in the bottom for each of the ten unit cells contained inside.

Chassis Assembly

As was illustrated in Figure 3, the lower portion of the case not only provides an electrolyte sump but also encloses the other operating equipment. The major items are: electrolyte pump, gas pump, chilling heat exchanger, hydrogen reactor, the chlorine hydrate store container, and the hydrate former and filter. Also the control valves to operate the various subsystems are contained inside this case. To facilitate an assembly line approach to module build-up, the dividing shelf is developed into a chassis frame structure. This three layer assembly is constructed of several molded plastic parts bonded together to form a network of fluid distribution passages and several related mounting pads. It also provides a framework to which each of the major components of the system can be bench-assembled. As each of these components is mounted in place the internal conduits of

Figure 6.. Proposed assembly procedure for one submodule. Note that one set of zinc electrodes on a comb is meshed with set of chlorine electrodes on previous comb. Next in sequence is placed a tray section, then the set of zinc masks.

Figure 7. Detail of a typical tray section showing inner and outer parts with fluid passages inside.

the chassis automatically provide the liquid and gas interconnection required between each element. Thus, most of the "piping" and most of the supporting structure for the battery module is provided by this chassis. In keeping with the assembly line concept, the chassis is also designed to provide all the external connections required to the module. The terminal posts are brought out through sealing glands located in this area. Here also is provided the inlet ports for the chilling coolant and the connectors for the various electrical control and data harnesses. By grouping all these outlets in the edge frame of the chassis structure they can be accomplished during final assembly and tested before being enclosed by the case.

Pumps

The two pumps needed to operate this system are one of the important cost items and must be considered an important area of reliability concern. This design incorporates a highly specialized fully-submersible pump-motor combination with a magnetically coupled canned rotor for each assembly. The total overall efficiency of these pump-motor units is very important in meeting the design goals for this system. Achieving these necessary high efficiencies will require a specific pump design engineered with absolute minimum losses in bearings and seals as well as very low hysteresis losses. Submersion eliminates any case openings and possible sealing problems. It also provides constant cooling and greatly facilitates assembly of the module. It is acknowledged that a good deal of effort will be spent to develop such a single purpose special package. However, at this time no particular technical problem is seen that would prevent successful achievement of this goal.

Final Assembly

Once the bottom section is complete and checked, the stack will be assembled on the upper side of the chassis structure. As each submodule is placed in position on this shelf a set of tubular sleeves connect each unit cell manifold to an electrolyte feed chamber within the chassis. These are internal passages designed to uniformly distribute the supply electrolyte at constant velocity from the chassis-mounted pump outlet to each individual unit cell in every submodule. Also provided are channels to collect and route the returning electrolyte from each cell through openings in the chassis to the sump.

After the stack has been assembled the electrical bus connections at the ends of each submodule are made. Titanium-clad copper connectors lead from each external terminal post to pick up the flex connectors for each end submodule. At the opposite end of these terminal submodules, and at alternate ends of all other submodules, a short titanium-clad copper bar connects to the adjacent cell. In this manner all submodules are bussed in series with each other. A portable spot-welder will be used to make these hook-ups. The flex connectors for each submodule are finger-like extensions

of the titanium plate previously attached to the end intercell bus bars. At this point, with assembly complete except for enclosure, the module will likely be given a final electrical and functional check followed by a thorough cleaning.

The case parts, upper and lower, that enclose the entire battery module are designed to be manufactured by the structural foam plastic process. Corrugated surfaces for stiffness and fiber reinforcement for strength will help the case walls resist the slight pressure differentials encountered in battery operation. Though relatively new, structural foam manufacturing is rapidly becoming a well-established, widely used process for molding large rigid plastic parts. Such parts are typically very lightweight and stiff as they result in a firm cellular foam-cored part surfaced with a dense skin on each side. Fiber reinforcing techniques for this process are now under development by material suppliers. Successful use of this technique for zinc chlorine battery cases will also require the development of foamable materials and foaming agents that are compatible with the cell environment. The insulating value of such a case is desirable to maintain temperature control of the battery.

After inspection, each case section will be brought into place enclosing the upper and lower portions of the entire battery assembly. Each section will be pressure sealed to the edge section of the chassis structure. Leak testing to insure a proper seal will complete the assembly procedure.

Section 4

COSTING

INTRODUCTION

The costing presented below projects the selling price of the zinc-chlorine battery when produced in high volume and supported by a semi-mature technology. Further, the cost study attempts to be more comprehensive than previous costings. In so doing, estimates were made for a number of accounts that have a minor effect on the overall costing. The value in this is that it focuses thought and discussion on the implications of those estimates. Of immediate value is the identification of areas requiring further research and development to achieve the semi-mature technology assumed.

In the preceding sections, the engineering specification and a design concept were presented. For the purposes of this report, the presumption was made that they describe the ultimate battery. It must, however, be emphasized that many trade-offs remain to be made between the engineering and the production designs. Also, as these cost and design studies become more detailed, the discrepancies between these designs become more evident. It follows that many evolutionary changes are to be expected as the gap narrows between present technology and a semi-mature technology.

The method of presentation simulates a manufacturing plan. This allows the various cost estimates to be assigned to specific and well-defined cost areas. The sequence which follows lists the cost of materials, process plan, equipment required, plant cost, direct and indirect labor requirements, projection of plant overhead, and the manufacturing selling price.

MATERIALS

The materials cost project those costs existing at the production level of 100 batteries (modules) per day or 25,000 per year. The dollar figures are referenced to mid-1977. Presented below are discussions of the major cost items: graphite, pumps, heat exchangers, and plastics.

Graphite

Three different graphite materials are being specified. The first is a low density porous material to be used for preparing the chlorine electrodes. The other two are denser graphites, one being harder than the other. The softer graphite is used for the zinc electrode whereas the harder material is used for the bus. In respect to the relative costs of the graphites, the porous material is far more expensive. The current price of available porous graphite is \$2.31 per pound. This material has a density of 1.35 grams per cubic centimeter. The direct material cost per plate is computed

by converting the volume of a plate and dividing by an efficiency factor. This efficiency is determinable as the product of the efficiencies of two operations. The first is a block sizing which divides the block as received into small blocks whose height and width correspond to the plate dimensions. The efficiency of this sizing operation depends on the size of the block received. Since the number of the blocks purchased is sufficiently large, the block can be ordered to a pre-specified dimension. A reasonable efficiency for this sizing is 0.90. Substantial waste results from the kerf loss associated with wafering the sized blocks. For every electrode thickness of 0.05 inches, a kerf of 0.030 inches is required. This is a conservative estimate easily achievable by existing wafering machines. Work is in progress to determine its lower limit. The wafering efficiency is 0.625 giving a total efficiency of 0.563 for producing the electrode plates. The direct material cost per plate is, therefore, 11.3 cents.

A similar calculation can be performed for the denser graphite to be used as the zinc electrode. The cost of a selected material is 90 cents per pound in the form of blocks. Since this electrode is 0.04 inches in thickness, the overall efficiency is reduced. Given the graphite density of 1.76 grams per cubic centimeter, the overall cutting efficiency and cost per plate are 0.514 and 5.0 cents, respectively.

The direct material cost per bus bar is computed from the following consideration. The blank has the finished dimensions, 9.625" x 5.000" x 0.250". The specified graphite sells for 84 cents per pound. The cutting is expected to be done by a band saw producing a kerf loss of 0.0625" per bus bar. Allowing a 10% loss for sizing, the efficiency of cutting is calculated as 0.720. Taking the density of the graphite as 1.74 grams per cubic centimeter, the direct material cost per blank is 88.2 cents. The cost of the graphite components per module is determined from the materials list, i.e., there are 6 submodules per module with each submodule containing 11 bus bars, 210 zinc electrodes and 400 porous electrode plates.

Pumps

The pumps required for each module will be of a submersible type and made of materials fully compatible with the system environment. The concept is well known. However, such a pump requires some development. Discussions with pump manufacturers indicate that a sealed pump-cooling-motor combination could be manufactured in the quantities desired for under \$100. The two pumps, although slightly different in terms of the pumping mechanism, are substantially identical. The cost figure selected represents an extrapolation of the costs of smaller pumps that are commercially available. It is highly probable that the eventual pump cost will be less than that projected in the costing.

Heat Exchangers

Two heat exchangers are required for the mobile battery -- the chiller and the radiator. Each is conceived as a standard production item made from

titanium sheet stampings or tube assemblies. Discussions with a commercial titanium fabricator indicated that the proposed design is amenable to low cost production provided that the volume of production is high enough to distribute the cost of the extensive tooling and equipment required. The projected cost of the heat exchangers is considered a reasonable component price of the projection volumes being considered.

Plastics

Throughout the construction of the battery, plastics of various kinds are used in different places and for different purposes. No fluoroplastic materials will be used. Three generic plastics are being considered. They are reinforced polyesters, high density polyethylene and polyvinyl chloride. Materials programs currently in progress are in the process of specifying the total compound to be used for each plastic. These materials will be formed or molded into the shapes required with insignificant material losses.

The case and store container are significant cost items constructed from plastic materials. Glass reinforced polyester is the material of choice having an average wall thickness of 0.25 inches. The method of production will be or resemble a matched die process. The capital investment required is warranted by virtue of the large production volume. The cost estimate for this component is based on calculating the material cost and allowing a fabrication cost equal to the direct material cost. This cost estimate may be somewhat conservative and could be reduced after further analysis.

Materials Summary

Table VIII groups the battery components and assemblies in terms of their direct material content. The major material contributions were discussed earlier. It is the purpose of this costing to project the labor content together with a reasonable justification. Accomplishing this requires that consideration be given to the manner in which the battery is processed. Below is one possible way of conceiving the sequence of operations. Except in the case of graphite cutting, make or buy decisions were not substantiated by an economic analysis of alternatives. In most cases the buy approach was selected. This was done as a convenience. It should be kept in mind that making is usually the more economical route provided that the increased capital expenditure can be afforded and anti-trust laws are not violated. Evidently, further cost reductions, beyond the estimates given in this cost study are conceivable.

PROCESS DESCRIPTION

The processing operations are listed in Tables IX and X. The sequencing shows the flow lines such that materials and assemblies merge from the above or from the left. All descriptions on the right of the flow lines identify the operation. Given for the purposes of reference are the estimated man-hours to perform that operation. Their rationale is presented later in the

Table VIII

MATERIALS COST PER BATTERY (MODULE)

<u>CATEGORY</u>	<u>DIRECT MATERIALS</u>
STACK SUBASSEMBLY	
Zinc electrodes (36.0 lbs)	\$ 63.00
Chlorine electrodes (66.0 lbs)	271.20
Electrode masking (20.7 lbs)	9.62
Bus bars (49.9 lbs)	58.21
Comb and end comb assembly	.00
Submodule trays (13.1 lbs)	10.61
Submodule assembly	.00
MODULE ASSEMBLY	
Chassis structure	37.31
Hydrogen reactor	9.60
Store filter assembly	2.00
Store coil	8.56
Case components and store container	117.22
Electrolyte pump	99.70
Gas pump	99.70
Heat exchangers	156.62
Electrical connectors	35.95
Valve	3.00
Electrolyte	71.52
Battery assembly	.00
Misc. (fittings, probes, adaptors, fan, small hardware)	15.00
PRIME COST TOTAL	\$1068.82

Table IX

SUBMODULE ASSEMBLY FLOW SHEET

(Labor given in manhours per module)

Table X

MODULE ASSEMBLY FLOW SHEET

(Labor given in manhours per module)

TO FINISHED INVENTORY

text. Each of the operations is identified by number. A physical description is presented below for each operation. As conceived here, the processing begins with graphite blocks that are fabricated into electrode combs. The remaining steps are assembly operations using purchased components.

THE MANUFACTURING FACILITY

In order to project the labor requirements and estimate the investment required, a production capacity of 100 batteries per day is assumed. Further, in order to best utilize the equipment, certain operations will be performed on a three shifts per day, five days per week basis. The other operations are based on a two shift day. The description which follows includes estimates of the major process equipment required. For the sake of convenience, a distinction was made between the process equipment and the physical plant. The latter is to be understood to include the remaining investment in the plant equipment. Another way of viewing this is that it includes all equipment that affects the processing indirectly. Tables listing the specific items and costs will be presented later in the text. In respect to the labor figures given, these estimates are understood to be production standards for the purposes of cost estimation. No attempt was made to calculate the actual production standards. For the purposes of consistency, the miscellaneous item in the overhead account, presented later, is presumed to include all positive and negative variances from the standards.

PROCESS DESCRIPTION

Operation
Number

Description

SUBMODULE ASSEMBLY

1	Graphite blocks to be used for preparing graphite buses are received, inspected and inventoried.
2	These graphite blocks are transported from inventory and fed into band saws that reduce them into smaller sized blocks having the length and width dimensions of the bus.
3	The sized block is conveyed to another set of band saws that slice the sized blocks into bus bar blanks.
4	The blanks are passed between a set of ganged saws producing slots in the buses.
5	The buses are cleaned and inspected for conformance with specification.
6	A portion of the prepared buses are sorted for construction into end-buses. Holes are bored into the buses.
7	These buses are backed by titanium sheet and fastened to the bus through the holes.

8. Graphite blocks to be used for preparing the zinc electrode plates are received, inspected and inventoried.
9. The graphite blocks are transported from inventory and fed into band saws that shape them into smaller sized blocks having the length and width dimensions of the plate.
10. The sized blocks are transported and loaded into wafering machines that slice the blocks into plates of specified thickness.
11. The wafered plates are cleaned and inspected. They are then conveyed to the comb assembly, operation 17.
12. Porous graphite blocks to be used for preparing the chlorine electrode plates are received, inspected and inventoried.
13. The graphite blocks are transported from inventory and fed into band saws that shape them into smaller sized blocks having the length and width dimensions of the plate.
14. The sized blocks of porous graphite are transported and loaded into wafering machines that slice the blocks into plates of specified thickness.
15. The wafered plates are cleaned and inspected.
16. The plates are assembled into plastic frames producing chlorine electrode assemblies. These are conveyed to operation 17 - comb assembly.
17. The buses and end buses from operation 7 merge with the electrodes from operations 11 and 16 in the comb assembly machines. The electrodes are pressed into the slots in the buses.
18. The finished combs are transported to the submodule assembler. This device alternately positions combs and tray sections together to build up a submodule. The assembly is inverted so as to be ready for the next operation.
19. This submodule assembly is transported to a test stand where it is filled with activating solution and activated.
20. The submodules are tested upon completion of the activation in order to assess conformance with specifications. This operation completes the submodule assembly.

MODULE ASSEMBLY

21. The chassis structure is received partially assembled. The manifold assembly parts are cleaned and prepared for subsequent operations. The reactor assembly is installed in the receptacle provided. The valve is installed on the side of the manifold plate. The probe connections are threaded through and sealed into the orifices provided. The external current terminals are installed at this time.

- 22 The chassis structure assembly is placed on a conveyor with the top surface down. The filter assembly is then attached.
- 23 Through the center of the filter assembly, the store coil is passed and inserted into the chassis structure.
- 24 The store tub is placed over the store coil and filter assembly. It is then sealed to the chassis structure.
- 25 The electrolyte pump, coupling and motor combination is installed with a stand pipe that serves to route the outgoing flow through the chassis structure. The electrical lines from the pump motor are threaded through the designated opening in the integrated manifold.
- 26 The gas pump, coupling and motor combination is installed together with connecting tubes. These tubes are inserted and sealed into the chassis structure.
- 27 The heat exchanger is installed and connected into the designated openings in the chassis structure.
- 28 The lower case is installed and sealed in place. The assembly is now turned over for the next operation.
- 29 Six submodules, as prepared in step 7, are installed on the top surface of the chassis structure.
- 30 The electrical connectors are installed so as to interconnect each submodule and the electrode terminal taps on the chassis structure.
- 31 The case cover is placed over this assembly and bonded in place.
- 32 The module is filled with helium and leak checked.
- 33 The production batteries are filled with ZnCl_2 and a 1% sample is cycled as a performance check. The batteries are then transported to finished inventory.

Process Equipment, Man Power and Plant
Capacity Requirements

Capacity Note - Operations 1-20 produce 600 submodules per day on a three-shift per day basis. This is consistent with a 100 module per day (6338 kWh/day) production level.

Operation
Number

Requirements

- 1 The incoming inspection and inventorying of the dense graphite blocks is an indirect item. The indirect labor requirements and general plant requirements have been estimated. This listing is presented in another tabulation.

Process equipment cost No major equipment
Estimated direct labor No direct labor

- 2 The block is sized by passing it through a series of belt sanders. This operation removes both the surface skin of the graphite and brings these blocks to within the length and width dimensional tolerances. This is a fast operation capable of removing thin layers of graphite at 40 feet per minute. This same equipment, also, removes the skin from the blocks in operations 9 and 13. The blocks are loaded and handled automatically.

Process equipment cost
 2 Compound belt sanders
 at 50 K\$/each 100,000
Estimated direct labor 4 man hours

- 3 The blocks are cut into slabs on automatically fed band saws. The daily production is 6,600 blanks. Each requires a 10 inch cut at a feed rate of 3 inches/min plus a 0.5 minute reset per blank. This requires 421 hours of cutting. On a twenty-four hour basis, 20 bandsaws in continuous operation are required.

Process equipment cost
 20 bandsaws at 15K\$/ea 300,000
Estimated direct labor 24 man hours

- 4 The blanks produced in the preceding operation pass between an upper and lower set of ganged saws producing slots. Allowing a fifty second cycle time for each of the 6,600 blanks produced per day, 4 machines are required for operation on a 24 hour basis.

Process equipment cost
 4 slotting machines
 at 20 K\$/ea 80,000
Estimated direct labor 24 man hours

- 5 The bus bars are cleaned and inspected. This is an automatic operation in which the blanks are cleared of dust and inspected for cracks and broken edges.

Process equipment cost
Bus cleaner and
comparator
2 machines at 15K\$/ea 30,000
Estimated direct labor 24 man hours

- 6&7 For every eleven (11) buses, two are prepared as end buses. This operation involves drilling six holes per end bus, attaching a titanium sheet to one side and then fastening the sheet to the bus through the holes. Twelve hundred end buses are required every 24 hours corresponding to a production rate of 50 pieces per hour.

Process equipment cost
2 driller-fasteners at
25K\$/ea 50,000
Estimated direct labor 24 man hours

- 8 Same as operation 1.

Process equipment cost No major equipment
Estimated direct labor No direct labor

- 9 The skin is removed from the block using the same equipment described under operation 2. The resulting blocks are then sized so as to produce a block having the length and width dimensions of the electrode plate. This sizing is done by bandsaws having a 4.5 minute cycle time. Two cuts are required in order to produce three sized blocks. In order to make 1,067 cuts over a 24 hour period, 4 bandsaws are required.

Process equipment cost
4 bandsaws at 15K\$/ea 60,000
Estimated direct labor 24 man hours

- 10 The blocks are automatically loaded into wafering machines. These machines are required to produce 126,000 plates per day. Taking a 13.5 second cycle time per plate, 20 machines are required.

Process equipment cost
20 wafering machines at
36K\$/ea 720,000
Estimated direct labor 24 man hours

- 11 Same as operation 5. Also, the operation must process 96 plates per minute over a twenty-four hour period.
Process equipment cost	
Plate cleaner and comparator	
4 machines at 10K\$/ea	40,000
Estimated direct labor	24 man hours
- 12 Same as operation 1 except that the graphite blocks are porous material.
Process equipment cost	No major equipment
Estimated direct labor	No direct labor
- 13 The skin is removed from the block using the same equipment described under operation 2. The block is then sized as described in operation 9, except that approximately twice the number of plates are required.
Process equipment cost	
8 bandsaws at 15K\$/ea	120,000
Estimated direct labor	24 man hours
- 14 Same as operation 10 except that the machines are required to produce 240,000 plates over a 24 hour period. Forty machines are required.
Process equipment cost	
40 wafering machines at 36K\$/ea	1,440,000
Estimated direct labor	24 man hours
- 15 Same as operation 5 except that the cleaning and inspection is of the plates made of porous graphite. Also, the operation must process 167 plates per minute over a 24 hour period.
Process equipment cost	
Plate cleaner and comparator	
8 machines at 10K\$/ea	80,000
Estimated direct labor	24 man hours
- 16 The porous plates are assembled into chlorine electrodes by bonding them into an injection molded plastic frame. This machine is automatically loaded and has a cycle time of 35 seconds. Forty machines are required for production over a 24 hour period.
Process equipment cost	
40 chlorine electrode assembly machines at 45K\$/ea	1,800,000
Estimated direct labor	48 man hours

- 17 The combs are assembled in this operation. The buses, zinc electrodes and chlorine electrodes are conveyed and loaded into the assembly machines. The comb assembly operation presses these assemblies into the slots on one side of the bus counterbalanced by the pressing of the dense electrodes into the groove on the other side of the bus. This operation also schedules the end bus assembly which requires that electrodes be inserted on only one face. The comb assembly has a cycle time of 3.8 minutes so that sixteen machines are required.

Process equipment cost	
16 comb assemblers at	
45K\$/ea	720,000
Estimated direct labor	48 man hours

- 18 The submodule assembly operation requires an assembly machine that locates the comb assemblies and end comb assemblies and interlaces the submodule tray sections. Upon completing this assembly, the submodule is turned over, and placed on a conveyor taking it to the next sequential operation. The cycle time for this operation is three minutes per submodule. This operation is staffed by one worker per shift.

Process equipment cost	
2 assembly machines at	
100K\$/ea	200,000
Estimated direct labor	24 man hours

- 19&20 The submodules are transported to the activation and test work station. Twenty-five test positions are required having a sixty minute cycle time. The associated equipment includes a hood, rectifiers and a data acquisition system. The automated operation and the visual inspection of twenty-five submodules per hour per shift is attended by two workers.

Process equipment costs	
25 test stations complete	250,000
Estimated direct labor	48 man hours

Note: Operations 21-38 are based on a two shift per day.

- 21 The module assembly begins by the inspection and check of the chassis structure. All ports are checked for obstructions. A valve, three probes and the reactor are installed. This operation is performed by 2 workers per shift.

Process equipment cost	No major equipment
Estimated direct labor	
Assembly	32 man hours

22-24

On an assembly line, the assembly from operation 8 is modified by three successive operations at a single station. The filter, the store coil and the store tub are installed. These are fast hand operations performed by one worker per shift. These are routine hand operations.

Process equipment cost	No major equipment
Estimated direct labor	16 man hours

25

At this point the chassis structure lies flat on the assembly line with the tub attached. The electrolyte pump is connected with a section of plastic manifold piping. The sealed electrical wires are threaded through the chassis structure. The operation is performed by one man per shift.

Process equipment cost	No major equipment
Estimated direct labor	16 man hours

26

Similarly, the gas pump is installed.

Process equipment cost	No major equipment
Estimated direct labor	16 man hours

27

The heat exchanger is installed rapidly by hand. One man is required for the entire production.

Process equipment cost	No major equipment
Estimated direct labor	16 man hours

28

The lower case is placed over the assembly and bonded in place. One man per shift operates the bonding equipment that seals the lower case to the integrated manifold assembly.

Process equipment cost	
Lower case sealing equipment	10,000
Estimated direct labor	16 man hours

29

In this operation, the submodule assemblies arrive together with the lower case assemblies. The lower case is inverted and the submodules located and secured. The finished assembly is then conveyed to the next station. An estimated 2 men per shift is required.

Process equipment cost	No major equipment
Estimated direct labor	32 man hours

30

The electrical connectors (i.e., the internal module buses) are installed and connected. This assembly is estimated to require 2 people per shift.

Process equipment cost	No major equipment
Estimated direct labor	32 man hours

- 31 The case cover is bonded in place. This is performed by one man per shift.

Process equipment cost	
Case cover sealing equipment	10,000
Estimated direct labor	16 man hours

- 32 The modules are Helium leak tested to check the sealing. One man performs this task per shift.

Process equipment cost	
Helium leak test equipment	30,000
Estimated direct labor	16 man hours

- 33 Each module is filled with electrolyte and the lot is sampled. A test cycle is run to determine adherence to operating specifications. The batteries are transported to finished inventory. The quality assurance check does not involve direct labor. One man, however, performs the filling and sealing task.

Process equipment cost	
Rectifier, Controller, Data Acquisition System	60,000
Estimated direct labor	16 man hours

Having quantified the labor and equipment requirements for achieving the desired plant capacity, a layout of the manufacturing facility can be projected. Such a layout is shown in Figure 8. This plant will occupy 125,000 ft², have a labor requirement of 163 employees (84 staff and 79 operators) and be divided into two major production departments:

- A graphite processing department where purchased graphite blocks are skimmed, sliced, assembled into combs, combs assembled into submodules and finally the submodules are activated. This operation will require a total of 17 operators on each of the shifts, 3 operators on each of the four comb assembly lines, 1 each on the two bus production lines, 1 on submodule assembly and 2 operators to man the activation equipment.
- An assembly department where the battery modules are assembled on a line comprising ten individual work areas. This line is designed to allow the building of battery modules by successive addition of components to the battery module chassis. This department will require 14 operators on each of two shifts.

INVESTMENT, INDIRECT AND OVERHEAD COSTS

It must be emphasized that the foregoing constitutes only one approach for

processing the battery at the specified production volume. This analysis is the basis and justification for the labor estimates given in Table XI. For the purposes of easy reference, this table also reproduces the materials cost as shown in Table VIII, earlier. A basis now exists for projecting the plant investment. Table XII summarizes the process equipment and their associated costs. Having achieved this, Table XIII was compiled as a basis for estimating the remainder of the physical plant investment. The cost figures are estimates based on the experience of the persons queried. No attempt was made to write a specification for this equipment. The cost figures, therefore, constitute what is believed to be a reasonable allowance for a large number of small items. Consequently, the total should be a good estimate of the aggregate whole. Further, this figure makes a small contribution to the total investment given in Table XIV.

Figure 8. A projected manufacturing plant layout.

Table XI

MATERIALS AND LABOR COST PER BATTERY (MODULE)

<u>CATEGORY</u>	<u>DIRECT MATERIALS</u>	<u>DIRECT LABOR</u>
STACK SUBASSEMBLY		
Zinc electrodes	\$ 63.00	\$ 5.40
Chlorine electrodes	271.20	5.40
Electrode masking	9.62	.00
Bus bars	58.21	7.50
Comb and end comb assembly	.00	7.20
Submodule trays	10.61	.00
Submodule assembly	.00	5.40
MODULE ASSEMBLY		
Chassis structure	37.31	2.40
Hydrogen reactor	9.60	.00
Store filter assembly	2.00	.00
Store coil	8.56	.00
Case components and store container	117.22	.00
Electrolyte pump	99.70	.00
Gas pump	99.70	.00
Heat exchangers	156.62	.00
Electrical connectors	35.95	.00
Valve	3.00	.00
Electrolyte	71.52	.00
Battery assembly	.00	14.40
Misc. (fittings, probes, adaptors, fan, small hardware)	15.00	.00
PRIME COST TOTALS	\$1068.82	47.70

Table XII

PROCESS EQUIPMENT COST

<u>Operation Number</u>	<u>Number Required</u>	<u>Item</u>	<u>Cost (000 Omitted)</u>
2, 9, 13	1	Compound belt sander @ 50K\$/ea	50
3, 9, 13	34	Band saws @ 15K\$/ea	510
4	3	Slotting machines @ 20K\$/ea	60
5	1	Bus cleaner and compactor @ 20K\$/ea	20
11, 15	2	Plate cleaner and comparator @ 65K\$/ea	130
10, 14	54	Wafering machines @ 40K\$/ea	2,160
6, 7	2	Driller-fastener @ 25K\$/ea	50
16	43	Chlorine electrode assembler @ 45K\$/ea	1,935
17	16	Comb assemblers @ 45K\$/ea	720
18	2	Assembly machines @ 100K\$/ea	200
19, 20	25	Submodule test stations @ 10K\$/ea	250
28, 31	2	Case sealing equipment @ 10K\$/ea	20
32	1	Helium leak test equipment @ 30K\$/ea	30
33	1	Rectifier, controller and data acquisition system @ 60K\$/ea	60
Subtotal			6,195
10% Installation			620
30% Contingency			1,860
COST			8,675

Table XIII

PHYSICAL PLANT

(Excludes Process Equipment)

<u>Item</u>	<u>Cost</u> <u>(000 Omitted)</u>
Building, parking lot, heating and air conditioning	rented
Plumbing and drains	40
Shipping and receiving docks	50
Air make-up system	50
Compressed air system	30
Deionized water system	10
Lunchrooms, showers, change rooms	10
First aid and nurse's room	10
General storage	10
Security and supervisory services	20
Computer system	100
Waste treatment system	120
Dust collection and bagging	80
Storage tanks	20
Fume hoods and scrubber system	150
Refrigeration equipment	100
Electrical shop	60
Machine shop	100
Quality Control laboratory	80
Standards laboratory	60
Custodial storage and equipment	20
Shipping and packaging	10
Hi-lo transports: 4 @ \$10,000 each	40
Electrical power conditioning equipment	40
Welding equipment	30
Workbenches, cabinets, etc.	30
Office furniture and partitions	40
Emergency standby power system	40
Engineering laboratory	100
Design and drafting equipment	20
Transports and conveyors	500
Physical Plant Investment	\$1,970

Table XIV

SUMMARY OF INVESTMENT COST

<u>Item</u>	<u>Cost</u> <u>(000 Omitted)</u>
Process equipment	8,675
Physical Plant	1,970
Working capital (0.30 x prime factory cost)	<u>8,313</u>
INVESTMENT	\$18,958

Table XV

LABOR REQUIREMENTS

INDIRECT

<u>Functional Area</u>	<u>Staff</u>
Finance	7
Personnel	4
Manufacturing	
Production Scheduling and Purchasing	8
Production Control	8
Quality Control	13
Manufacturing Engineering	15
Process Engineering	5
Engineering	
Design Engineering	8
Evaluation and Test Engineering	10
Marketing (Customer Service)	<u>2</u>
TOTAL - INDIRECT	80

DIRECT

<u>Area</u>	<u>Personnel</u>
Submodule Assembly	51
Module Assembly	<u>28</u>
TOTAL - DIRECT	79

Table XVI

OVERHEAD COST DISTRIBUTION

	Cost (000 Omitted)
Indirect Labor	
80 people x 12\$/hr (avg.) x 40 hr/wk x 52 wk/yr =	1,996
Depreciation (straight line over 10 years)	
Process equipment 8,675	
Physical plant 1,970	
<u>10,645 ÷ 10</u>	1,065
Rent for Building (including taxes and insurance)	
125,000 ft ² x \$3.75/ft ² /yr	469
Indirect Materials	200
Utilities	100
Repairs and Maintenance	200
Miscellaneous	<u>100</u>
TOTAL OVERHEAD COST	\$4,130

Table XVII

OVERHEAD RATE

	Cost (000 Omitted)
Direct Labor Cost (636mh/day x 250 days/yr x \$7.50/mh)	1,193
Fringes @ 30% of Direct Labor	358
Established Overhead Cost	4,130
Overhead rate (= $\frac{\text{Overhead costs} \times 100}{\text{DL} + \text{Fringes}}$)	266.3%

Table XVIII

MANUFACTURING COST

Yearly Production - 25,000 Batteries

	Cost (000 Omitted)
Direct Materials	
\$1068.82/module x 25,000 modules/yr	26,721
Direct Labor & Fringes	1,551
Overhead	4,130
	<hr/>
FACTORY COST	32,402
General Service and Administration (9%)	2,916
Investment 18,958	
ROI (30% of Investment)	5,687
	<hr/>
PROJECTED BATTERY SALES	41,005
SELLING PRICE PER KILOWATT HOUR	\$32.54

Section 5

DISCUSSION

INTRODUCTION

The cost analysis for the zinc-chlorine battery presented above serves the immediate purpose of projecting and justifying a selling price for the battery. The organization of the presentation, however, had a greater purpose in its design. It should be evident to the reader that only one plan or model was presented for achieving the cost goals for the battery. Obviously, many alternate plans are conceivable. By selecting one, breaking it into its component parts and reviewing its consequences, the analysis provides a sound basis for decision making. Substantially, a model has been conceived together with criteria and values for measuring it against others. Also, considerations that are essential to the successful achievement of the commercialized battery become evident. This is another way of saying that in respect to the battery development program, yesterday's minor details are today's major concerns. Further, it is to the advantage of the developmental effort to identify and define its predictable problems in order that solutions might be anticipated.

In that perspective, an engineering specification was detailed that included the energy and mass flows together with schematics illustrating the operational aspects. Also, a system design, consistent with the engineering specification, was drawn to illustrate the battery as well as attempt to identify possible problem areas. A completely detailed design is not available. However, more than enough is available for envisioning the physical battery structure. The costing was considered from its broadest perspective. That is, the costing is intimately related to the design considered, the materials used, the processing, the production volume, the investment, and the technology available. An attempt was made to reconcile all of these factors and calculate a selling price. The costing was presented in the form of an abbreviated manufacturing plan and as internally self-consistent as possible.

OBSERVATION

The manufacture of the battery, as described earlier, is not complex at all. As shown, graphite blocks are purchased, fabricated into electrode combs and assembled into batteries using purchased parts. None of the equipment required is beyond the state-of-the-art.

It is of interest that some of the make-or-buy decisions made for the purpose of modeling the processing were arbitrary. The graphite parts could also have been purchased. By the same token, more parts could have been made. This would have required a larger investment and, very likely, a net reduction in the product cost. Economic analyses have not been performed for the purpose of testing the advantages of the make-or-buy decisions. Nevertheless, areas of potential business interest are the manufacture of:

- graphite blocks
- heat exchangers
- pumps

In view of the manufacturing needs in these areas, appropriate action could be taken to vertically structure the business in order to reduce production costs.

COMPONENTS AND EQUIPMENT DEVELOPMENT

In the projected cost estimates for the heat exchangers and pumps, the component costs projected by qualified vendors are considered reasonable in terms of materials, labor, and vendor contribution margin. However, development of specific designs remain to be done followed by appropriate capital expenditures by the vendors in order to increase their productivity. The production volume of 25,000 batteries per year can support the amortized investment cost in the vendor's selling price. The plastics considered are in the final stages of qualification. Those materials must then be molded or fabricated for specific battery applications. Appropriate tooling and equipment design must take place. For example, complex molded pieces must be produced and the cell casing must be prepared using minimum amount of material yet have sufficient mechanical strength. As is evident from the process description, assembly and transportation equipment of some complexity must be specified and designed. This is not inherently difficult but would be costly by virtue of the number of machines required. This latter point already has raised some comment. In certain situations, large numbers of identical pieces of machinery were specified. This equipment is currently available for the prices quoted.

However, the investment in the aggregate of identical machines would, very likely, pay for a specialized piece of equipment that would do the entire job for a substantially smaller investment. Although this is probably the case, such a machine does not yet exist. The probability of designing and building such a machine is good. For the purpose of the costing, the available equipment was used.

INFLUENCE OF POROUS GRAPHITE COST ON SELLING PRICE

Graphite is the most expensive single component in the zinc-chlorine battery. Porous graphite - one of the graphite types used - contributes in largest part to the cost of the graphite. As a result, an equation was

derived to mathematically describe the selling price as a function of the cost of porous graphite. This equation is written as follows:

$$S = 2.012 G + 27.87$$

where S is the selling price in \$/kWh and G is the cost of porous graphite in \$/lb. Doing this permits plotting and/or tabulating the function. Table XIX lists a series of selected points.

Table XIX

SELLING PRICE AS A FUNCTION OF GRAPHITE COST

Porous Graphite \$/lb	Battery Selling Price \$/kWh
0	27.87
1	29.88
(2.32)	(32.54)
3	33.91
4	35.92
5	37.93
(5.67)	(39.28)
6	39.94

The bracketed quantities refer to the actual costs of specific materials. The figure 2.32 refers to the cost per pound of the graphite material on which the costing given earlier was based. The 5.67 figure is the present cost per pound of graphite from another source in block form. As used here, the selling price calculation implies that the graphites have the same physical properties - conductivity, resistance to liquid flow, and density. The table shows the sensitivity of the selling price to the specified graphitic material. The table shows that variations in the cost of porous graphite do not reflect themselves as gross changes in the battery selling price.

VEHICLE COST ESTIMATE

Having projected a battery cost, the electric vehicle cost can be projected. For the purposes here, the projection will use the criteria stemming from the method created by Exxon Enterprises as part of its Advanced Battery and Electric Vehicle Development Programs³.

<u>Vehicle Component</u>	<u>Weight (lbs)</u>
Battery	1101
Drive train (50 kW x 5.6 lb/kW)	280
Chassis (Base + Incremental)	1606
Total Vehicle Weight	2987
+ Passengers	350
Operating Weight	3357

Having distributed the vehicle weight, a cost analysis can be made following the same method:

<u>Component</u>	<u>Cost (mid-1977 dollars)</u>
Battery*	1640
Chassis	
Base	1296
Incremental	229
Drive Train	
Base	108
Incremental	648
	3921
Mark-up (28.8%)	1129
Consumer Cost	<u>\$5,050</u>

*The battery cost is \$32.54/kWh, its weight is 1101 lbs and it can deliver 50.4 kWh.

Using the Los Angeles Driving Cycle as a reference³, the energy consumption at the wheels is taken as 0.075 Wh/lb-mile and a transmission energy efficiency, 72%. The projected vehicle range is calculated as 150 miles. As a result, the zinc-chlorine powered electric vehicle would fall into the ERDA classification of a Mid-Term automobile goal⁴. The Exxon report tends to supplement the NASA study quoted in the Introduction¹. That is, if the Los Angeles Driving Cycle is assumed, vehicle price is more dependent upon battery cost than battery energy density for mid to far term systems. Once again, it would appear that the zinc-chlorine battery is an excellent candidate for electric vehicle applications.

BATTERY CHARGER

The estimate and projections made in this report have specifically excluded the battery charging system. This area is of current interest in terms of the design and cost analysis. This study is in its preliminary stages and will be the object of a report to be issued in the near future. Generally, the charging system will be composed of a refrigerator and a rectifier sized for vehicle battery charging. These major components will be integrated into an operational package and a cost estimated assuming production rate of 25,000 units per year. Although preliminary, a cost in the area of \$400 per unit (\$8/kWh) is considered a reasonable allowance at this time.

THE FUTURE

Progress, in the area of cost and design, eventually leads to the development of a manufacturing plan. The preceding report is a preliminary version

of that plan by describing what is to be built, how it is to be accomplished and what is needed to do the job. By virtue of the detail in the presentations, it is, thereby, thrown open to further analysis, commentary and discussion. It is anticipated that better problem definition will result so as to better crystallize the direction toward eventual production. The work that is to follow will open the above process plan to greater scrutiny and result in more detailed documentation. A detailed manufacturing plan is the proximate goal. Ultimately, a detailed business plan will result.

Section 6

REFERENCES

- 1 "The Computer Simulation of Automobile Use Patterns for Defining Battery Requirements for Electric Cars": J.J. Schwartz, Fourth International Electric Vehicle Symposium, Dusseldorf, 1976.
- 2 "Engineering Design and Cost Analysis of Chlorine Storage Concepts for a Zinc-Chlorine Load-Leveling Battery"; prepared by Bechtel Corporation, San Francisco, California; EPRI EM-259, Final Report November, 1976.
- 3 "Modeling of Electric Vehicle Battery Applications"; L.H. Gaines, H.B. Sykes; Extended Abstracts, Electrochemical Society, Spring Meeting, May 1977.
- 4 "Electric Vehicle Design"; ERDA RFP No. E(04-3) 1213, March 1976.