Advanced Vehicle Systems Assessment

Volume V: Appendices

March 1985

Prepared for
U.S. Department of Energy
Through an Agreement with
National Aeronautics and Space Administration
by
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Advanced Vehicle Systems Assessment, Vol. V: Appendices

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Volume V, the Appendices, includes reports on battery design, battery cost, aluminum vehicle construction, IBM PC computer programs, and battery discharge models. Other volumes are Volume I, Executive Summary, Volume II, Subsystems Assessment, Volume III, Systems Assessment, and Volume IV, Preference and Aftermarket Analyses.
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JPL NASA Task RE-152, Amendment 170, DOE Intergovernment Agreement No. DE-AL01-78CS54209.
ABSTRACT

This report, which is divided into five volumes, documents the evaluation of advanced electric and hybrid vehicles for potential development by the early 1990s. The primary objective of the assessment is to recommend subsystem research priorities based on a comparison of alternatives as part of complete vehicle systems with equivalent performance. The assessment includes evaluations of candidate technologies as well as technical and economic comparisons of vehicle systems for specified missions. The availability of nonpetroleum fuel is also addressed, and preference analyses are used to assist in the evaluation of the relative merits of competing systems.

Volume V, the Appendices, includes reports on battery design, battery cost, aluminum vehicle construction, IBM PC computer programs, and battery discharge models. Other volumes are Volume I, Executive Summary, Volume II, Subsystems Assessment, Volume III, Systems Assessment, and Volume IV, Preference and Aftermarket Analyses.
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APPENDIX A

GUIDELINE FOR CONTRACTOR RESPONSE
GUIDELINE FOR CONTRACTOR RESPONSE

This version of the guideline addresses the concerns expressed by the review board and battery developers at the Electric Hybrid Vehicle (EHV) Systems Assessment Seminar. Battery sizes are expressed explicitly, and the questions are geared toward complete battery systems rather than specific energy or power.

Table A-1 illustrates the differences in power and energy requirements determined for vehicles simulated to date, depending on the application (using the current models). Several examples of electric vehicles and perhaps the most extreme hybrid vehicle (full-power capability in electric mode) are shown, which bound the extremes of power-to-energy ratio (P/E). The P/E ratio defines the ratio of the power available for acceleration and the energy required to meet the range requirement so that the vehicle would "run out" of power and energy at the same time, and therefore would not be overdesigned with respect to either characteristic. The variation in the specification is the result of the differences in specific energy and specific power between the batteries, which resulted in variations in vehicle weight.

Table A-1. Differences in Power and Energy Requirements

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Power, kw</th>
<th>Vehicle Specific Power, W/kgvtw</th>
<th>Energy, kWh</th>
<th>Vehicle Specific Energy, WH/kgvtw</th>
</tr>
</thead>
<tbody>
<tr>
<td>4-Pass 80-km HV</td>
<td>36-41</td>
<td>30</td>
<td>9-11</td>
<td>8-9</td>
</tr>
<tr>
<td>(P/E = 3.3-3.8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-Pass 80-km HV</td>
<td>44-50</td>
<td>30</td>
<td>13-15</td>
<td>8-9</td>
</tr>
<tr>
<td>(P/E = 3.3-3.8)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/4 Ton 96-km Van</td>
<td>46-57</td>
<td>23</td>
<td>20-23</td>
<td>9-10</td>
</tr>
<tr>
<td>(P/E = 2.3-2.6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*aBattery energy requirements are on the Federal Urban Driving Schedule and do not include self-discharge, thermal losses, etc. Power requirements are for 30 seconds at low state of charge (i.e., typically 10 to 15%).
bVehicle Test Weight.
### Table A-1. Differences in Power and Energy Requirements (Continued)

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Power, kW</th>
<th>Vehicle Specific Power, W/kgVTW</th>
<th>Energy, kWh</th>
<th>Vehicle Specific Energy, WH/kgVTW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Pass 128-km EV</td>
<td>20-26</td>
<td>25</td>
<td>9-12</td>
<td>11-12</td>
</tr>
<tr>
<td>(P/E = 2.1-2.3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-Pass 160-km EV</td>
<td>37-58</td>
<td>30</td>
<td>18-26</td>
<td>13-14</td>
</tr>
<tr>
<td>(P/E = 2.1-2.3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-Pass 240-km EV</td>
<td>44-58</td>
<td>30</td>
<td>27-36</td>
<td>19-20</td>
</tr>
<tr>
<td>(P/E = 1.5-1.6)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4-Pass 400-km EV</td>
<td>32-43</td>
<td>30</td>
<td>46-56</td>
<td>30-32</td>
</tr>
<tr>
<td>(P/E = 0.9-1.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5-Pass 400-km EV</td>
<td>40-53</td>
<td>30</td>
<td>53-56</td>
<td>30-32</td>
</tr>
<tr>
<td>(P/E = 0.9-1.0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Battery energy requirements are on the Federal Urban Driving Schedule and do not include self-discharge, thermal losses, etc. Power requirements are for 30 seconds at low state of charge (i.e., typically 10 to 15%).

*Vehicle Test Weight.

Interpretation of the information in Table A-1 would lead to the following estimates of delivered energy and power requirements for batteries in advanced vehicles, although detailed analysis is ultimately required for each case (due to self-discharge, etc.):

1. **Commuter vehicle battery** - 12 kWh, 25 kW.
2. **Hybrid vehicle battery** - 15 kWh, 50 kW.
3. **General-purpose Electric Vehicle (EV) or commercial van battery** - 25 kWh, 60 kW.
4. **Full-performance EV battery** - 50 kWh, 50 kW.

These specifications are distinct, and the following questions are designed to determine the specific performance, cost, and volume of these batteries. The guideline has been organized into seven basic categories: performance modeling, cost projections, technical support for projections, energy balance, life considerations, other operational characteristics, and
packaging flexibility. You should make every effort to respond to all the categories and supply any appropriate data or designate where there is insufficient data to support a projection.

Several ground rules must be established in an effort to standardize the projections as much as possible. Battery projections should be made for a one-year-old battery operating in 70°F ambient air. The technology projections should be limited to batteries that could be demonstrated in prototype form in the early 1990s (i.e., 1990 to 1992) and the range of applicability should be stated (i.e., 10 to 50 kWh?).

1. PERFORMANCE MODELING

(a) Battery discharge characteristics for the present battery and projections for batteries with the previous specifications. If unable to meet the extremes, specify the limiting cases. Please respond in tabular form below with the specific energy yielded as a function of the constant discharge rate specified. Identify range of applicability and any scaling concerns.

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Specific Energy (Wh/kg) Versus Discharge Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 W/kg</td>
</tr>
<tr>
<td>1 - Present</td>
<td></td>
</tr>
<tr>
<td>2 - Commuter</td>
<td></td>
</tr>
<tr>
<td>3 - Hybrid</td>
<td></td>
</tr>
<tr>
<td>4 - EV or Van</td>
<td></td>
</tr>
<tr>
<td>5 - Full-Perf.</td>
<td></td>
</tr>
</tbody>
</table>

(b) 30-second peak specific power capability versus state of charge (as defined for the standard C/3 or C/4 rates).

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>30-second power capability (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80% SOC</td>
</tr>
<tr>
<td>1 - Present</td>
<td></td>
</tr>
<tr>
<td>2 - Commuter</td>
<td></td>
</tr>
<tr>
<td>3 - Hybrid</td>
<td></td>
</tr>
<tr>
<td>4 - EV or Van</td>
<td></td>
</tr>
<tr>
<td>5 - Full-Perf.</td>
<td></td>
</tr>
</tbody>
</table>

2. COST PROJECTIONS

Production price to the Original Equipment Manufacturers (OEMs) in quantities of 100,000 units per year. The estimates should be per A. D.
Little guidelines and your opinion of the assumed values in the guidelines should be specified where they differ from your own. Estimates should include all thermal management or servicing systems (i.e., watering).

### Battery Design

<table>
<thead>
<tr>
<th>Design</th>
<th>$/battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td></td>
</tr>
<tr>
<td>Commuter</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
</tr>
<tr>
<td>EV or Van</td>
<td></td>
</tr>
<tr>
<td>Full-Perf.</td>
<td></td>
</tr>
</tbody>
</table>

#### 3. TECHNICAL SUPPORT FOR PROJECTIONS

List how the performance improvements would be obtained over the present battery capabilities in the following format. Try to be as specific as possible to allow the review board to adequately assess the credibility of the projections (i.e., current collectors, active material, separators, case, auxiliaries, etc.). Specify trends if nothing else, and supplement the table with explanation, if necessary.

<table>
<thead>
<tr>
<th>Component</th>
<th>Present Status</th>
<th>Design Change</th>
<th>Performance Change</th>
<th>Cost Change</th>
<th>Comments</th>
</tr>
</thead>
</table>

#### 4. ENERGY BALANCE

It is necessary to quantify sources of energy use other than that reflected in the performance modeling. This includes any notable start-up or shut-down energy, self-discharge and shunt currents, parasitics, thermal effects (i.e., heat transfer that must be replaced by electricity), charge efficiency, etc. This is necessary to reflect in-use efficiency over 24-hour driving schedules as simulated in the AV Assessment. A simplified 24-hour driving pattern is used here to allow your estimation of energy use (see Table A-1). The driving portion (designated driving cycle 3) was proposed by JPL to the EHV Battery Task Force as a greatly simplified version of the Federal Urban Driving Schedule to be used for life-cycle testing. This cycle retains the peak power as well as other critical parameters of the original cycle. The distance of 46 km (29 mi) is approximately the average daily trip length of a 16,000 km/yr (10,000 mi/yr) vehicle. You are asked to estimate the energy use by segment of the cycle in the table supplied on the following page. The details of the cycle are included at the end of the guideline to support detailed analyses, if necessary. The values in the table should be specified as power (Watts) assumed continuous over the segment or total energy (Watt-hours) for the segment. Please comment if there are special circumstances to consider or any other concern for the way the estimates are to be used.

A-6
**Figure A-1. Simplified 24-h Driving Pattern**

**ESTIMATES OF IN-USE ENERGY CONSUMPTION**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-up and</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>shut-down</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Self-discharge</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shunt current</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parasitics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal loss(^a)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Charge Eff.(^b)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Only that which requires replacement by electricity (specify electrical-to-thermal efficiency).
\(^b\)Specify charger efficiency as well if unique to battery.
5. LIFE CONSIDERATIONS

(a) Present status of cycle life, including statistical background and life-limiting mechanisms.

<table>
<thead>
<tr>
<th>Cycle Life</th>
<th>Depth-of-Discharge</th>
<th>Life-limiting Mechanisms</th>
<th>Statistical Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modules</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Batteries</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Projected cycle life, including approach to solving failure modes and effects on cost. Specify any differences between high-power and high-energy designs.

(c) Life effects on specific power and energy, efficiency, thermal characteristics (i.e., linear degradation with cycle life?)

(d) Estimate of reliability of smallest replaceable block of cells in a battery, failure modes, mean-time-to-failure, etc.

6. OTHER OPERATIONAL CHARACTERISTICS

(a) Special Charge Requirements

What happens if the cells are over-charged or over-discharged?

Is individual cell balancing required? If so, how often?

Is periodic complete discharge required? If so, how often?

Is equalizing necessary? If so, how often?
(b) Maintenance Requirements

What regular maintenance is required? How often?

What potential exists for battery refurbishment rather than replacement? How does this compare in cost with replacement?

7. Packaging Flexibility

(a) Volumetric considerations for various designs

<table>
<thead>
<tr>
<th>Design</th>
<th>Volumetric Considerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td></td>
</tr>
<tr>
<td>Commuter</td>
<td></td>
</tr>
<tr>
<td>Hybrid</td>
<td></td>
</tr>
<tr>
<td>EV or Van</td>
<td></td>
</tr>
<tr>
<td>Full-Perf.</td>
<td></td>
</tr>
</tbody>
</table>

(b) Size limitations

What are the minimum possible measurements of the battery cells or modules (i.e., height, width, length), and what are the primary considerations in changing from the present configuration?

(c) Any special consideration for relative placement of subsystems in a vehicle (i.e., necessity to place fluid reservoir near cell stack)?

(d) Scale effects in the 10- to 50-kWh range, if applicable.
### CYCLE 3

<table>
<thead>
<tr>
<th>No.</th>
<th>Time, s</th>
<th>Type&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Energy consumed, W-s/kg</th>
<th>Average Power, W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 - 26</td>
<td>A</td>
<td>298</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>26 - 30</td>
<td>A</td>
<td>358</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>30 - 74</td>
<td>A</td>
<td>1428</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>74 - 76</td>
<td>A</td>
<td>94</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>76 - 171</td>
<td>D</td>
<td>-265</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>171 - 196</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>196 - 211</td>
<td>A</td>
<td>497</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>211 - 236</td>
<td>C</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>236 - 251</td>
<td>D</td>
<td>-155</td>
<td>-10</td>
</tr>
<tr>
<td>3</td>
<td>251 - 276</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>276 - 291</td>
<td>A</td>
<td>497</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>291 - 316</td>
<td>C</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>316 - 331</td>
<td>D</td>
<td>-155</td>
<td>-10</td>
</tr>
<tr>
<td>4</td>
<td>331 - 356</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>356 - 371</td>
<td>A</td>
<td>497</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>371 - 396</td>
<td>C</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>396 - 411</td>
<td>D</td>
<td>-155</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>411 - 436</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup> A - acceleration.  
D - deceleration.  
S - stand.  
C - cruise.
APPENDIX B

NICKEL-IRON BATTERY DESIGN ANALYSIS
NICKEL-IRON BATTERY DESIGN ANALYSIS
IN SUPPORT OF THE
ELECTRIC AND ELECTRIC HYBRID VEHICLE
PROJECT

BY:

EAGLE-PICHER INDUSTRIES, INC.
JOPLIN, MISSOURI

FOR:

JET PROPULSION LABORATORY
CONTRACT 956781
TASK RE-152/170

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<th>DESCRIPTION</th>
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</table>
1.0 SUMMARY

The estimates presented in this report are based on the established performance of the nickel-iron battery from 1980 through 1983. The projections for the advanced batteries, 1986, are based on the extrapolation of existing data as designs are modified to favor specific energy or power. The narrow difference between the present and the "advanced" battery indicates the maturity of this technology compared to what is ultimately possible in the nickel-iron system. Additionally, the relatively modest differences between "power" and "energy" designs indicates that standardization to eliminate manufacturing differences and reduce costs slightly would be advantageous for this near term battery. The cost estimate for the battery is based on the analysis completed for ANL in May 1983. Because the main cost driver in this system is the nickel metal, the advanced batteries have less metallic nickel in the positive electrodes. The estimate is based on 85% porous plaque. The higher cost reflected in the EHV batteries compensates for the extra nickel to improve the power capability of the battery.

This analysis indicates that the nickel-iron battery will yield adequate performance for the Commuter, Hybrid and EV-Van type vehicles. In the full performance 5 passenger 400 KM EV the present battery would approach 50% mass fraction of the vehicle. The advanced battery would still be 45% of the total weight. The nickel-iron unit seems appropriate for the near term in all but the full performance applications.
### TABLE 1-1

**SUMMARY OF PRESENT BATTERY CHARACTERISTICS**

<table>
<thead>
<tr>
<th>MISSION</th>
<th>ENERGY</th>
<th>POWER</th>
<th>SP. ENER.</th>
<th>SP. PK. PWR.</th>
<th>COSTxx</th>
<th>VOLUME</th>
<th>WT.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KWH</td>
<td>KW</td>
<td>WH/KG</td>
<td>W/Kg</td>
<td>$Batt.</td>
<td>(L)</td>
<td>KG</td>
</tr>
<tr>
<td>Commuter</td>
<td>12</td>
<td>25</td>
<td>48</td>
<td>&gt; 80</td>
<td>2100</td>
<td>130</td>
<td>250</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>50</td>
<td>45</td>
<td>&gt; 120</td>
<td>2760</td>
<td>175</td>
<td>333</td>
</tr>
<tr>
<td>EV or Van</td>
<td>25</td>
<td>60</td>
<td>48</td>
<td>&gt; 80</td>
<td>4370</td>
<td>260</td>
<td>520</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>50</td>
<td>50</td>
<td>48</td>
<td>&gt; 80</td>
<td>8740</td>
<td>520</td>
<td>1042</td>
</tr>
</tbody>
</table>

x 20% SOC

xx For Production Quan 10,000 batt/yr.

MFG - Costs

### TABLE 1-2

**SUMMARY OF ADVANCED BATTERY CHARACTERISTICS**

<table>
<thead>
<tr>
<th>MISSION</th>
<th>ENERGY</th>
<th>POWER</th>
<th>SP. ENER.</th>
<th>SP. PK. PWR.</th>
<th>COSTxx</th>
<th>VOLUME</th>
<th>WT.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KWH</td>
<td>KW</td>
<td>WH/KG</td>
<td>W/KG</td>
<td>$BATT</td>
<td>(L)</td>
<td>KG</td>
</tr>
<tr>
<td>Commuter</td>
<td>12</td>
<td>25</td>
<td>56</td>
<td>&gt; 100</td>
<td>1400</td>
<td>110</td>
<td>214</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>50</td>
<td>50</td>
<td>&gt; 140</td>
<td>1830</td>
<td>155</td>
<td>300</td>
</tr>
<tr>
<td>EV or Van</td>
<td>25</td>
<td>60</td>
<td>56</td>
<td>&gt; 100</td>
<td>2960</td>
<td>223</td>
<td>446</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>50</td>
<td>50</td>
<td>56</td>
<td>&gt; 100</td>
<td>5800</td>
<td>446</td>
<td>893</td>
</tr>
</tbody>
</table>

x @ 20% SOC

xx For Production Quan 10000 Bat/yr.

including 15% factor to approximate OEM price.
2.0 INTRODUCTION

The Eagle-Picher Nickel-Iron Battery is being developed under DOE sponsorship especially for electric and electric hybrid vehicles. The approach has been to strive for the ultimate performance from the battery while eliminating all superfluous weight. The result is a battery consisting of sintered electrodes which are light weight and of low resistance while retaining the structural integrity to survive 100% DOD cycling for over 1000 cycles. The program has progressed to the point where the achievement of its goals is imminent.

The suggested cell discharge reactions for this battery are:

\[ \text{Fe} + 2\text{OH}^{-} \rightarrow \text{Fe(OH)}_2 + 2\text{e} \quad \text{(anode)} \]

\[ 2\text{NiOOH} + 2\text{H}_2\text{O} + 2\text{e} \rightarrow 2\text{Ni(OH)}_2 + 2\text{OH}^{-} \quad \text{(cathode)} \]

\[ 2\text{NiOOH} + \text{Fe} + 2\text{H}_2\text{O} \rightarrow 2\text{Ni(OH)}_2 + \text{Fe(OH)}_2 \quad \text{(combined)} \]

This battery system has many advantages when compared to other units. The battery has demonstrated:

A doubling of vehicle range with the attending improved utility and decreased maintenance.

It requires no unique auxiliary equipment or periodic equalization.

It has excellent life expectancy which yields increased vehicle reliability and lowers life cycle cost.

The nickel in the battery is not consumed and is fully recoverable from expended batteries.

The present status of the Nickel-Iron Battery Development program indicates that the traditional long life expectancy of the system has not been compromised. Cells have demonstrated life cycle capability in excess of 2000, 100% DOD cycles. Modules and full size batteries have
been tested to in excess of 1000 cycles with tests continuing. One battery
has been in practical service for four (4) years without degradation of
performance.

3.0 BATTERY DATA

The objective of this report is to help estimate nickel-iron batteries
for electric vehicles. This section presents the data upon which all the
performance, size, weight and cost estimates are based. Included with the
data generated by EPI is published data from JPL publication 82-91 and NBTL
reports.

3.1 Specific Energy

The projected specific energy of the nickel-iron battery is 56 WH/
Kg. This is the goal of the development program sponsored by DOE. Table
3-1 shows the design highlights of the present battery with alternate pro-
posed designs to achieve the specific energy goals. A detailed comparison
of the weight distribution in these designs follows in Figure 3-1, a scale
weight representation of each component. The advanced battery designs save
weight by reducing the electrolyte and the iron content of the cells with
minor reductions in nickel grid, case material and separator weight. The
accomplishment of either design, "A" or "B", requires only that the pos-
tive electrode achieve its desired performance. The status is that
electrodes up to 4.0 mm in thickness have been developed. The one
remaining problem is to improve their strength to be comparable with the
2.0 mm electrodes which have demonstrated excellent life characteristics.

3.2 Performance

The self explanatory data of Figures 3-2 through 3-8 outlines the
general characteristics of the nickel-iron battery from constant current
<table>
<thead>
<tr>
<th></th>
<th>&quot;A&quot;</th>
<th>&quot;B&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present Status</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 Pos. 2.0 mm</td>
<td>8 Pos. 3.0 mm</td>
<td>6 Pos. 4.0 mm</td>
</tr>
<tr>
<td>80% Porous</td>
<td>85% Porous</td>
<td>80% Porous</td>
</tr>
<tr>
<td>85% Utilization</td>
<td>85% Utilization</td>
<td>85% Utilization</td>
</tr>
<tr>
<td>13 Neg. 1.2 mm</td>
<td>7 Neg. 1.5 mm</td>
<td>5 Neg. 2.0 mm</td>
</tr>
<tr>
<td>2 Neg. 0.8 mm</td>
<td>WORKED @ 0.8 AH/CC</td>
<td>WORKED @ 0.8 AH/CC</td>
</tr>
<tr>
<td>WORKED @ 0.65 AH/CC</td>
<td>WORKED @ 0.8 AH/CC</td>
<td></td>
</tr>
<tr>
<td>24 Separator @ 0.85 mm</td>
<td>16 Separator @ 0.7 mm</td>
<td>12 Separator @ 0.7 mm</td>
</tr>
<tr>
<td>295 AH</td>
<td>295 AH</td>
<td>295 AH</td>
</tr>
<tr>
<td>1.23 V</td>
<td>1.21 V</td>
<td>1.21 V</td>
</tr>
<tr>
<td>7.0 kg</td>
<td>5.5 kg</td>
<td>5.6 kg</td>
</tr>
<tr>
<td>51.8 WH/kg</td>
<td>64.9 WH/kg</td>
<td>63.7 WH/kg</td>
</tr>
</tbody>
</table>

**Table 3-1**

ADVANCED BATTERY
MORE HIGHLY WORKED IRON PLATES
WITH COINING AND SUPHIDE ADDED
MORE HIGHLY WORKED IRON PLATES WITH COINING AND SULFIDE ADDED
IRON AT 0.8 AH/CC
POS AT 85% UTILIZATION

PRESENT STATUS

<table>
<thead>
<tr>
<th>ELECTROLYTE</th>
<th>POS. ACT. MAT.</th>
<th>85% POROUS PLAQUE</th>
<th>85% POROUS PLAQUE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7.0 kg.</td>
<td>5.49 kg.</td>
<td>5.57 kg.</td>
</tr>
<tr>
<td>POS. MAT.</td>
<td>6.09 kg.</td>
<td>4.74 kg.</td>
<td>4.86 kg.</td>
</tr>
<tr>
<td>CASE</td>
<td>6.52 kg.</td>
<td>3.62 kg.</td>
<td>3.84 kg.</td>
</tr>
</tbody>
</table>

INACTIVE NICKEL (PLAQUE)

<table>
<thead>
<tr>
<th>POS. ACT. MAT.</th>
<th>85% UTIL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.73 kg.</td>
<td>3.25 kg.</td>
</tr>
<tr>
<td>1.2 kg.</td>
<td>2.38 kg.</td>
</tr>
</tbody>
</table>

INACTIVE IRON

<table>
<thead>
<tr>
<th>POS. ACT. MAT.</th>
<th>85% UTIL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.41 kg.</td>
<td>3.62 kg.</td>
</tr>
</tbody>
</table>

ACTIVE IRON

<table>
<thead>
<tr>
<th>POS. ACT. MAT.</th>
<th>85% UTIL.</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.90 kg.</td>
<td>3.25 kg.</td>
</tr>
</tbody>
</table>

FIGURE 3-1
Figure 3-2

Eagle-Picher Industries
Nickel-Iron
Constant Current Discharge Profiles
Cell #33
Rating: 260.0 Amp Hour

Discharge Voltage vs. Amp-Hour Output

- 45.0 Amp Discharge
- 90.0 Amp Discharge
- 180 Amp Discharge
- 360 Amp Discharge

Original Page Is of Poor Quality
Figure 3-3

Nickel-Iron Cell
Open Circuit Stand Capacity Retention

Cell No. 33
Theoretical Capacity: 326 Ah (Positive Electrodes)
Rated Capacity: 280 Ah

Legend:
Ambient Temperature (20°C) Throughout Charge, Open Circuit, and Discharge

Output (amps)
FIGURE 3-5
NICKEL IRON CELL VHF-270
CHARGE ACCEPTANCE
VS.
IMPUT AND RATE

Legend, A.H. Charge

- 280
- 210
- 140

Discharge Capacity, A.H.

Cell 33

Cell 34

Charge Time, Hrs

10 20 30 40
discharge to charge efficiency.

3.2.1 Specific Energy vs Rate, KWh vs KW

This type presentation of the data on the VNF-270 can be derived from Figure 3-2 using the 140 AH voltage as average for the discharge, and 7.0 Kg for the weight of the cell. Each curve represents a nearly constant wattage discharge. The decrease in energy density is in proportion to the voltage decrease.

The graph of Figure 3-9 from JPL publication 82-91 shows the EPI battery energy density near 40 WH/Kg from 10 to 20 watts/Kg discharge. With an electrolyte change that battery is now operating in the region indicated near 50 WH/Kg.

The graph of Figure 3-10 shows the Ragone plot derived by the NBTL at ANL. The similarity of these curves confirms the relatively flat output vs rate characteristic of the nickel-iron battery.

3.2.2 Peak Specific Power W/Kg

The original data for this characteristic was published by NBTL in the DOE Electric and Hybrid Vehicle Program Quarterly Report No. 11. That data is reproduced here as Figure 3-11. Figures 3-12 and 3-13 are provided to support the projections for the advanced designs. Figure 3-12 shows the immediate improvement in power available from reduced height electrodes. All the advanced batteries are based on electrodes about 130 mm high. Figure 3-13 shows that additional gains may be realized by improving the conductivity of the electrodes. Investigations to determine the optimum design continue.

3.3 Cost Projections

This information regarding the cost projection for nickel-iron
Figure 3-9

Specific Energy vs Rate

Recent Meas. Same E.P.I. Battery
EPI Battery
Globe Battery (Estimated)
Westinghouse Battery

Average Power, kW

Capacity of the EPI, Globe, and Westinghouse Batteries Immediately After Charge Termination

Specific Energy, Wh/kg
FIGURE 3-10

An NBTL Derived Ragone Plot Showing Specific Energy as a Function of Specific Power for Several Types of Aqueous Mobile Batteries.
Six sustained peak power versus time plots for each of six depths of discharge of an Eagle Picher 5-cell, 280 Ah, nickel/iron battery.

Specific peak power sustained for 30 second duration corresponding to three depths of discharge (DOD) for six batteries tested at the NBTL.
FIGURE 3-12

POSITIVE PLATE SHAPE

INFLUENCE ON POWER CAPABILITY

% DISCHARGE

165 x 150 MM
2.0 MM THICK

165 x 195 MM
2.0 MM THICK

SP PEAK POWER 25 SEC W/KG

100

80

60

40

30

20

10

0

140

160

180
batteries has been abstracted from an analysis performed for ANL. This information has been supplied in detailed reports to both ANL and JPL supporting the contention that battery manufacturing costs in the region of $100/KWH are reasonable.

**Assumptions**

1. The high energy design (using 85% porosity nickel plaque) is successful.
2. Impregnation and other plate processes under development would be utilized.
3. Battery production level at 10,000 units, 25 KWH each, per year.
4. Quotations were received late 1982 and not upgraded by cost indexing.
5. Iron electrodes would be manufactured in U.S.A.

Table 3-2 cost analysis results in 1982 dollars follows:

4.0 **RESULTS AND DISCUSSION**

4.1 **Performance Modeling**

The nickel-iron battery has not been designed for continuous discharge rates higher than 60 W/Kg. However, since it is a moderately low specific energy battery it does deliver sufficient wattage for all the vehicles. Only the watts per kilogram appear low because of the batteries weight. Table 4-1 gives the results of the calculations on the present battery 1980-1983. Table 4-2 shows the estimates for the advanced battery, 1986.
### TABLE 3-2

**COST ANALYSIS RESULTS**

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>$/KWH</th>
<th>TOTAL DOLLARS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELL</td>
<td>67.02</td>
<td>1742.30</td>
</tr>
<tr>
<td>MODULE/BATTERY</td>
<td>8.76</td>
<td>227.68</td>
</tr>
<tr>
<td>PROCESS</td>
<td>7.15</td>
<td>185.97</td>
</tr>
</tbody>
</table>

**LABOR**

<table>
<thead>
<tr>
<th>LABOR</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>ELECTRODE PROCESSING</td>
<td>12.00</td>
<td>312.00</td>
</tr>
<tr>
<td>POSITIVE (8.26)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEGATIVE (3.74)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MODULE/BATTERY ASSEMBLY</td>
<td>3.74</td>
<td>97.20</td>
</tr>
<tr>
<td>MATERIAL HANDLING</td>
<td>2.67</td>
<td>69.60</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$101.34</td>
<td>$2634.75</td>
</tr>
</tbody>
</table>
TABLE 4-1

PRESENT BATTERY PERFORMANCE

SPECIFIC ENERGY, WH/KG, VS. DISCHARGE RATE

<table>
<thead>
<tr>
<th>BATTERY DESIGN</th>
<th>20 W/KG</th>
<th>60 W/KG</th>
<th>80 W/KG</th>
<th>100 W/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>48</td>
<td>36</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>Hybrid</td>
<td>45</td>
<td>39</td>
<td>36</td>
<td>33</td>
</tr>
<tr>
<td>EV or Van</td>
<td>48</td>
<td>36</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>Full Performance</td>
<td>48</td>
<td>36</td>
<td>30</td>
<td>24</td>
</tr>
</tbody>
</table>

Note that 100 W/Kg is close to the peak specific power exhibited by this battery. The hybrid battery was designed as the VNF 80x9 battery to favor power discharge. It can sustain higher discharge rates. However, the small differences in energy density to 60 W/KG discharge show that individual designs for each of the vehicle types are unnecessary.
TABLE 4-2
ADVANCED BATTERY PERFORMANCE, 1986
SPECIFIC ENERGY, WH/KG VS. DISCHARGE RATE

<table>
<thead>
<tr>
<th>BATTERY DESIGN</th>
<th>20 W/KG</th>
<th>60 W/KG</th>
<th>80 W/KG</th>
<th>100 W/KG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>56</td>
<td>46</td>
<td>39</td>
<td>31</td>
</tr>
<tr>
<td>Hybrid</td>
<td>50</td>
<td>44</td>
<td>41</td>
<td>37</td>
</tr>
<tr>
<td>EV or Van</td>
<td>56</td>
<td>46</td>
<td>39</td>
<td>31</td>
</tr>
<tr>
<td>Full Performance</td>
<td>56</td>
<td>46</td>
<td>39</td>
<td>31</td>
</tr>
</tbody>
</table>

Again 100 Watts/Kg is close to the peak specific power for these batteries.

The 30 second peak specific power capability of the present battery has been measured and the data published by the NBTL. In Table 4-3 the Hybrid battery is based on the VNF 80 x 9 design which yields significantly higher peak power.

TABLE 4-3
PRESENT BATTERY PERFORMANCE 1980-1983
30 SECOND POWER CAPABILITY (W/KG)

<table>
<thead>
<tr>
<th>BATTERY DESIGN</th>
<th>80% SOC</th>
<th>50% SOC</th>
<th>30% SOC</th>
<th>15% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>110</td>
<td>100</td>
<td>85</td>
<td>70</td>
</tr>
<tr>
<td>Hybrid</td>
<td>170</td>
<td>155</td>
<td>135</td>
<td>115</td>
</tr>
<tr>
<td>EV or Van</td>
<td>110</td>
<td>100</td>
<td>85</td>
<td>70</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>110</td>
<td>100</td>
<td>85</td>
<td>70</td>
</tr>
</tbody>
</table>

Note that the batteries, of the EV or Commuter type have demonstrated sufficient power and energy to operate the SCT and the ETV-1 and -2 vehicles for over 70 miles of the J227 "C" cycles or 55 mph driving for 100 miles.
TABLE 4-4
ADVANCED BATTERY PERFORMANCE, 1986
30 SECOND POWER CAPABILITY W/KG

<table>
<thead>
<tr>
<th>BATTERY DESIGN</th>
<th>80% SOC</th>
<th>50% SOC</th>
<th>30% SOC</th>
<th>15% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>160</td>
<td>140</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Hybrid</td>
<td>190</td>
<td>170</td>
<td>150</td>
<td>130</td>
</tr>
<tr>
<td>Ev or Van</td>
<td>160</td>
<td>140</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>160</td>
<td>140</td>
<td>120</td>
<td>100</td>
</tr>
</tbody>
</table>

4.2 Cost Projections

These cost projections are based on the data provided in section 3.3. A factor of 15% was added to the manufacturing cost data to approximate an OEM price for the batteries. The battery size in KWH delivered for 100% DOD is indicated for each type.

TABLE 4-5
BATTERY COST PROJECTIONS

<table>
<thead>
<tr>
<th>BATTERY DESIGNER</th>
<th>SIZE KWH</th>
<th>PRESENT '80-'83 $</th>
<th>ADVANCED $</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>12</td>
<td>2100</td>
<td>1400</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>2760</td>
<td>1830</td>
</tr>
<tr>
<td>Ev or Van</td>
<td>25</td>
<td>4370</td>
<td>2900</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>50</td>
<td>8740</td>
<td>5800</td>
</tr>
</tbody>
</table>

4.3 Technical Support for Projections

The technical support for the projections presented in this report are tabulated in Table 4-6. The statements are based on the detailed data presented in Section 3.
## TABLE 4-6

**SUPPORT FOR PROJECTIONS**

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>PRESENT STATUS</th>
<th>DESIGN CHANGE</th>
<th>PERFORMANCE CHANGE</th>
<th>COST CHANGE</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Case</td>
<td>Moulded ABS Plastic</td>
<td>Polypropylene Plastic</td>
<td>Smaller case Lighter Weight Higher Strength</td>
<td>Slight Reduction</td>
<td>Heat sealing tooling required high prod. rate for cost justification.</td>
</tr>
<tr>
<td>Pos. Electrode</td>
<td>2.0 mm thick 165 x 195 mm 80% porous</td>
<td>4.0 mm 165 x 137 mm 85% porous</td>
<td>Equal Performance per unit volume power &amp; energy</td>
<td>Up to 25% savings in Ni Powder</td>
<td>Performance is maintained by plate shape change and if necessary grid improvements.</td>
</tr>
<tr>
<td>Pos. Electrode</td>
<td>2.0 mm thick 165 x 130 mm 80% porous</td>
<td>1-Deep Tabs 2-Imp. Grid 3-Coining</td>
<td>Imp. Power Capability</td>
<td>1-Cost incr. 2-Min. Cost Increase</td>
<td>Alternate methods may be appropriate Deep tabs are last resort.</td>
</tr>
<tr>
<td>Neg. Electrode</td>
<td>1.2 mm thick 165 x 195 mm</td>
<td>2.0 mm 165 x 137 mm</td>
<td>Higher Energy per unit wt.</td>
<td>Slight Rd. Grid savings Lower process costs</td>
<td>Same process costs result in more kWh per unit volume plate</td>
</tr>
<tr>
<td>Neg. Electrode</td>
<td>1.2 mm thick 160 x 130 mm</td>
<td>2.0 mm 160 x 137 mm W/coin</td>
<td>Improved Power Capability</td>
<td>Slight Increase</td>
<td>7 mm Top portion of plate devoted to conduction</td>
</tr>
<tr>
<td>Separator</td>
<td>0.85 mm Thickness</td>
<td>0.70 mm Thickness</td>
<td>Higher Energy Density</td>
<td>None</td>
<td>Less electrolyte per per unit capacity Aggravates thermal problem.</td>
</tr>
</tbody>
</table>
4.4 Energy Balance

The nickel-iron battery operates at normal ambient temperature and pressure conditions. It will charge and discharge efficiently at initial temperature from -20 to +40°C. The battery requires no auxiliary energy expenditures to compensate for:

Start up or shut down procedures.
Shunt currents, parasitic losses or thermal effects.

The stand losses for the nickel-iron battery have been determined and are represented by the graph in section 3, Figure 3-3 of this report. Under the conditions of the simplified 24 hour driving pattern the stand losses can be applied at the rate represented by the 160 hour section of the graph. When the discharge is begun immediately after the completion of a charge cycle the rapid loss shown from zero to 40 hours does not occur. That loss is due to rapid oxygen evolution from the positive electrode which stops when the discharge is begun. The stand loss for this nickel-iron battery would be only .03% per hour under these conditions. The loss in watts during the stand periods is in proportion to the battery capacity.

The data in Table 4-7 is for the 12 KWH commuter vehicle.

The total energy efficiency of the nickel-iron battery is taken as the product of voltage efficiency and the coulombic efficiency of charging. The voltage efficiency is the ratio of the average discharge voltage at the three hour rate to the average voltage for an eight hour charge. At present the coulombic efficiency is set, by the specified recharge procedure, to yield the highest output from the battery. We expect that the advanced batteries could be operated at 90% coulombic efficiency with only a small reduction in output, see Figure 3-8.

The data which is applicable to the battery is tabulated in Table 4-7.
### Table 4-7

**Estimated In Use Energy Consumption**

<table>
<thead>
<tr>
<th>SEGMENTS</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PARAMETERS</strong></td>
<td>DRIVE</td>
<td>STAND</td>
<td>DRIVE</td>
<td>STAND</td>
<td>RECHARGE</td>
</tr>
<tr>
<td>Self Discharge</td>
<td>4 Watts</td>
<td>4 Watts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Eff.*</td>
<td>64% (72%)</td>
<td>64% (72%)</td>
<td>64% (72%) (56%)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Voltage efficiency is 80% for Ni-Fe system.*

( ) advanced battery, only if considered important.

(56%) represents periodic equalization recharge to recover full iron capacity. It is believed that 110% AH return would not fully recharge the iron plate.

### 4.5 Life Consideration

#### 4.5.1 Present Status

The Eagle-Picher nickel-iron battery is the one "Near Term Battery" of the DOE program to exceed its life goals. Tests at the NBTL, Eagle-Picher and SU, Sweden are summarized in Table 4-8 below:

### Table 4-8

**Present Status of Cycle Life**

<table>
<thead>
<tr>
<th>CYCLE LIFE*</th>
<th>DEPTH OF DISCHARGE</th>
<th>LIFE LIMIT MECH</th>
<th>STATISTICAL BACKGROUND</th>
</tr>
</thead>
<tbody>
<tr>
<td>CELLS</td>
<td>1500/1700</td>
<td>80 - 100%</td>
<td>xx</td>
</tr>
<tr>
<td>MODULES</td>
<td>1200/1700</td>
<td>80 - 100%</td>
<td></td>
</tr>
<tr>
<td>BATTERIES</td>
<td>1000/1500</td>
<td>80 - 100%</td>
<td></td>
</tr>
</tbody>
</table>

* Cycle life shown is demonstrated/projected.

xx Life limiting mechanisms and their correction follows in the discussion.

xxx A statistical calculation on battery reliability has not been performed.
For the purpose of this report we have confined the discussion of life limiting mechanisms to those which have been observed in the battery test programs at NBTL, EPI and S.U.

Both failure mechanisms were manifested in the first cell failures at the NBTL at about 800 cycles at 80% DOD. Post test analysis on two cells from different modules revealed sludge shorting and split separators. The sludge shorts were alleviated in two different manners. In one case the sludge space was more than doubled in height. An alternate solution was to lower the separator to contact the case bottom. This confined the sludge to the region of the negative plate which generated it. It reduced the corner and edge "build up" which caused the problem. The separator had split at the fold around the positive electrode. Positive electrode growth caused the split. The separator had already been rearranged to fold around the negative electrode which does not expand with age. No further action was taken. The separator has since been changed to flat individual sheets to eliminate the fold.

4.5.2 Projected Cycle Life

The projected cycle life is based on the separator corrections already included and further refinements more recently included in the designs. The rapidity with which sludge accumulates has been more than halved. Edge coining of the iron electrode eliminates most of the sludge. Newer cell designs accommodate the positive electrode growth. Elimination of the bottom plate support will relieve the terminal seal stress as the electrode expands. None of these changes has an impact on cost. The edge coining would be accomplished in the same operation as the tab area is coined for welding.
The difference between energy and power designs is not sufficient to have a significant effect on battery life. However, in theory the power designs should exhibit greater endurance. The power oriented batteries will have lower specific energy and internal resistance. Both tend to lower the maximum temperatures during discharge. The cooler battery will exhibit the longer life.

4.5.3 Life Effects on Battery Operating Characteristics

Actual measurements of battery operating characteristics during life cycle testing have not been made. However, the peak specific power, specific energy, efficiency, and thermal losses will be related to electrode aging. The nickel-iron battery exhibits very stable output during its useful life indicating that at moderate rates, 2 to 3 hours discharge, plate degradation is not significant. Consequently specific energy, efficiency, and the thermal characteristics of the battery will remain practically constant for the life of the battery. When peak specific power is considered the ultimate capability is being measured. This characteristic must be influenced by age since it demands that the total plate volume be effective. The iron electrode is corroded and recharged in each cycle. The reaction can not be 100% reversible. There is a reduction in peak specific power vs. cycle life. The rate at which it occurs has not been measured.

4.5.4 Reliability

In the absence of a mathematical reliability estimate for the nickel-iron battery, it is suggested that it would prove to be excellent. The battery is conventional in design and construction. It requires no auxiliaries for its operation. Each battery is performance
tested as part of the manufacturing procedure. The cycle to cycle reliabil-
ity of the unit is the best possible.

At present the smallest replaceable block of cells in 
operating batteries is a five cell module. The modules are repairable in 
that plate groups in individual cells can be recased. This has been the 
only repair required. New batteries will incorporate polypropylene heat 
sealed cases. This will correct the problems caused by cemented ABS 
plastic cell jars.

4.6 Other Operational Characteristics

4.6.1 Special Charge Requirements

**Overcharge** - The Ni-Fe battery is unaffected by 
overcharging at low or ordinary currents. Overcharging is routine in 
reestablising capacity after extended periods of shelf storage. Cells and 
modules have been charged at the 10 hour rate until they were completely 
dry without damage or reduction in subsequent performance.

**Overdischarge** - Forced overdischarge, as a weak cell in a 
battery or power discharge on a module, which causes oxygen evolution on 
the iron electrode will damage those plates. The Ni-Fe battery does have 
considerable protection against this situation by virtue of design and the 
chemistry of the reaction. First the cells are designed so that a 20% 
overdischarge is required to exceed the first plateau capacity of the 
electrode. The second plateau discharge, \( \text{Fe}^{2+} \) to \( \text{Fe}^{3+} \) offers in theory 
another 50% protection before oxygen is evolved. When it occurs this type 
failure of the iron is characterized by corrosion detaching the active 
material from the grid and plugging the fine pores in the double porosity 
structure of the plate. Recovery from overdischarge is dependent upon its
severity.

**Cell Balancing** - Not required. The normal amount of overcharge in each cycle is sufficient to cover efficiency differences.

**Periodic Complete Discharge** - Not required. The test programs have not indicated any problem with repeated partial discharges on this battery.

**Equalization** - To be determined. This type routine might be used with reduced charging return. If less than maximum performance is satisfactory, then decreased recharge levels would reduce watering frequency and increase charging efficiency. Under this type service some periodic equalization might be required to keep the iron electrode fully charged.

4.6.2 Maintenance

**Charging** - By proper and timely charging the user can reduce significantly the maintenance the Ni-Fe batteries require. Recharging daily after only fractional discharge reduces the charge efficiency and increases the water usage.

**Watering** - Typical designs require watering after five full cycles of 120-130% AH recharging. Watering frequency has been about once per week. Ultimately the watering interval might be one month.

**Inspection** - Monthly, to observe that watering caps are in place and not causing electrolyte salt bridges between terminals. Clean or rinse if required.

**Refurbishment** - Factory refurbishment of batteries is possible at fractional cost. This has already been demonstrated to replace breached ABS cell jars. Each occasion will require individual consideration.
4.7 Packaging Flexibility

4.7.1 Volume

The volumetric considerations for the various designs are listed in Table 4-9. The volume predicted is for battery cells only. No module trays are included.

<table>
<thead>
<tr>
<th>DESIGN</th>
<th>ENERGY KWH</th>
<th>STATE-OF-ART LITERS</th>
<th>ADVANCED LITERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>12</td>
<td>130</td>
<td>110</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>175</td>
<td>155</td>
</tr>
<tr>
<td>EV or Van</td>
<td>25</td>
<td>260</td>
<td>233</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>50</td>
<td>520</td>
<td>446</td>
</tr>
</tbody>
</table>

4.7.2 Size Limitations

The conventional design of the nickel-iron battery imposes a limit on the height of a cell. In the capacities required for electric vehicles, batteries less than eight inches high would have poor volumetric efficiency. The space required above the tops of the plates becomes proportionally larger as the cell gets shorter.

The advanced designs will be about 9 inches high, because EV's will need "short" batteries and this shape improves the power capability per unit of weight.
4.7.3 **Subsystems**

The nickel-iron battery requires small I.D. tubing to vent battery gases to a safe location and feed make up water to the individual modules.

4.7.4 **Scale Effects**

The scale effects between 12 and 25 KWH batteries would be small. Table 4-9 indicates that up to 4% more volume is allowed for the smaller batteries.
APPENDIX C

DESIGN ANALYSES OF
EXXON ZINC/BROMINE BATTERIES
FOR VARIOUS ELECTRIC VEHICLES
DRAFT

DESIGN ANALYSES OF
EXXON ZINC/BROMINE BATTERIES
FOR VARIOUS ELECTRIC VEHICLES

MARCH 17, 1984

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C-3
INTRODUCTION

This report is a brief description of a series of design analyses performed by the author as part of a program being conducted by JPL to determine the feasibility of using various energy storage and energy conversion technologies in "Advanced Vehicles" for use on US roads in the 1990's. Unlike most of the battery developments being considered in this phase of the JPL study, the zinc/bromine battery designs and the analyses thereon reported here were not the result of work done by the developer – the Exxon Research & Engineering Company. Although this unit of Exxon is a DOE developer, they declined to respond to an offer to conduct the work requested by JPL under contract from the latter. The personnel at Exxon who are involved in zinc/bromine battery development did, however, agree to aid the author in developing a response to the questions being posed by JPL in this phase of the JPL analysis. The questions being posed by JPL referred to are given in the work statements of those battery developers who did agree to conduct the required analyses under contract, and are further delineated in the "Guidelines" sent to such contractors, and to Exxon, as part of the study. The questions and guidelines will not be reviewed further here and are incorporated in this report by reference. We must recognize that this report, unlike most of the others that will be reviewed by the technical panel assembled for this purpose by JPL (the "Review Board") has not been prepared by the battery developer but by a member of the Review Board. The time and manpower devoted to the analysis of Exxon zinc/bromine batteries is thus a small fraction of that used in analysing
EXXON has been in the process of developing zinc/bromine batteries for almost a decade, although their power capabilities have not had the development that are believed to be needed for advanced EVs. Although we should note that the batteries that have been built and tested with relatively large devices makes the job of projecting the performance of developed in a parallel DOE program by Ford Motor Company. The experience in an electric vehicle battery that will be tested in an EV that is being the process of developing, under a program funded by the Department of Energy, zinc/bromine batteries somewhat more straightforward than it might otherwise have been tested more-or-less successfully during the past two years. Exxon has in zinc/bromine batteries, incorporating somewhat different design details, have been assembled and tested by Exxon. Thus, both 10 kWh and 20 kWh work has progressed to the point where relatively large zinc/bromine batteries have been built, although their experience with some of the components of their system extends for a substantially longer period than this. This development a decade, although their experience with some of the components of their system extends for a substantially longer period than this. This development
been carried out, was as potential electric vehicle candidates. Work on the system was funded exclusively by the parent company of Exxon R & E (through another unit - Exxon Enterprises) until early 1980, when Phase I of a DOE program was initiated. Since that time, Exxon has cost-shared the DOE program, and the work has been directed, until recently at least, to the development of batteries that might be applicable to solar photovoltaic system energy storage. Exxon maintained its interest in the EV application however, and during the past year or so, a development project on EV batteries has been underway in addition to the one for solar PV batteries. Sandia National Laboratories has had responsibility for managing and/or monitoring the Exxon zinc/bromine battery programs for DOE.

The technology on which the Exxon zinc/bromine battery is based is fully described in two reports on their DOE program published by SNLA - "Development of a Circulating Zinc-Bromine Battery", Phase I Final Report, SAND82-7022, and Phase II Final Report, SAND83-7108. In essence, the Exxon zinc/bromine battery technology has the following features:

* Circulating electrolyte, with two separated flows into each cell and "flow-past" the zinc and bromine electrodes. Sculptured microporous polyolefin, "Daramic", used to separate and space zinc and bromine electrodes and to form compartments of each cell.

* Conductive carbon/plastic electrodes, high surface area carbon "attached" to the faces to be used as bromine electrodes. Carbon/plastic composites and insulating (polyolefin) edges formed by inexpensive co-extrusion method.

* Bipolar cell-stack utilizing Exxon's "shunt-current protection" to prevent maldistribution of zinc growth on cycling. Flow frames (with channels to direct flows as necessary) made by injection molding with Daramic separators as inserts in mold.

* Bromine complexing agents to store the elemental bromine formed during charge as a separate phase in a special compartment of the battery.
Complexing agents dissolved in battery electrolyte before charge; brominated complex "carburretted" into flowing electrolyte to supply bromine during discharge.

The flow arrangement proposed by Exxon for their zinc/bromine batteries is shown in Figure 1. A photograph of the components that are used to make cell-stacks of the design currently favored by Exxon are shown in Figure 2. Exxon believes that this technology will give zinc/bromine batteries that will be reasonably high in performance and yet will be inexpensive. The calendar and cycle-life of Exxon zinc/bromine batteries is projected by them to be relatively short, however, although they believe that the low cost that will be attainable will counterbalance this short lifetime so as to give a low life-cycle-cost. The reader is referred to the reports cited above for further details of the Exxon zinc/bromine battery technology.

In the balance of this report, we will describe and discuss the answers to the questions that have been posed of various battery developers by JPL, the latest version of these questions, as described in the "Guidelines" described above, being addressed. In the next section - METHODOLOGY OF THE STUDY - we will describe the methodology used in making the quantitative and qualitative estimates asked for by JPL. The third section - STUDY RESULTS - will give the answers to the questions posed by JPL in the last version of the guidelines. The fourth and final section will deal with the VALIDITY OF THE ESTIMATES and in it we will discuss the answers to the JPL questions that were derived from the information given to us by Exxon.
METHODOLOGY OF THE STUDY

In the "Guidelines" sent to battery developers, JPL indicated that there were eight vehicle types for which they would like preliminary designs to be made. From these preliminary designs, it was hoped that battery developers could make reasonably reliable projections of the specific energy, specific power, volume and OEM price of batteries that would give the desired EV performance. It was recognized from the beginning that any particular battery on which information was being sought would not necessarily meet the requirements of all eight vehicle types specified by JPL. In the present study, we decided to eliminate vehicle types for which we thought that zinc/bromine batteries would be inherently unsuitable. Additionally, we combined some vehicle types for which the battery requirements were very similar. The EV types and battery requirements on which we hoped to develop outline designs were, therefore, as follows:

* Two-passenger commuter EV	 12kWh	 25kW
* Hybrid 4/5-passenger EV	 15kWh	 50kW
* General purpose electric car or van	 25kWh	 60kW
* Full performance 4/5-passenger EV	 50kWh	 50kW

We note at this point that the present design for a zinc/bromine EV battery leads to nominal ratings of about 20kWh and 30kW.

Ideally, we had hoped to answer the questions posed by JPL in the "Guidelines" by making projections of battery performance on the basis of
actual preliminary designs for zinc/bromine batteries optimized to the four vehicle types listed above. However, since Exxon did not find it possible to accept a contract from JPL to perform such work, it was necessary for us to adopt a different approach. The methodology we used to make the necessary projections therefore consisted of the following steps:

* Careful review of the literature available on the design of Exxon zinc/bromine batteries for electric vehicle use.

* Development of a set of forms (attached as Appendix A) to facilitate recording information received from battery developers who agreed to respond to the JPL "Guidelines".

* Quantification of the weight, volume, projected OEM price and expected performance of the present state-of-the-art battery.

* In face-to-face and telephone discussions, and written communications with Exxon personnel, establishment of projections for the performance, weight, volume and OEM price of a zinc/bromine battery with an optimized present-day design.

* Acquisition of information on the non-quantifiable questions in the JPL "Guidelines" by face-to-face questioning of Exxon personnel.

* Acquisition of the coefficients of the Symons Equations for the weight, volume and OEM price of batteries with performances different from those given to us for the optimized present-day design. This information was requested of Exxon personnel during our meeting and received in writing at a later date. For a further discussion of the Symons Equations, see below.

* Calculation of the weight, volume and expected OEM price of Exxon zinc/bromine batteries for the four vehicle types listed above, and calculation and projection of the specific energy, specific power and battery OEM price projections requested by JPL. Note that the specific energy versus discharge rate and specific peak power versus state-of-discharge projections were made on the basis of the overall weight projected for the various batteries combined with the projected performance of the optimized present-day design battery.

* Submission of the final projections to Exxon by way of a first draft of this report and modifications of the projections as necessary through telephone conferences with their personnel and by means of written communications from them.

It should be noted that a zinc/bromine battery of the type specified in the
"Guidelines" as "Present" has not yet been built by Exxon, and that the projections given under this heading in the next section have been made on the basis of the performance of a 20kWh battery designed for solar PV storage. This approach was taken because the final design details of the zinc/bromine battery to be built under the DOE/EHV/Ford project have not yet been determined, and use of the expected performance, weight and volume characteristics of this battery would therefore be premature.

The Symons Equations, referred to above, that represent an inherent part of the projection methodology used in the present study, were derived by the author as part of a study conducted by Argonne National Laboratory. The derivation of the equations was described in detail in an internal report to ANL (1982) and has been summarized in a number of open-literature publications (see, for example, P. C. Symons, Extended Abstracts of the Electrochemical Society, Volume 82-2, pg. 7). In essence, the formulae that are now described as the Symons Equations relate the weight, volume and projected OEM price of a battery to the energy and power that are to be delivered by it. The three equations are as follows:

- Battery weight (W) = A \times E + B \times P + C
- Battery volume (V) = A' \times E + B' \times P + C'
- Battery price (X) = A'' \times E + B'' \times P + C''

where E is the energy to be delivered by the battery to the motor-controller of EV in kWh, P is the power required to give accelerations in kW, and A, A', A'', B, C etc. are coefficients that are derived from a particular battery design. The energy and power used in the Symons Equations must be specified.
carefully if the equations are to be useful (see references for a further discussion of this). Please note that the coefficients of the Symons Equations refer to a particular group of batteries that are designed according to the same set of principles; these equations cannot be used for batteries of the same generic type at different stages of development. Any particular set of coefficients refer, of course, to batteries of the same generic type. In addition, it should be noted that the Symons Equations are only intended for use over relatively small ranges of energy and power. The ranges appropriate for any particular set of Symons Coefficients will depend on the battery type and the actual battery design that was used to derive them. The use of estimating formulae such as the Symons Equations to project the performance or price must never be taken out of the context in which the coefficients were derived.

The methodology used to estimate the characteristics of various zinc/bromine batteries that has been used herein necessarily results in projections that are based on the same set of critical design and performance assumptions. In other words, we do not assume different degrees of success in developing the various batteries required for different vehicle types. Improvement over the present state of the art is assumed, however, as will be discussed in the final section of the report. In the next section, we describe the results of the design analysis that has been performed on Exxon zinc/bromine batteries.
STUDY RESULTS

As described in the preceding section of the report, the information on Exxon zinc/bromine batteries for the JPL study has been received in two separate ways. Firstly, during a visit to Exxon, the author got projections on the expected performance, OEM price and life characteristics of an EV battery with a design which is basically an optimized version of the one presently under development for solar PV storage. Information on batteries designed specifically for the EVs of interest to JPL was not available directly but was obtained in the form of coefficients for the Symons Equations. These coefficients, supplied in writing to the author, represent the second way in which the information required for the JPL study was obtained. We note that the two types of information obtained from Exxon are supposed to refer to batteries designed according to the same basic design principles and that different degrees of advancement of the technology are not assumed for the various EV types. Both types of information obtained is summarized below, this being presented as completed "JPL Forms" (see preceding section) at the end this section. A commentary on the assumptions believed to have been used by Exxon is given first, and then the values of the coefficients of the Symons Equations are described and discussed, before the overall information requested by JPL is given.

The design basis on which the quantitative information given below was calculated or projected is as follows:

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* Overall system designed according to the principles of Exxon zinc/bromine batteries outlined in the INTRODUCTION to this report and described in Exxon's SNLA reports referenced above.

* Fully charged electrolyte has composition comprising 3 molar zinc bromide, 0.5 molar each of MEMBr and MEPBr (bromine complexing agents), 4 molar of a mixture of potassium and ammonium bromides.

* Utilization of dissolved zinc, i.e. fraction of zinc that would be plated during a full charge with a 100% coulombic efficiency, taken as 70% for all designs. This implies that the minimum concentration of zinc bromide will be about 0.9 molar, neglecting the coulombic inefficiency and any volume change of the electrolyte that may occur.

* Baseline (i.e. "Present") design based on a charge zinc loading of 90mAhr/sq.cm. and a charge time of 3 hours. The Exxon method used to make calculations of battery weight as a function of expected capability is shown in Table 1. EV battery designs with a different P/E ratio would have a different loading and charge time.

* Values of energy deliverable given for a continuous discharge at the stated rate, such discharge immediately following the preceding charge. Values for energy deliverable do not, unless otherwise stated, include the energy required for auxiliaries - pumps and shunt current protection - during discharge. The actual energy that can be delivered must be reduced by the energy required to drive the auxiliaries during the discharge.

* The "Present" design gives a nominal 20kWh and 30kW battery that is projected to weigh 303 kg. and to occupy 284 litre. A breakdown of the weight and volume of this battery is shown in Table 2. A 20kWh battery with an unoptimized design of the same type as that used for the projection actually weighs 330kg. However, the power of this battery is not as high as that projected for the "Present" design. A new cathode layer (CP-3), already under test in small cell-stacks, is thought to be capable of the required performance.

* The energy deliverable under sustained discharge was projected by Exxon on the basis of data obtained on Stack # PAM01Z, this being designed and tested according to the principles listed herein. Experimental discharge curves for this cell-stack are given in Fig 3.

* Projections for peak power capability of the "Present" battery were made by Exxon on the basis of data obtained on a 10kWh cell-stack identified as Z-10. This stack has a design similar to that assumed in making the projections. The raw data used in making the projections is shown in Fig 4. The state-of-charge (SOC) is defined relative to the energy deliverable (see above) at the three-hour discharge rate.

* Estimates of the OEM price of an Exxon zinc/bromine battery of 20kWh
nominal capacity were made by the developer according to the ADL method in 1981. The results of this Exxon analysis are given in the Phase II SNLA Report referenced above, and are summarized in Table 3. The battery coated is presumably of the same design as that for which weight and volume estimates are given above. An OEM price of about $800 for the 20kWh battery resulted from this estimate.

These design principles represent the basis for projections made for the "Present" design battery and for batteries with different performance capabilities.

For batteries that are required to have capabilities different from the baseline ("Present") design, Exxon submitted coefficients for the Symons Equations to the author. Thus, the following formulae were projected by Exxon to be applicable to the calculation of the weight, volume and OEM price of the zinc/bromine batteries required for the EV applications being analysed by JPL:

Weight = kWh x 12.3 + kW x 1.35 + 38.3 kg
Volume = kWh x 12.3 + kW x 1.36 + 99.8 litre
OEM Price = kWh x 16.0 + kW x 4.58 + 344.3 1981$

- where kWh represents the energy that can be delivered by the battery at the three hour rate and kW is the peak power deliverable at 30% SOC. It should be noted that these definitions of the energy and power are not the same as those used in deriving the Symons Equations, and as a result, some further care should be taken in applying the formulae than normally is needed.

In deriving these formulae, we understand that Exxon assumed that changes to the power capability of a battery could be achieved by adding or removing individual bipolar electrodes and their associated frames, separators and electrolyte to or from baseline design, and that the energy could be changed
by means of changes to the amount of electrolyte in the battery. The weight,
volume and OEM price formulations then follow from the breakdowns referenced
above and the assumed performance (20kWh, 30kW) of the baseline design. On
the basis of these assumptions, the sustained and peak power projections asked
for by JPL for batteries other than the baseline case can be derived by using
ratios from the values projected for the baseline design.

The projections requested in the latest version of the JPL "Guidelines" are
given in Tables 4 to 12. The quantitative projections given in these tables
should be only used in EV optimization calculations in conjunction with the
background information in this report. In the tables, there is some
information that is referred to by means of numbered notes. These notes
follow and should also be used in conjunction with the projections in the
tables.

Note 1: Energy consumption by the items shown in Table 8 (pumps, shunts, self-
discharge, etc.) should be regarded as proportional to the nominal power of
the battery.

Note 2: There has not, as yet, been a great amount of formal cycle-life
testing conducted at Exxon on zinc/bromine batteries. The life of the active
carbon layers now used is not known at present. Reliability of small flow
battery systems is of some concern because of the pumps and other mechanical
components.

Note 3: The volume of the baseline 20kWh/30kW battery calculated from the
Symons Equation given to the author by Exxon is 384 litre. This value does
not coincide with either of the volumes given for this battery during the
meeting with Exxon. This is troublesome because the volume of Exxon
zinc/bromine batteries is one of the principal concerns in EV applications.

The values given for the characteristics of Exxon zinc/bromine batteries designed for EV use in this section are those given to us by Exxon personnel during a meeting and/or in writing. The validity of the estimates made in this section is discussed in the next and last section of the report.
VALIDITY OF THE ESTIMATES

THIS SECTION WILL BE WRITTEN FOLLOWING FURTHER DISCUSSIONS WITH EXXON, PARTICULARLY AFTER THEY HAVE HAD A CHANCE TO REVIEW THE PRECEDING SECTIONS OF THE REPORT.
Table 1. 20 kWh Battery Design Calculations

- Basis: 90 mAh/cm² Zn loading
- 70% Zinc utilization
- 80% Coulombic Efficiency
- 3M ZnBr₂ Electrolyte

Electrolyte Volume and Weight

Volume = \frac{\text{(electrode area) \times (Zn loading)}}{\text{(zinc concentration) \times (zinc utilization)}}

= \frac{(1160 \text{ cm}^2/\text{electrode}) \times (156 \text{ electrodes}) \times (0.090 \text{ mAh/cm}^2) \times (3600 \text{ s/hr})}{(2 \times 0.965 \times 10^5 \text{ As/mole}) \times (3 \text{ mole Zn/liter}) \times (0.7 \text{ utilization})}

= 147.7 \text{ l}

Weight = 147.7 \text{ l} \times 1.7 \text{ kg/l} = 245.9 \text{ kg}

Capacity

Capacity = \frac{(Zn \text{ loading})(\text{av. discharge voltage})(\text{coul. effic.})(\text{electrode area})}{(\text{electrode area})}

= \frac{(0.090 \text{ Ah/cm}^2)(1.676 \text{ V})(0.8 \text{ coul. eff.})(1160 \text{ cm}^2/\text{electrode})(156 \text{ electrodes})}{1160 \text{ cm}^2/\text{electrode}}

= 21.8 \text{ kWh gross}

Net Capacity = Gross Capacity - Auxiliary = 21.8 - 3.1 = 18.7 \text{ kWh}

Power (50% SOC at 70% of OCV)

Power = \frac{(\text{voltage}) \times (\text{current density}) \times (\text{electrode area})}{(\text{electrode area})}

= \frac{(1.232 \text{ V}) \times (0.189 \text{ A/cm}^2)(1160 \text{ cm}^2/\text{electrode})(156 \text{ electrode})}{(1160 \text{ cm}^2/\text{electrode})}

= 42.0 \text{ kW}

Base Case (20 kWh, 90 mAh/cm², 70% utilization)

Energy Density = \frac{18.7 \text{ kWh}}{325 \text{ kg}} = 57.5 \text{ Wh/kg}

Power Density = \frac{42 \text{ kWh}}{325 \text{ kg}} = 129 \text{ W/kg}
Table 2. 20 kWh EV/PV Design - Inventory - Weight and Volume Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Part Dimensions (cm)</th>
<th>Number of Parts (#)</th>
<th>Volume (liter)</th>
<th>Density (g/m/cm²)</th>
<th>Weight (kg)</th>
<th>Volume (liter)</th>
<th>Height (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Stacks</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bipolar Electrode</td>
<td>36.5 x 51 x .06</td>
<td>154</td>
<td>17.2</td>
<td>.9</td>
<td>15.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Collectors</td>
<td>36.5 x 51 x .10</td>
<td>4</td>
<td>.7</td>
<td>.9</td>
<td>.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separators</td>
<td>36.5 x 51 x .21</td>
<td>156</td>
<td>61.0</td>
<td>.9</td>
<td>24.1*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neg. Feed Blocks</td>
<td>36.5 x 51 x 2</td>
<td>2</td>
<td>7.4</td>
<td>.9</td>
<td>3.3*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pos. Feed Blocks</td>
<td>36.5 x 51 x 3</td>
<td>2</td>
<td>11.2</td>
<td>.9</td>
<td>5.0*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tie Rods</td>
<td>53 x .65 D.</td>
<td>4</td>
<td>.02</td>
<td>7.9</td>
<td>.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electrolyte</strong></td>
<td>144.7</td>
<td>1.55</td>
<td>245.9</td>
<td></td>
<td></td>
<td></td>
<td>224.3</td>
</tr>
<tr>
<td>Reservoir</td>
<td>106.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stacks</td>
<td>38.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliaries/Misc.</strong></td>
<td>80.2</td>
<td>30.2</td>
<td>80.2</td>
<td>30.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump Heads</td>
<td>8 x 8 x 8</td>
<td>2</td>
<td>1</td>
<td>.2†</td>
<td>.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump Motors</td>
<td>8 x 8 x 12</td>
<td>1</td>
<td>.8</td>
<td>4.0†</td>
<td>3.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valves</td>
<td>4 x 6 x 12</td>
<td>2</td>
<td>.6</td>
<td>1.0†</td>
<td>.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plumbing</td>
<td>100 x 3 D.</td>
<td>4</td>
<td>.6*</td>
<td>1.0</td>
<td>.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controller</td>
<td>5 x 5 x 1</td>
<td>1</td>
<td>.2†</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>40 x 45 x 4</td>
<td>1</td>
<td>7.2</td>
<td>1.4†</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fan (HX)</td>
<td>30 x 30 x 20</td>
<td>1</td>
<td>.1†</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pump (HX)</td>
<td>10 x 10 x 10</td>
<td>1</td>
<td>1.2</td>
<td></td>
<td>.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coolant</td>
<td>-</td>
<td>-</td>
<td>1.1</td>
<td>6.6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensors</td>
<td>-</td>
<td>-</td>
<td>.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation/Packaging</td>
<td>3.5 M² x 1</td>
<td>1</td>
<td>35</td>
<td>.2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voidage</td>
<td>-</td>
<td>-</td>
<td>.2</td>
<td></td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tankage/Supports</td>
<td>-</td>
<td>-</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Void Volume Adjustment  †Void Volume Adjustment

Totals 284.4 303.2
Table 3. **Total Factory and Capital Costs**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost (US$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material (Includes Electrolyte @ $220/Module)</td>
<td>321.36</td>
</tr>
<tr>
<td>Purchased Components (Includes Outside Molding Costs and Accessories)</td>
<td>211.71</td>
</tr>
<tr>
<td>In-House Labor Costs</td>
<td>68.74</td>
</tr>
<tr>
<td>Total Material, Components &amp; Labor Cost/20 kWh Module</td>
<td>601.81</td>
</tr>
<tr>
<td>Total Material, Components &amp; Labor Cost/kWh</td>
<td>30.09</td>
</tr>
<tr>
<td>1. @ 2500 MWh Material, Components &amp; Labor Cost per Year</td>
<td>$75,225,000.00</td>
</tr>
<tr>
<td>2. Marked-up Equipment Costs (10% of estimated ($12,500,000)</td>
<td>1,250,000.00</td>
</tr>
<tr>
<td>3. Rent (100 sq. ft. Plant @ 5.00/ft²)</td>
<td>500,000.00</td>
</tr>
<tr>
<td>4. Total Factory Costs (Lines 1 + 2 + 3)</td>
<td>76,975,000.00</td>
</tr>
<tr>
<td>5. Working Capital Requirement (30% line 4)</td>
<td>23,092,500.00</td>
</tr>
<tr>
<td>6. Total Investment ($12,500,000 + line 5)</td>
<td>35,592,500.00</td>
</tr>
<tr>
<td>7. Return on Investment &amp; Taxes (30% line 6)</td>
<td>10,677,750.00</td>
</tr>
<tr>
<td>8. Additional @ $5.00/kWh</td>
<td>12,500,000.00</td>
</tr>
<tr>
<td>9. Total Capital Cost (lines 4, 7 &amp; 8)</td>
<td>100,152,750.00</td>
</tr>
<tr>
<td>Capital Cost per 20 kWh Module</td>
<td>801.22</td>
</tr>
<tr>
<td>Capital Cost per kWh</td>
<td>40.06</td>
</tr>
</tbody>
</table>

- Net Capital Costs Following Page -

C-21
1. PERFORMANCE MODELING

(a) Battery discharge characteristics:

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Specific Energy (Wh/kg) vs Discharge Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20 W/kg</td>
</tr>
<tr>
<td>1. Present,  64 kWh/30 kW</td>
<td>64</td>
</tr>
<tr>
<td>2. Commuter, 20 kWh/25 kW</td>
<td>60</td>
</tr>
<tr>
<td>3. Hybrid,  220 kg</td>
<td>60</td>
</tr>
<tr>
<td>4. Electric Vehicle or Van, 25 kWh/60 kW</td>
<td>60</td>
</tr>
<tr>
<td>5. Full-Perf., 427 kg</td>
<td>60</td>
</tr>
</tbody>
</table>

aW/0 and W signify Without and With Auxiliaries.
Table 5. Forms for Recording Information for JPL
January/February, 1984 - Page 2

DATE: 03/18/84 LOCATION: EEC, Inc.
DEVELOPER: Exxon SYSTEM: Zn/Br$_2$

1. PERFORMANCE MODELING

(b) 30-second peak specific power capability:

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>80% SOC</th>
<th>50% SOC</th>
<th>30% SOC</th>
<th>10% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present, 20 kWh/30 kW</td>
<td>146</td>
<td>120</td>
<td>100</td>
<td>75$^a$</td>
</tr>
</tbody>
</table>

2. Commuter
(See text)

3. Hybrid
(See text)

4. Electric Vehicle or Van
(See text)

5. Full-Perf.
(See Text)

$^a$By extrapolation.
Table 6. Forms for Recording Information for JPL  
January/February, 1984 - Page 3

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>1981 $/battery</th>
<th>Basis of Estimate/Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Present,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 kWh/30 kW</td>
<td>802</td>
<td>Phase II Report</td>
</tr>
<tr>
<td>2. Commuter,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12 kWh/25 kW</td>
<td>651</td>
<td>Symons Equations</td>
</tr>
<tr>
<td>3. Hybrid,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 kWh/50 kW</td>
<td>814</td>
<td>Symons Equations</td>
</tr>
<tr>
<td>4. Electric Vehicle or Van,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>25 kWh/60 kW</td>
<td>1019</td>
<td>Symons Equations</td>
</tr>
<tr>
<td>5. Full-Perf.,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 kWh/50 kW</td>
<td>1374</td>
<td>Symons Equations</td>
</tr>
</tbody>
</table>
Table 7. Forms for Recording Information for JPL

January/February, 1984 - Page 4

DATE: 03/18/84 LOCATION: EEC, Inc.
DEVELOPER: Exxon SYSTEM: Zn/Br2

ENTER SUB-PAGE #: A

3. TECHNICAL SUPPORT FOR PROJECTIONS

How are improvements assumed in all the above to be achieved? a

Component

Present Status

Design Change

Performance Change

Cost Change

Comments

aSee text of report.
Table 8. Forms for Recording Information for JPL
January/February, 1984 - Page 5

| DATE: 03/18/84 | LOCATION: EEC, Inc. |
| DEVELOPER: Exxon | SYSTEM: Zn/Br₂ |

4. IN-USE ENERGY CONSUMPTION

Quantification of sinks of energy consumption other than those accounted for by performance modeling:

<table>
<thead>
<tr>
<th>Segment/Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-up and shut-down</td>
<td>Pumps On</td>
<td>Pumps off</td>
<td>Pumps on</td>
<td>Pumps off, till charge.</td>
<td></td>
</tr>
<tr>
<td>44 min.</td>
<td>Continuously, Stack (See 1)</td>
<td>(See 2) Charge 2h at end of period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>lmA h/cm²</td>
<td>3 Wh</td>
<td>312 Wh</td>
<td>3 Wh</td>
<td>312 Wh</td>
<td>3 Wh</td>
</tr>
<tr>
<td>Self-discharge</td>
<td>688 Wh</td>
<td>0</td>
<td>688 Wh</td>
<td>0</td>
<td>2156 Wh</td>
</tr>
<tr>
<td>3mA/cm²</td>
<td>161 Wh</td>
<td>0</td>
<td>161 Wh</td>
<td>0</td>
<td>520 Wh</td>
</tr>
<tr>
<td>Shunt currents</td>
<td>95 Wh</td>
<td>0</td>
<td>95 Wh</td>
<td>0</td>
<td>260 Wh</td>
</tr>
<tr>
<td>Parasites</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100 Wh</td>
</tr>
<tr>
<td>Cooling Pump</td>
<td>15 Wh</td>
<td>15 Wh</td>
<td>0</td>
<td>0</td>
<td>40 Wh</td>
</tr>
<tr>
<td>Thermal loss</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Charge eff.</td>
<td>Regen.</td>
<td>NA</td>
<td>Regen.</td>
<td>NA</td>
<td>Charge</td>
</tr>
<tr>
<td>Voltaic Effs only</td>
<td>90%</td>
<td>90%</td>
<td>87%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Above based on 20 kWh/30 kW "Present" design. See Note 1.*
Table 9. Forms for Recording Information for JPL

January/February, 1984 - Page 6

DATE: 03/18/84          LOCATION: EEC, Inc.
DEVELOPER: Exxon
SYSTEM: Zn/Br

5. LIFE CONSIDERATIONS

(a) Present status of cycle life.

<table>
<thead>
<tr>
<th>Individual cells</th>
<th>Cycle life</th>
<th>Depth-of-discharge</th>
<th>Life-limiting mechanisms</th>
<th>Statistical background</th>
</tr>
</thead>
<tbody>
<tr>
<td>cannot be tested</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8-cell-stacks</td>
<td>~400</td>
<td>100%</td>
<td>Warpage Failed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Current Collector</td>
<td>10</td>
</tr>
<tr>
<td>8-cell-stack</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thicker Electrodes</td>
<td>640</td>
<td>100%</td>
<td>Still under test</td>
<td>1</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>1200</td>
<td>100%</td>
<td>None Detected</td>
<td>1</td>
</tr>
</tbody>
</table>

| Batteries        |            |                    |                          |                        |
| 10 kWh Sub-scale | ~100       | 100%               | Did not fail             |                        |
| 20 kWh Full size | None       |                    | Taken apart              | 1 + 1 on test          |
|                  |            |                    | Cycle tested to date     |                        |

(b) Projected cycle life, approach to solving failure modes, effects of these on cost. Specify any differences between high-energy & high power designs.

1000 Deep Cycles Projected. Approaches to get this TBD.

(c) Life effects on specific power & energy, efficiency and thermal characteristics (i.e., linear with cycling).

Slow decline in efficiency, possibly lower deliverable capacity.

(d) Estimate of reliability of smallest replaceable block of cells, failure modes, mean-time-to-failure, etc.

Don't know

See Note 2.
6. OTHER OPERATIONAL CHARACTERISTICS

(a) Special charge requirements:

What happens if cells are overcharged or overdischarged?

No permanent damage.
See Note 3.

Is individual cell balancing required? If so, how & how often?

No

Is periodic complete discharge required? If so, how & how often?

Yes. TBD - thought to be 20 to 100 cycles.

Is equalizing necessary? If so, how & how often?

No

(b) Maintenance requirements?

What regular maintenance is required? How often?

pH (?), Air (?), Inerts Venting (?), Check Pumps and Motors (?)

What potential exists for periodic battery refurbishment rather than replacement? How does this compare to cost with replacement?

Stacks replaceable in principle, pumps/motors could be serviced. Battery could be repaired. Cost of repair labor (unknown now) will determine if done.
Table 11. Forms for Recording Information for JPL

January/February, 1984 - Page 8

DATE: 03/18/84  LOCATION: EEC, Inc.
DEVELOPER: Axxon  SYSTEM: Zn/Br₂

7. PACKAGING FLEXIBILITY

(a) Estimated volume of each of the designs:

<table>
<thead>
<tr>
<th>Battery</th>
<th>Liters</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present, 20 kWh/30 kW</td>
<td>300</td>
<td>Based on component volumes</td>
</tr>
<tr>
<td>31-5/8 in. x 25 in. x 34 in.</td>
<td>440</td>
<td>Design Envelope for Battery</td>
</tr>
<tr>
<td>Commuter, 12 kWh/25 kW</td>
<td>281</td>
<td>From Symons Equations</td>
</tr>
<tr>
<td>Hybrid, 15 kWh/50 kW</td>
<td>352</td>
<td>From Symons Equations</td>
</tr>
<tr>
<td>Electric Vehicle or Van, 25 kWh/60 kW</td>
<td>489</td>
<td>From Symons Equations</td>
</tr>
<tr>
<td>Full-Perf., 50 kWh/50 kW</td>
<td>783</td>
<td>From Symons Equations</td>
</tr>
</tbody>
</table>

(b) Size limitations, minimum possible measurements of battery cells or modules (H x W x L), primary considerations if change must be made from present configuration, other?

Minimum height of 6 in. in reservoir. Asymmetry of electrodes 3:1. Change from present dimensions will mean redesign.

(c) Any special consideration for relative placement of components/sub-systems, i.e., necessity to place fluid reservoir near cell-stack?

Reservoir and stack(s) on same level, to keep volume at minimum. Reservoir and stack(s) could be separated.

(d) Scale effects in the 10-50 kWh range, if applicable?

Larger batteries were advantageous - even more than shown by volumes above.
ZINC-BROMINE CIRCULATING BATTERY

Electrochemical Reactions:

\[
\begin{align*}
\text{Zn}^0 & \rightarrow \text{Zn} + 2e^- \\
\text{Br}_2 + 2e^- & \rightarrow 2\text{Br}^- \\
\text{Self discharge:} & \quad \text{Zn}^0 + \text{Br}_2 \rightarrow \text{ZnBr}_2
\end{align*}
\]

Figure 1. Circulating Zinc-Bromine Battery
Figure 2. Zinc-Bromine 1200-cm$^2$ Battery Components
Figure 3. ZN-Br2 1kWh Battery Stack-PAMO17
8 Cell Stack-1. DM2 Electrode Area
CHARGE-DISCHARGE VOLTAGE PROFILE OF 10 kWh (Z-10) BATTERY

10 kWh ZINC—BROMINE SUB-MODULE 120V-1200 cm² ELECTRODES

POLARIZATION CURVES OF 10 kWh BATTERY (Z-10) (20 SECOND PULSES)

Figure 4.
APPENDIX D

DESIGN ANALYSES OF
ZINC-CHLORIDE BATTERIES
FOR ELECTRIC VEHICLES
EDA PERSPECTIVE

This report describes the characterization of the zinc-chloride batteries for a variety of electrical vehicle missions, with specific emphasis on the fixed power to energy batteries defined in this contract with JPL. The fixing of the power and energy levels does not allow the trade-offs of battery stored energy (vehicle range) and total vehicle weight for a particular vehicle type. This trade-off is a very important characteristic for flowing electrolyte batteries, such as the zinc-halogen systems. In the case of the zinc-chloride battery, incremental energy can be stored for a given power level at a cost of $10/kWh and at a very high incremental energy density of 220 Wh/kg. A graphic example of this is the general purpose van having a 60-kW, 25-kWh battery defined in this contract. A zinc-chloride battery as per these specifications would weigh 399 kg and sell for $3,684. In reality, however, the range of this vehicle could actually be doubled for an increase in selling price of only $250 and a weight increase of 250 pounds. This increased stored energy has to be considered as a very attractive option, since the 100-mile plus range it would allow, will greatly improve the usefulness of such a van. The subject of incremental stored energy has not been specifically addressed in this report because of the fixed power to energy definition. However, this subject is an important element in quantifying the zinc-chloride battery for vehicle market applications and must be taken into account if an accurate and comprehensive assessment is to be made.
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<th>Page</th>
</tr>
</thead>
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</tbody>
</table>
Energy Development Associates has been developing zinc-chloride batteries for electric-vehicle applications since 1972. By early 1976 it had developed the comb-type bipolar stack structure. Under an R&D contract with the U.S. Department of Energy, EDA developed and demonstrated a 36-kWh engineering prototype battery in a Volkswagen Rabbit by 1980. Early in 1980 Gulf+Western Industries (G+W) -- EDA's parent company -- initiated its own program to demonstrate 40-kWh zinc-chloride batteries in specially-designed four-passenger vehicles. Upon demonstrating the technical viability of zinc-chloride powered passenger vehicles -- the Rabbit exhibiting a 117-mile range at average speeds above 40 mph in highway/city driving and a four-passenger G+W vehicle exhibiting a 200-mile range at 40 mph on a 2.5-mile oval track --, the emphasis was shifted to delivery vehicle battery development and engineering. In 1983 EDA demonstrated a 40-kWh engineering prototype battery in a converted half-ton Renault Trafic van. During independent testing of this vehicle at Ohio's Transportation Research Center, it exhibited a 90-mile range at an average speed of 35 mph.

The basic objective of this contract -- Contract Number 956811 with the California Institute of Technology, Jet Propulsion Laboratory (JPL) -- is to assess and report on the design flexibility, cost sensitivity, and technical feasibility of zinc-chloride battery designs targeted for development through the early 1990s. In preparing this report EDA has made every effort to follow the guidelines established by JPL. It should be noted however, that zinc-chloride batteries have some unique features which the pre-established guidelines fail to bring out. Many of these features are common to flow batteries and will be touched upon as a prelude to the main body of this report.

**Design and Operational Description**

Figure 1 schematically illustrates the operation of a zinc-chloride battery during charge. A pump is used to circulate electrolyte through the battery stack. The chlorine gas formed during charge is transferred from the stack to the store using a gas pump. The chlorine is mixed with chilled store liquid at the inlet to the pump and chlorine hydrate is formed in the pump and at the outlet from the pump. The circulating store liquid is separated from the solid hydrate particles using a filter shown at the bottom of the store. A heat exchanger utilizing glycol or Freon is used to chill the recirculating store liquid.
Figure 1. Zinc-Chloride Battery During Charge

Figure 2 shows the battery during discharge. Electrolyte is again circulated through the stack using a pump. A portion of this warm electrolyte is tapped from the main manifold and flowed through a heat exchanger to decompose the hydrate. The evolved chlorine gas from the store is injected and dissolved in the electrolyte stream which is feeding the stack. The gas pump is not used during discharge.

Figure 2. Zinc-Chloride Battery During Discharge
Figures 1 and 2 show the battery stacks inside the sump. In most vehicle batteries, the battery stacks are actually packaged separately from the sump and are connected to the sump by electrolyte supply and return piping. Also heat transfer between stack and store is most frequently accomplished by a direct interchange of electrolyte between the two compartments.

Figure 3 shows the present construction of a zinc-chloride comb-type battery stack. Graphite wafers, which serve as the zinc-electrode substrates, are press-fitted into one side of a bipolar busbar. Pairs of chlorine electrodes are press-fitted into the other side of the busbar. The result is a double-sided comb, hence the comb-type designation. In assembling the battery stacks, the zinc electrodes of one comb interleave with the chlorine-electrode pairs of another comb to form the unit cell. The stack terminates with a thick graphite busbar at one end with chlorine electrodes, while at the other end, there is a thick graphite busbar with zinc-electrode substrates.

![Zinc-Chloride Unit Cell Construction](image)

**Figure 3. Zinc-Chloride Unit Cell Construction**

**Design Flexibility of Zinc-Chloride Mobile Batteries**

Design parameters that reflect the performance and cost of zinc-chloride batteries in mature production in the early 1990s were utilized to develop the relationships between power, energy, weight, and cost of vehicle batteries.
Figure 4 shows the general relationship between specific power and specific energy for P/E ratios of 1:1 to 2:1. The band illustrates that the relationship varies with different battery capacities. P/E ratios greater than 2 would be achieved by adding more stack volume.

![Figure 4: Specific Power and Specific Energy Relationship](image)

Figure 4. Specific Power and Specific Energy Relationship

Figure 5 illustrates the relationship between battery power, energy, and weight. This figure more clearly shows the effect of battery power on weight. Doubling the power of a 30-kWh battery from 30 kW to 60 kW, the weight increases from ~650 pounds to ~930 pounds (100 Wh/kg → 70 Wh/kg, respectively). By increasing the battery energy for any design power level increases the battery weight at a rate of only ~10 lb/kWh (4.5 kg/kWh).
Figure 5. Battery Power, Energy, and Weight Relationship

Figure 6 shows the relationship between battery power, energy, and selling price. This figure shows the sensitivity of battery selling price to battery power level and the relative insensitivity of price to battery energy. A 30-kW, 30-kWh battery would sell for $2,500 and a 60-kW, 30-kWh battery would sell for $3,750, a 50% increase in selling price. Conversely an increase in battery energy increases the selling price of higher power batteries at a rate of only ~$10/kWh.
RESPONSE TO JPL GUIDELINES

This section of the report summarizes the results of the assessment conducted in accordance with the "Guideline For Contractor Response." The order of presentation is consistent with the format of the guideline document.

Battery Technological Projections

Zinc-chloride battery performance and cost projections were made for four specific vehicle batteries. The four batteries and their delivered energy and power requirements are as follows:

- Commuter Vehicle Battery -- 42 kWh, 25 kW
- Hybrid Vehicle Battery -- 15 kWh, 50 kW
- General Purpose EV or Commercial Van Battery -- 25 kWh, 60 kW
- Full Performance EV Battery -- 50 kWh, 50 kW

The technological projections for these four batteries as well as other zinc-chloride batteries in this report are limited to batteries which could be demonstrated in prototype form in the early 1990s. The projections are for one-year old batteries operating in 70°F ambient air.

Performance Modeling

A battery model was used to project performance and weight of zinc-chloride batteries for various battery energy storage and power requirements. The basic design parameters for this model are as follows:

- Delivered capacity of 160 mAh/cm² of electrode surface
- Delivered energy of 300 W/cm² at 30-sec peak power
- Chlorine storage density of 0.27 g/cc of store volume

Projected discharge characteristics of the four specified vehicle batteries are compared in Tables 1 and 2. These projected characteristics are compared with a 43-kWh, 40-kW battery that reflects the present state-of-the-art of zinc-chloride battery technology.

Table 1 compares the specific energy (Wh/kg) at various discharge rates for the subject batteries.
Table 1

SPECIFIC ENERGY (Wh/kg) FOR VARIOUS DISCHARGE RATES

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Discharge Rate (W/kg)</th>
<th>30 Sec Peak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20  60  80  100</td>
<td>(W/kg)</td>
</tr>
<tr>
<td>1. Present</td>
<td>67  51</td>
<td>63</td>
</tr>
<tr>
<td>2. Commuter</td>
<td>66  50  58  55</td>
<td>133</td>
</tr>
<tr>
<td>3. Hybrid</td>
<td>50  47  46  44</td>
<td>162</td>
</tr>
<tr>
<td>4. Gen. Purpose EV or Van</td>
<td>65  61  58  56</td>
<td>150</td>
</tr>
<tr>
<td>5. Full Performance</td>
<td>110 100 93 85</td>
<td>108</td>
</tr>
</tbody>
</table>

Table 2 compares the 30-second peak power capability at various state-of-charge percentages. These values reflect the relatively flat voltage profile of the zinc-chloride battery throughout the entire battery discharge.

Table 2

30-SECOND PEAK SPECIFIC POWER (W/kg) AT VARIOUS PERCENT STATE-OF-CHARGE AS DEFINED BY A STANDARD C/4 RATE

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>80</th>
<th>50</th>
<th>30</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>80 % SOC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Present</td>
<td>62  61  61</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Commuter</td>
<td>132 130 128</td>
<td>127</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Hybrid</td>
<td>160 158 156</td>
<td>154</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Gen. Purpose EV or Van</td>
<td>149 147 145</td>
<td>144</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Full Performance</td>
<td>107 105 104</td>
<td>103</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cost Projections

Estimates of battery selling price of the four specified vehicle batteries and a present state-of-the-art 43-kWh, 40-kW battery are compared in Table 3. The estimates are for batteries in mature production of 100,000 units per year.
Table 3
SELLING PRICE OF VEHICLE BATTERIES

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>$/Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Present</td>
<td>4,000*</td>
</tr>
<tr>
<td>2. Commuter</td>
<td>2,026</td>
</tr>
<tr>
<td>3. Hybrid</td>
<td>3,154</td>
</tr>
<tr>
<td>4. Gen. Purpose EV or Van</td>
<td>3,684</td>
</tr>
<tr>
<td>5. Full Performance</td>
<td>3,525</td>
</tr>
</tbody>
</table>

*Engineered for manufacturing

Technical Support for Projections

Research and development in several areas to advance the state-of-the-art of zinc-chloride batteries is a continuing effort at EDA. Development of the following components, systems, and processes is expected to lead to the achievement of the battery performance and price projected for the early 1990s.

Store (hydrate storage process): Increasing the chlorine hydrate storage density significantly impacts on battery weight and volume as well as reduces cost. Using straight filtration, chlorine packing densities of 0.20 g/cc of store volume are presently achieved in 40-kWh size stores and densities up to 0.25 g/cc have been achieved in 20-kWh size stores. Chlorine storage densities in the range of 0.30-0.40 g/cc have been demonstrated with hydrate pellets.

Cell Electrodes: Lower cost graphite electrodes and improved activation processes have a direct effect on battery performance, weight, volume, and cost.

Unit Cell: Development of unit cell designs offer promise of reduced cost through reduced component parts, fabrication, and assembly. Unit cell design development also has promise of significant improvements in stack performance and efficiency.

Materials of Construction: Improvement of materials promises reduced fabrication costs and reduced maintenance costs due to a reduction of contaminants in the electrolyte.

Battery System: Battery system development aimed at system and component simplification promises reduced costs and improved reliability.
Energy Balance

To quantify sources of energy use such as self discharge, parasitic losses, etc., under vehicle driving conditions, a total energy balance was performed for a zinc-chloride battery through an entire driving cycle. The cycle utilized for this energy balance is the simplified 24-hour driving pattern requested in the "Guidelines for Contractor Response" furnished by JPL. This driving pattern, which certainly cannot be considered as a typical EV driving cycle, is illustrated in Figure 7. The driving portion of this pattern (designated driving cycle 3) was proposed by JPL to the EHV Battery Task Force as a greatly simplified version of the Federal Urban Driving Schedule to be used for life-cycle testing. This driving cycle is detailed in Table 4.

Figure 7. Simplified 24-Hour Driving Pattern
### Table 4

**DETAILED DRIVING CYCLE 3**

<table>
<thead>
<tr>
<th>Cycle Segment</th>
<th>Time (s)</th>
<th>Type*</th>
<th>Energy Consumed (W-s/kg)</th>
<th>Average Power (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-26</td>
<td>A</td>
<td>298</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>26-30</td>
<td>A</td>
<td>358</td>
<td>89</td>
</tr>
<tr>
<td></td>
<td>30-74</td>
<td>A</td>
<td>1428</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>74-76</td>
<td>A</td>
<td>94</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>76-171</td>
<td>D</td>
<td>-265</td>
<td>-3</td>
</tr>
<tr>
<td>2</td>
<td>171-196</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>196-211</td>
<td>A</td>
<td>497</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>211-236</td>
<td>C</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>236-251</td>
<td>D</td>
<td>-155</td>
<td>-10</td>
</tr>
<tr>
<td>3</td>
<td>251-276</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>276-291</td>
<td>A</td>
<td>497</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>291-316</td>
<td>C</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>316-331</td>
<td>D</td>
<td>-155</td>
<td>-10</td>
</tr>
<tr>
<td>4</td>
<td>331-356</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>356-371</td>
<td>A</td>
<td>497</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>371-396</td>
<td>C</td>
<td>175</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>396-411</td>
<td>D</td>
<td>-155</td>
<td>-10</td>
</tr>
<tr>
<td></td>
<td>411-436</td>
<td>S</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

* A - acceleration  
C - cruise  
D - deceleration  
S - stand

All calculations of the total energy balance were based on the ETV-1 vehicle battery weight of 488 kg.

The total energy balance was calculated for a zinc-chloride battery design based on performance levels projected in the early 1990s. This battery has a design 30-second peak power of 50 kW, a delivered energy of 52.7 kWh at a C/4 discharge rate, and a total weight of 472 kg. Although the total energy consumed in the 24-hour driving pattern is small compared to the energy storage capacity of this battery, this size battery was chosen to approach the weight of the ETC-1 vehicle battery (488 kg) used as the calculation base.
The estimates of in-use energy consumption and the energy balance of the zinc-chlorine battery for the 24-hour driving pattern are shown in Table 5.

Table 5

ESTIMATES OF IN-USE ENERGY CONSUMPTION (Wh)
FOR 24-HOUR DRIVING PATTERN

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Start-up/</td>
<td>0</td>
</tr>
<tr>
<td>Shut-down</td>
<td></td>
</tr>
<tr>
<td>Self-discharge &amp;</td>
<td>931</td>
</tr>
<tr>
<td>Shunt Current</td>
<td>157</td>
</tr>
<tr>
<td>Parasitics</td>
<td>0</td>
</tr>
<tr>
<td>Thermal Loss</td>
<td>924</td>
</tr>
<tr>
<td>Net Heat Rejection</td>
<td></td>
</tr>
</tbody>
</table>

Total Energy Delivered (segments 1 & 3) = 5,634 Wh
Total Energy Input on Charge (segment 5) = 11,660 Wh
System Discharge Efficiency = 64.4%
System Charge Efficiency = 75.0%
Overall Round-Trip Efficiency = 48.3%

Net battery ampere hours and watt hours delivered and ampere hour and watt hour losses for the discharge segments (segments 1 and 3) of the 24-hour driving pattern were calculated by a detailed analyses of the four modes of operation in the segments, i.e., acceleration, cruise, deceleration, and stand. The 8-hour charge segment (segment 5) of the 24-hour pattern was calculated as a 0.5-hour period for store electrolyte cool down to hydrate formation temperatures and a 7.5-hour battery charge. The net heat rejected in each segment includes all parasitic, shunt, self discharge, thermodynamic heat, heat of hydrate formation (charge) or decomposition (discharge), and voltaic losses. Regenerative braking is assumed during deceleration and the associated voltaic losses are included. The total energy input on charge, the system charge efficiency, and the overall round-trip efficiency include the energy input of the refrigeration unit for the 8-hour duration of segment 5.
Because the consumed energy in segments 1 through 4 is only a fraction of the storage capacity of the zinc-chloride battery in this weight class, the values in the charge segment (segment 5) are normalized by this fraction to permit proper battery evaluation. With this zinc-chloride battery, the driving pattern could be repeated approximately seven times on a single charge. Due to the fact that the zinc-chloride battery has no start-up or shut-down losses and operates at near ambient with no thermal losses, these parameters in Table 5 are designated as such.

It is assumed that the 24-hour driving pattern requested in the Guide-line is for battery evaluation purposes only. EDA does not consider this pattern to be representative of any urban driving cycle and is considered to be a worst-case duty cycle for flowing electrolyte batteries because of the many active stand requirements. The round-trip efficiency for this driving pattern is 48% as compared to a round-trip efficiency of 60% for a standard C/4 discharge cycle. The efficiency for a truly representative driving pattern would be somewhere between these values; more likely in the range of over 50% and under 60%.

**Life Considerations**

Due to the cost and time required for cycle life testing with vehicle batteries, life cycle test data are limited. Most of the data available are for zinc-chloride cells and batteries that are indicative of but not identical to vehicular batteries. EDA has operated a zinc-chloride battery-powered vehicle approximately 25,000 equivalent miles with varying states of charge. The number of cycles on this vehicle battery is 202 to date. Modules in load-leveling batteries -- which incorporate the same basic cell design and materials -- have performed through the equivalent of 1,724 cycles. Although not part of any formal life-cycle test program, experimental zinc-chloride cells have operated over more than 600 cycles. Data collected from these cells and batteries indicate that the gradual oxidation of the porous-graphite chlorine electrodes will establish the useful life of zinc-chloride electric-vehicle batteries. Carbon dioxide formation rates suggest that the chlorine electrodes will experience only a 10% reduction in weight after 150,000 vehicle miles.

These data are summarized in Table 6.

**Other Operational Characteristics**

Zinc-chloride batteries offer the capability of over-charge and over-discharge without producing any serious safety hazards or permanent damage to the batteries. The depletion of zinc ions during overcharge results in an increased H₂ formation rate at the zinc electrodes. This is handled by recombining the H₂ with Cl₂ in the gas phase using the recombination reactor. Due to the fact that excess chloride ions are present -- in the form of supporting salts --, the major anodic reaction during over-charge continues to be the oxidation of chloride ions to chlorine. This chlorine is then available for recombination with the H₂ and return to the electrolyte as HCl.
Table 6

PRESENT STATUS CYCLE LIFE

<table>
<thead>
<tr>
<th></th>
<th>Cycle Life</th>
<th>Depth of Discharge</th>
<th>Life-limiting Mechanisms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cells</strong></td>
<td>&gt;600*</td>
<td>Varied</td>
<td>CO$_2$ formation rates indicate 10% wt. loss in chlorine electrodes at 150,000 vehicle miles.</td>
</tr>
<tr>
<td><strong>Modules</strong></td>
<td>&gt;1700</td>
<td>100%</td>
<td>Chlorine-electrode loss due to extensive accidental overcharges.</td>
</tr>
<tr>
<td><strong>Batteries</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle</td>
<td>200</td>
<td>100%</td>
<td>Both units remain operational.</td>
</tr>
<tr>
<td>Load-Leveling</td>
<td>170</td>
<td>100%</td>
<td></td>
</tr>
</tbody>
</table>

*Cells employed for developmental purposes and were not part of a formal life test program.

Upon overdischarge zinc-chloride cells revert to chlorine-chlorine cells due to the excess inventory of chlorine in the system. Typical 50-kWh zinc-chloride batteries contain a minimum inventory of 0.6 kg of excess chlorine as chlorine dissolved in the battery electrolyte and 1 atm absolute chlorine pressure in the gas phase of the battery. Upon depletion of metallic zinc from the dense-graphite zinc-electrode substrates, the electrode reaction becomes the anodic formation of chlorine from available chloride ions. The corresponding cathodic reduction of dissolved chlorine to chloride ions continues at the porous-graphite chlorine-electrode substrates of a reversed (overdischarged) cell.

Cell balancing in a zinc-chloride battery is accomplished by completely stripping zinc from all the cells in the battery, i.e., cell balancing is accomplished by periodic complete discharge. Zinc-electrode shape changes, associated with nonuniform shunt current and primary current distributions during partial depth-of-discharge operation, suggest the desirability of conducting periodic cell balancing operations after every 5,600 Ah of charge or the equivalent of every 10 complete charge/discharge cycles.
Maintenance operations on commercial zinc-chloride batteries will be conducted primarily to ensure the proper operation of mechanical and electrical components in the system. Valve seats, pump bearings and wear plates, etc., may require replacement on an annual or biannual basis. Electronic components — pressure transducers, temperature sensors, etc., -- could require annual recalibration and occasional replacement. Inerts-gas rejection will be handled automatically at complete discharge and adjustments to the electrolyte pH will be required on about a biannual basis.

Zinc-chloride batteries are designed to allow for the replacement or refurbishment of failed mechanical and electrical components or subsystems. The battery stack can, in accidental contamination situations, be refurbished by draining and chemical cleaning. Although present stack designs do not allow for easy electrode replacement, it is possible to replace unit cells and thereby refurbish a battery stack. Unit cell replacement offers cost savings over stack replacement for about two-thirds the life of the battery. Beyond the equivalent of 80,000 vehicle miles on the battery the cost of cell replacement may not be economically justified.

**Packaging Flexibility**

Table 7 compares the projected volumes of the four specified vehicle batteries and a present state-of-the-art 43-kWh, 40-kW battery.

Table 7

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Volume (liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Present</td>
<td>464</td>
</tr>
<tr>
<td>2. Commuter</td>
<td>144</td>
</tr>
<tr>
<td>3. Hybrid</td>
<td>253</td>
</tr>
<tr>
<td>4. Gen. Purpose EV or Van</td>
<td>325</td>
</tr>
<tr>
<td>5. Full Performance</td>
<td>366</td>
</tr>
</tbody>
</table>

A cell stack is a number of unit cells fabricated in series in bipolar fashion. The present minimum dimensions of a unit cell are 2.9 inches in length, 9.7 inches in width, and 5.5 inches in height including supply and return manifolds. A cell stack contains anywhere from 20 to 40 cells depending on the power and packaging requirements. Therefore the minimum stack dimensions are height 5.5", width 9.7", and length 2.9" x number of cells.
The main battery components are the stacks, sump, and store. From an operational standpoint these components can be packaged anywhere in the vehicle that is practicable. The only special consideration as to their relative placement is weight distribution in the vehicle.

CONCLUSIONS

The results of this assessment indicate that zinc-chloride batteries can provide a cost-effective power source ($70/\text{kWh}) for electric vehicles which have a power-to-energy ratio of approximately one. Although life-cycle costs are not specifically addressed in the report guidelines, they will be very low for zinc-chloride batteries because of the low capital cost, low-maintenance, and long-life features of this system.

With regards to efficiency, zinc-chloride batteries will operate with round-trip efficiencies in the range of 50-60% depending upon the duty cycle. The projected efficiency for the duty cycle specified in the guidelines is 48%. This cycle is unduly severe on flow-type batteries — due to the large number of active stands involved — and does not appear to be representative of an urban driving cycle. The projected overall efficiency for the same battery on a simple charge/discharge (at the C/4 rate) cycle is approximately 60%. These two types of duty cycles establish the extremes and operating efficiencies on typical driving cycles will likely be in the range of 53-57%.

In the areas of specific energy and specific power, zinc-chloride batteries with power-to-energy ratios of approximately one will offer values of at least 100 Wh/kg and 100 W/kg, respectively. It seems very logical that users of this type of battery, where energy can be added for a minimum penalty — only 10 lb/kWh added weight and only 10 $/kWh added selling price —, will choose the full energy capability. The extra energy can be used for creature conveniences and/or eliminate the need to recharge a route-type vehicle on a daily basis.
APPENDIX E

IRON-AIR BATTERY DESIGN
FOR THE JET PROPULSION LABORATORY
IRON-AIR BATTERY DESIGN ANALYSIS FOR THE JET PROPULSION LABORATORY

D. Zuckerbrod and E. S. Buzzelli

February 9, 1984
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IRON-AIR BATTERY DESIGN ANALYSIS
FOR THE JET PROPULSION LABORATORY

by

D. Zuckerbrod and E. S. Buzzelli

Abstract

The iron-air battery system was modeled mathematically to predict performance, peak power, cost and the size of batteries designed for various specific electric vehicle missions. Near term (late 1980's) and advanced technology (early 1990's) performance cases were considered for commuter, hybrid, van and full performance type electric vehicles. Technical support was given for projections and consideration was given to known system losses. Boundary conditions were given for battery performance indicating design flexibility. The results of this modeling effort indicate that the iron-air couple could meet the established goals for each mission in a low cost battery system.
1. Summary

The iron-air battery system was modeled mathematically to obtain estimates of battery performance, cost, weight and size for various missions using individual electrode performance characteristics based on available data and conservative projections. Mission specifications, given in terms of energy and power, and their respective battery characteristics are summarized in Table 1-1 for the near term case (late 1980's) and in Table 1-2 for the advanced technology case (early 1990's). Details of the calculations and of the model used to calculate the derived quantities expressed in this report are available upon request. They were not included as they were beyond the scope of this work.

Table 1-1. Summary of Near Term Battery Characteristics.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>12</td>
<td>25</td>
<td>98</td>
<td>203</td>
<td>880</td>
<td>102</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>50</td>
<td>72</td>
<td>240</td>
<td>1524</td>
<td>208</td>
</tr>
<tr>
<td>EV or Van</td>
<td>25</td>
<td>60</td>
<td>90</td>
<td>215</td>
<td>1831</td>
<td>279</td>
</tr>
<tr>
<td>Full Perf</td>
<td>50</td>
<td>60</td>
<td>130</td>
<td>130</td>
<td>1744</td>
<td>260</td>
</tr>
</tbody>
</table>

Table 1-2. Summary of Advanced Technology Battery Characteristics.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>12</td>
<td>25</td>
<td>126</td>
<td>282</td>
<td>636</td>
<td>81</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>50</td>
<td>93</td>
<td>300</td>
<td>1031</td>
<td>147</td>
</tr>
<tr>
<td>EV or Van</td>
<td>25</td>
<td>60</td>
<td>115</td>
<td>277</td>
<td>1230</td>
<td>187</td>
</tr>
<tr>
<td>Full Perf</td>
<td>50</td>
<td>60</td>
<td>181</td>
<td>181</td>
<td>1187</td>
<td>204</td>
</tr>
</tbody>
</table>

1. requirement defined in *Guidelines for Contractor Response*
2. using *Cycle 3* driving cycle
3. from 100% to 20% SOC
The results of the modeling effort clearly indicate that the iron-air battery system could meet the goals for each mission. Battery cost, weight and size all fall within the range judged necessary for an electric vehicle propulsion battery.
2. Introduction

The iron-air cell, consisting of a porous sintered iron electrode coupled to a carbon-based bifunctional air electrode, has the characteristics necessary for the development and demonstration of a successful battery system for electric vehicle propulsion. The cell reaction during discharge is as follows:

\[
\begin{align*}
\text{Fe} + 2 \text{OH}^- & \rightarrow \text{Fe(OH)}_2 + 2 \text{e}^- \quad \text{(anode)} \\
1/2 \text{O}_2 + \text{H}_2\text{O} + 2 \text{e}^- & \rightarrow 2 \text{OH}^- \quad \text{(cathode)}
\end{align*}
\]

\[
\begin{align*}
\text{Fe} + \text{H}_2\text{O} + 1/2 \text{O}_2 & \rightarrow \text{Fe(OH)}_2 \quad E^0=1.283 \text{ V}
\end{align*}
\]

This system has many advantages in terms of battery design and commercial applicability. The most obvious advantage is the inexhaustability and therefore the invariance of the positive electrode. Oxygen is supplied from ambient air (scrubbed free of CO₂) during discharge and returned to it during charge. This, in part, helps to maintain the flat discharge curve (voltage vs. state of charge) exhibited by iron-air cells. The air electrode can neither be overcharged nor overdischarged with respect to cathode capacity and utilization thus making cell balancing unnecessary and simplifying equalization. The power and energy of a cell can be varied almost independently by varying the area of the cell (power) and the thickness of the iron electrode (energy). This allows great design flexibility and the tailoring of the battery to a specific mission requirement. This design flexibility is not available in other secondary battery systems.

The materials used in iron-air cells are low in cost and are available in an almost inexhaustable supply. The air electrode is catalyzed with a low loading of silver (1-2.5 mg/cm²) This low level of peroxide elimination catalyst represents only a small part of the estimated cost of the electrode (less than 25% of $8/oz.).

Finally, electrode life in excess of 500 cycles for both the iron and air electrodes has been demonstrated in half-cell tests. Full-cells have been tested
with lifetimes in excess of 100 cycles but these do not reflect state-of-the-art air electrodes which have since been improved considerably.

The present status of the Iron-Air Battery Development Program is as follows:

- The iron electrode has met the near term goal of 0.4 Ah/g for greater than 500 cycles.
- The air electrode is undergoing continued development and has improved in performance and reproducibility. Lifetime in excess of 500 cycles has been demonstrated.
- Iron-air cell testing and development was terminated in 1980 at the request of the sponsor in order to focus on advancing the cycle life characteristics of the air electrode.

Estimates of near term cell performance used in this study were based on previous cell testing with the results adjusted to reflect subsequent improvements in the air electrode.
3. The Model

The goal of this work was to estimate the performance, weight and cost of an iron-air battery for electric vehicle propulsion. Such a battery, with the desirable characteristics reported herein, has not been built. A mathematical model was employed to generate these values from existing half-cell and full-cell data. Two scenarios were considered, a near term (late 1980's) case and an advanced (early 1990's) case.

3.1 Assumptions

The driving cycle assumed for battery discharge was "Cycle 3", appended at the end of the "Guidelines for Contractor Response." Regenerative braking was disregarded as it was only a small factor in the design of the battery.

Cell polarization curves are shown in Figure 3-1. They include resistive losses in the electrolyte. For the purpose of the model, the curves were considered to be linear and a least squares fit was made through the input polarization data. The slope and intercept so obtained were used to calculate the characteristics of the battery. Physical assumptions used to calculate cell performance are given in Table 3-1. The low estimate for auxiliary weight was derived in part from the minimal cell casing required. The major faces of the cell container are the air electrodes, whose weight is included as the electrode itself.

The energy requirements for parasitic losses were defined not to exceed 5% of the battery energy based on the results of an earlier system study*. The power penalty for this steady load is minimal and was ignored. The parasitics need not operate when the vehicle is shut down. The system consists of a blower for cell air, an electrolyte circulation pump, a heat exchanger, a carbon

dioxide scrubber, and a packed-bed humidifier-dehumidifier. The cost estimate of $200 used for peripherals, shown in Table 3-2 with the iron and air electrode cost assumptions, appears reasonable at this stage of development of the iron-air battery system. Further development of real systems in a future hardware development program will provide more realistic costs for the peripherals.
Table 3-1. Physical Assumptions for the Battery Model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Near Term</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Electrode Density</td>
<td>1.14</td>
<td>1.14 g/cm³</td>
</tr>
<tr>
<td>Air Gap</td>
<td>0.1</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Air Electrode Weight</td>
<td>0.2</td>
<td>0.15 g/cm²</td>
</tr>
<tr>
<td>Iron Electrode Density</td>
<td>1.68</td>
<td>1.68 g/cm³</td>
</tr>
<tr>
<td>Iron Electrode Capacity</td>
<td>0.4</td>
<td>0.5 Ah/g</td>
</tr>
<tr>
<td>Electrolyte Density</td>
<td>1.23</td>
<td>1.23 g/cm³</td>
</tr>
<tr>
<td>Electrolyte Conductivity</td>
<td>0.48</td>
<td>0.48 ohm^{-1}cm^{-1}</td>
</tr>
<tr>
<td>Electrolyte Gap</td>
<td>0.1</td>
<td>0.1 cm</td>
</tr>
<tr>
<td>Theoretical Potential</td>
<td>1.283</td>
<td>1.283 V</td>
</tr>
<tr>
<td>Charging Potential</td>
<td>1.53</td>
<td>1.5 V</td>
</tr>
<tr>
<td>Current Efficiency (charge)</td>
<td>90</td>
<td>95 %</td>
</tr>
<tr>
<td>Auxiliary Weight</td>
<td>10</td>
<td>10 %</td>
</tr>
<tr>
<td>Auxiliary Volume</td>
<td>15</td>
<td>15 %</td>
</tr>
<tr>
<td>Parasitics</td>
<td>5</td>
<td>5 % Energy</td>
</tr>
</tbody>
</table>

Table 3-2. Cost Assumptions.

<table>
<thead>
<tr>
<th>Component</th>
<th>Near Term</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron Electrode</td>
<td>$2.00</td>
<td>2.00 $/kg</td>
</tr>
<tr>
<td>Air Electrode</td>
<td>30.00</td>
<td>20.00 $/m²</td>
</tr>
<tr>
<td>Peripherals</td>
<td>200.00</td>
<td>200.00</td>
</tr>
</tbody>
</table>

3.2 Calculations

The calculation of battery performance, weight and cost consisted of five parts:

1. Determination of the slope and intercept of a least squares fit of the cell polarization curve and calculation of peak power per unit area

2. Sizing the cell area to meet peak power requirements

3. Sizing the iron electrode thickness to meet energy requirements (range
to 0% SOC with some performance degradation expected from 20% to 0% SOC)

4. Iteration to converge at the desired energy with the driving cycle specified in W/kg of battery

5. Calculation of desired parameters using the battery designed in Step 4

The battery energy was increased to account for parasitic losses. Auxiliary volume and weight were factored in as part of Step 4. The calculations were performed using a "spreadsheet" program for a desktop computer.
4. Results and Discussion

4.1 Performance Modeling

The results of the performance modeling calculations are given in Table 4-1 for the near term battery performance and in Table 4-2 for the advanced performance using the assumptions given in Table 3-1.

Table 4-1. Near Term Battery Performance.
Specific Energy (Wh/kg) versus Discharge Rate (Specific Power)

<table>
<thead>
<tr>
<th>Bat. Design</th>
<th>20W/kg</th>
<th>60W/kg</th>
<th>80W/kg</th>
<th>100W/kg</th>
<th>200W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>104</td>
<td>98</td>
<td>95</td>
<td>92</td>
<td>60</td>
</tr>
<tr>
<td>Hybrid</td>
<td>77</td>
<td>73</td>
<td>71</td>
<td>69</td>
<td>55</td>
</tr>
<tr>
<td>EV or Van</td>
<td>96</td>
<td>91</td>
<td>88</td>
<td>85</td>
<td>62</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>151</td>
<td>137</td>
<td>120</td>
<td>120</td>
<td>*</td>
</tr>
</tbody>
</table>

* exceeds peak power

Table 4-2. Advanced Battery Performance.
Specific Energy (Wh/kg) versus Discharge Rate (Specific Power)

<table>
<thead>
<tr>
<th>Bat. Design</th>
<th>20W/kg</th>
<th>60W/kg</th>
<th>80W/kg</th>
<th>100W/kg</th>
<th>200W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>134</td>
<td>128</td>
<td>125</td>
<td>122</td>
<td>101</td>
</tr>
<tr>
<td>Hybrid</td>
<td>98</td>
<td>94</td>
<td>93</td>
<td>91</td>
<td>80</td>
</tr>
<tr>
<td>EV or Van</td>
<td>123</td>
<td>118</td>
<td>115</td>
<td>113</td>
<td>95</td>
</tr>
<tr>
<td>Full Perf.</td>
<td>195</td>
<td>182</td>
<td>175</td>
<td>167</td>
<td>*</td>
</tr>
</tbody>
</table>

* exceeds peak power

The flat discharge curve (potential vs. state of charge) for iron
electrodes and the invariance of the air electrodes indicate constant peak power independent of state of charge down to 20% SOC. After this, performance would be expected to degrade and polarization data to become erratic due to the characteristics of the iron electrodes and expected spread in the electrode capacities. The resistance of the iron electrode is essentially constant for the Fe(OH)$_2$ reaction, and as a result, the power characteristics for the cell/battery are constant during a discharge. This is unique to the iron-air system as compared to other secondary systems where impedance increases with depth of discharge. Peak power, which is constant from 100% to 20% SOC is given for the near term and advanced batteries in Table 4-3.

Table 4-3. Specific Peak Power (W/kg from 100% to 20% SOC).

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Near Term</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>203</td>
<td>262</td>
</tr>
<tr>
<td>Hybrid</td>
<td>240</td>
<td>300</td>
</tr>
<tr>
<td>EV or Van</td>
<td>215</td>
<td>277</td>
</tr>
<tr>
<td>Full Performance</td>
<td>130</td>
<td>181</td>
</tr>
</tbody>
</table>

4.2 Cost Projections

Using the assumptions shown in Table 3-2 and the iron weight and air electrode area requirements calculated by the model, the battery costs are projected in Table 4-4.

Table 4-4. Battery Cost Projections.

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Near Term</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>889</td>
<td>936</td>
</tr>
<tr>
<td>Hybrid</td>
<td>1524</td>
<td>1031</td>
</tr>
<tr>
<td>EV or Van</td>
<td>1831</td>
<td>1230</td>
</tr>
<tr>
<td>Full Performance</td>
<td>1744</td>
<td>1197</td>
</tr>
</tbody>
</table>

It must be noted that at the present stage of cell development, a detailed cost
study may not be meaningful. The assumed values appear to be reasonable in light of materials cost and the cost of related processes used in other Westinghouse products. A justification of the costs, is based on a 1980 manufacturing cost estimate completed at the request of Lawrence Livermore National Labs. The present electrodes may, in fact, provide a cost reduction to the 1980 estimate of $40/kWh.

4.3 Technical Support for Projections

Technical support for the projections made in this report is given in Table 4-5.

4.4 Energy Balance

The iron-air battery is an ambient temperature and pressure device. Therefore, start-up and shut-down losses are not encountered as they would be in high temperature fuel cells, molten salt or metal-halogen systems. Waste heat upon use will be sufficient to warm the battery to its operating temperature (35-45°C). Similarly, thermal loss is not seen as a problem.

The self discharge of iron-air cells has never been studied in detail at Westinghouse. However, it is felt that this is not a major problem. The air electrode can not self discharge in the usual sense (by evolving O₂ as nickel electrodes do). While mono-functional air electrodes tend to fail rapidly at open-circuit conditions due to carbon and catalyst oxidation (another sort of self discharge), the Westinghouse air electrode is fully bi-functional and thus is engineered to withstand the high potentials associated with oxygen evolution. The lower potentials associated with open circuit conditions do not appreciably damage the electrode. The iron electrode, however, may self discharge by evolving hydrogen. This can be controlled by minimizing impurities in the iron and the electrolyte to minimize the number of low overvoltage sites for hydrogen evolution. It is estimated, based on half cell test results, that the self discharge occurs at the rate of about 1% of the battery capacity (iron electrode capacity) per day, but there is no firm evidence here other than the half-cell observation.

Shunt currents can not be estimated at this stage of battery development, as
Table 4-5. Technical Support for Projections.

<table>
<thead>
<tr>
<th>Component</th>
<th>Present Status</th>
<th>Design Change</th>
<th>Performance Change</th>
<th>Cost Change</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Collector</td>
<td>Ni-fiber mat</td>
<td>Ni-plated steel wool mat</td>
<td>lower charge voltage</td>
<td>lower</td>
<td>extensive (W) experience</td>
</tr>
<tr>
<td>Active Material</td>
<td>Teflon\textsuperscript{bound} carbon + catalyst</td>
<td>non-fluorinated binder. improved catalyst</td>
<td>lower weight shorter break-in higher discharge voltage</td>
<td>much lower</td>
<td>new materials available study by CWBU</td>
</tr>
<tr>
<td>Hydropobic material</td>
<td>Teflon\textsuperscript{bound} carbon</td>
<td>Hostaflon\textsuperscript{bound} carbon</td>
<td>longer life less flooding</td>
<td>slight</td>
<td>cationic surfactant neutralized in base</td>
</tr>
<tr>
<td>Iron Electrode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Collector</td>
<td>Ni-EDMA\textsuperscript{TM}</td>
<td>improved configuration and tabbing</td>
<td>better utilization lower resistance</td>
<td>slight</td>
<td>tab welds show high resistance</td>
</tr>
<tr>
<td>Active Material</td>
<td>sintered porous iron</td>
<td>improved purity</td>
<td>better charge efficiency</td>
<td>slight</td>
<td></td>
</tr>
<tr>
<td>Separator</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
experience with other than single cells is extremely limited. Development of the full battery will surely attempt to minimize these shunt current losses.

Peripherals giving rise to parasitic losses during battery operation are an electrolyte pump, an air blower, and a packed-bed humidifier-dehumidifier. These need only operate when the vehicle is operating and perhaps shortly thereafter to avoid high temperatures after shut-down. A detailed thermal study of the iron-air battery system (1980) indicated that parasitic losses would not exceed 5% of the total battery energy for a nominal 20-40 kWh battery system.

The energy efficiency of the iron-air battery was resolved into the charge efficiency and discharge efficiency with the product of the two being the overall energy efficiency of the battery. The charge efficiency assumed a charge potential independent of rate because the rate will vary only slightly for an overnight charge. The discharge efficiency assumed the driving cycle used for the performance modeling. Regenerative braking was ignored as only an incremental benefit, but can be accepted by the battery.

The energy balance information is summarized in Table 4-6.

Table 4-6. Estimates of In-Use Energy Consumption.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Segments</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>1 2 3 4 5</td>
</tr>
<tr>
<td>Self Discharge*</td>
<td>- 20W - 20W</td>
</tr>
<tr>
<td>Parasitics*</td>
<td>1000W - 1000W - 100W</td>
</tr>
<tr>
<td>Energy Efficiency**</td>
<td>65(68)% - 65(68)% - 76(81)%</td>
</tr>
</tbody>
</table>

*Energy Consumption: Power, continuous over segment
**Energy Efficiency: Near term (Advanced Technology)%
4.5 Life Considerations

Iron electrodes and air electrodes have demonstrated lives of over 500 cycles in half cell tests. Actual iron electrodes have exceeded well over 1000 cycles with a somewhat different structure and lower electrode utilization. Full cells have demonstrated life of over 100 cycles with older, less stable air electrodes (pre 1980). The life limiting mechanism for air electrodes is the loss of structural integrity and hydrophobicity due to the corrosion of carbon and attack of the Teflon binder. This, in turn, limits the life of the cell. Cell life is not sensitive to depth of discharge (at least down to 0% SOC and perhaps further). Life test data does not exist for modules and batteries.

The life for an iron-air battery is presently projected to be greater than 500 cycles. No relationship between the ratio of power to energy and cycle life is foreseen for a properly designed cell, but once again, no experimental evidence exists in the cell engineering area. An ongoing air electrode research program is aimed at improved air electrode performance, uniformity, reproducibility and life. To date, improvements in both the air electrode structure and catalysis have involved either no change or a significant reduction in cost compared with earlier, less successful designs.

The performance of the air electrode remains constant for several hundred cycles after break-in (a few cycles). The performance then begins to decay linearly for perhaps another hundred cycles. At the end of life, the electrode may fail through gross leakage of electrolyte (case rupture) or flooding, whereupon oxygen reduction is not supported and hydrogen evolution occurs if the cell is driven. After the initial cycle, the iron electrode performance is essentially unchanging for many hundreds of cycles given chemically clean operating conditions (no CO₂ or low H₂ overvoltage impurities). So degradation of power, energy and efficiency follows the decay of the air electrode performance. No estimate of the reliability of a battery module (5 cells in parallel) is available at this time as experimental data is not available. It would be expected that the iron electrode could be manufactured to within ±2-3% of design capacity. The air electrode would probably be ±5 mV.
4.6 Other Operational Characteristics

It is impossible to overcharge or overdischarge the air electrode. As long as electrolyte and air are available, the electrode is invariant. Iron electrodes are not damaged by overcharging. This is well known for iron-nickel batteries, which require overcharging for proper operation. Overdischarging will take the iron electrode to a "second plateau" where the Fe$^{+2}$ is oxidized to Fe$^{+3}$. Thus the battery can be considered to have some emergency capacity if it were needed, albeit at very low power densities. Iron electrodes have been driven to oxygen evolution and then recharged with no apparent ill effects. Hence, the system is extremely tolerant to severe abuse in the form of extended overcharge and deep discharge well past the point of reversal, with no deleterious effects on performance or life. Individual cell balancing is never required in the iron-air battery due to the invariant air electrode. The cells are always in balance by definition. Periodic complete discharge is not required for proper cell operation. The battery is self-equalizing during charging as slight overcharging is normal and causes no damage while continuing to charge the cells of greater capacity.

Some regular maintenance is required for proper battery operation. Make-up water must be added to replace that lost to evaporation and electrolysis. The carbon dioxide scrubber will need its medium changed periodically and the electrolyte will also have to be changed at some relatively infrequent interval. Air and electrolyte filters will require cleaning and/or replacement and electrical connections may have to be inspected and cleaned. No estimate can be given for the frequency of these tasks as battery development has not yet reached a stage where estimates would be meaningful.

The low cost nature of the iron-air system will probably make battery refurbishment unnecessary with the exception of the replacement of a prematurely failed module.

4.7 Packaging Flexibility

Table 4-7 shows volumes predicted for various battery designs by the model. The values include a 15% volume penalty for auxiliary systems. The size and shape of the iron-air battery appears to be very flexible. The constraints, at
Table 4-7. Predicted Battery Volume.

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Near Term</th>
<th>Advanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commuter</td>
<td>102</td>
<td>147</td>
</tr>
<tr>
<td>Hybrid</td>
<td>185</td>
<td>147</td>
</tr>
<tr>
<td>EV or Van</td>
<td>236</td>
<td>187</td>
</tr>
<tr>
<td>Full Performance</td>
<td>200</td>
<td>204</td>
</tr>
</tbody>
</table>

this point in time, are that edge current collection is required by the system and air must be supplied to the air electrodes. A change in electrode shape would require redesign of the current collector with a possible weight penalty for an unfavorable shape. Both horizontal and vertical cell designs are being considered. Subsystems are required to handle air flow and electrolyte circulation. While placement of subsystems at a location remote from the battery will increase system complexity and weight and volume penalties, ducts and tubing can be designed as needed for spatial considerations.

While iron-air cells show no special scaling problems, the peripherals may have minimum sizes and weights adding a penalty to the low end of the 10-50 kWh range. Design of the auxiliaries will be performed as the iron-air development program proceeds toward a prototype system demonstration objective.
5. Conclusion

The iron-air battery system using the Westinghouse bi-functional air electrode, offers performance adequate for the specified electric vehicle propulsion missions proposed in this study. The flexibility offered by the invariant air electrode allows battery power and energy to be tailored to a specific task or vehicle mission need. The batteries are fabricated from inexpensive materials in abundant supply, resulting in a low cost battery system ($20-40 $/kWh). No special problems are expected due to start-up, shut-down or maintenance procedures and there are no inherent safety problems related to this particular system. Boundary conditions for iron-air battery performance, derived from the model used, are given in Figure 5-1. Estimates of the performance of peripheral systems include considerable uncertainty due to a lack of experimental data. Further research and development effort is required on the iron-air system to provide performance and life data which can be used to evaluate and compare this system to other candidates for the various EV missions. With respect to the three important battery criteria established by possible vehicle manufacturers, safety, reliability, and life, the Iron-Air system is a strong contender for use in vehicles in the 1990's.
Figure 5-1. Boundary Conditions for Iron-Air Battery Performance.
APPENDIX F

PERFORMANCE/COST PROJECTIONS
FOR LITHIUM/IRON SULFIDE BATTERIES
PERFORMANCE/COST PROJECTIONS
FOR LITHIUM/IRON SULFIDE BATTERIES

A. A. Chilenskas and H. Shimotake
Argonne National Laboratory
Argonne, Illinois 60439

February 1984
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I. INTRODUCTION

Research on the lithium/molten salt electrolyte system at ANL and several industrial developers has given rise to a family of electrodes containing lithium in the negative electrode and sulfur in the positive electrode. The electrode couple that has received the most attention has been Li-Al/FeS with its development carried well beyond the laboratory stage. Based upon the JPL study guideline of choosing technology that could be demonstrated in prototype form in the 1990-1992 era, the Li-Al/FeS technology rather than the potentially more energetic Li-Si/FeS2 technology has been chosen as a basis for the performance and cost projections.

The position the Li-Al/FeS couple holds in relation to other battery couples in terms of theoretical specific energy is shown in Fig. 1. As can be calculated from the values given, Li-Al/FeS has greater than 2 1/2 times the theoretical specific energy of Pb/PbO2. The most energetic couple in the lithium/molten salt family is Li/S and has about 15 times the theoretical specific energy of Pb/PbO2 and about 3 1/2 times that of the Na/S couple currently under development.

Research and development work on the lithium/molten salt system is worldwide. A brief summary of ongoing work is presented in Table 1.
Fig. 1. Theoretical Specific Energies of Selected Battery Systems.
<table>
<thead>
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<th>TABLE 1</th>
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<tbody>
<tr>
<td><strong>ONGOING PROGRAMS IN Li–ALLOY/MS BATTERY DEVELOPMENT</strong></td>
</tr>
</tbody>
</table>

- **DOE Work at ANL**
  - Research on advanced electrodes
  - Component design studies

- **U.S. Army (MERADCOM)**
  - Fork Lift Truck Program. Cells exceed 900 cycles

- **Electric Power Research Institute (EPRI)**
  - Van Battery Program
  - Li–Al/FeS modules
  - ANL and Gould

- **U.S. Air Force**
  - Satellite Battery Program. At Gould.

- **International**
  - Development Programs in England, Korea, Japan, U.S.S.R.
  - Commercialization of Li–Al/FeS by Chemelectron (Toronto) subsidized by Canadian government
II. PERFORMANCE MODELING

Two types of battery designs were evaluated for this study. The prismatic design, presently under development at ANL and Gould for the EPRI van battery program, has excellent prospects for meeting the requirements for the commuter car and the 3/4-ton van with improved state-of-the-art Li-Al/FeS technology. The bipolar design, being tested at Gould, has the potential for significant performance improvement over the prismatic design especially in terms of power density as required by the hybrid vehicle and high energy density as required by the long-range full performance automobile.

The specific energy and peak power projections for four classes of batteries are given in Tables 2 and 3. A prismatic design using Li-Al/FeS with a MgO separator and LiCl-KCl electrolyte was chosen for the class 2 battery because (1) the requirements for the commuter car and van can be met with modest improvements in the existing technology and (2) Li-Al/FeS with a MgO separator is the system with the lowest manufacturing cost.

The bipolar battery was chosen for the full-performance automobile and the hybrid vehicle. The main distinction between the class 3 and class 4 bipolar batteries is in the use of an all lithium electrolyte (LiBr-LiCl-LiF) in place of LiCl-KCl to improve the power performance of the hybrid battery. Li-Si is added to the Li-Al alloy in the negative electrode to provide an increase in the specific energy.

A discussion of the methodology used in projecting the performance of the prismatic batteries is given in Appendix A.

A discussion of the methodology used to project the performance of a bipolar Li-Al/FeS battery is given in Appendix B.
Table 2. Specific Energy, Wh/kg

<table>
<thead>
<tr>
<th>Class</th>
<th>Battery Designation</th>
<th>Battery Design</th>
<th>Discharge Rate (W/kg)</th>
<th>20</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Present Prismatic</td>
<td>Prismatic</td>
<td>63</td>
<td>50</td>
<td>43</td>
<td>35</td>
<td>30</td>
<td>0</td>
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<tr>
<td>2</td>
<td>Commuter Prismatic</td>
<td>Prismatic</td>
<td>87</td>
<td>75</td>
<td>67</td>
<td>60</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>3/4 ton van</td>
<td>Full-Performance</td>
<td>Bipolar</td>
<td>136</td>
<td>115</td>
<td>103</td>
<td>90</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Hybrid</td>
<td>Bipolar</td>
<td>136</td>
<td>115</td>
<td>103</td>
<td>90</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Peak Power, W/kg (30-second)

<table>
<thead>
<tr>
<th>Class</th>
<th>Battery Designation</th>
<th>Battery Design</th>
<th>State of Charge (80%</th>
<th>50%</th>
<th>30%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Present Prismatic</td>
<td>Prismatic</td>
<td>150</td>
<td>130</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>2</td>
<td>Commuter car</td>
<td>Prismatic</td>
<td>190</td>
<td>170</td>
<td>140</td>
<td>90</td>
</tr>
<tr>
<td>3/4 ton van</td>
<td>Full-Performance</td>
<td>Bipolar</td>
<td>242</td>
<td>187</td>
<td>146</td>
<td>114</td>
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<tr>
<td>4</td>
<td>Hybrid</td>
<td>Bipolar</td>
<td>278</td>
<td>215</td>
<td>168</td>
<td>131</td>
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</tbody>
</table>

*An 15% power increase over the full-performance bipolar battery is assumed due to the use of the all lithium electrolyte.*
III. COST PROJECTIONS

The projected OEM price for Li-Al/FeS batteries for the commuter car, 3/4-ton van, full-performance automobile and the hybrid vehicle is given in Table 4.

The basis for the cost projections is given in Appendix C.

IV. TECHNICAL SUPPORT FOR PROJECTIONS

The principle departures from existing technology used in making the performance and cost projections were:

(1) The use of a bipolar design for the full-performance and hybrid vehicle battery as a more appropriate for the high-power and high-energy outputs that are desired. The feasibility of the bipolar design hinges to a large extent upon the development of an adequate peripheral seal. Bipolar cells have been built and tested at the British Admiralty, ANL, Gould, and Eagle-Picher. The starved-electrolyte concept being developed at Gould lends itself to bipolar designs by immobilizing the electrolyte to a significant degree. Various concepts for seals have been proposed that appear to have the potential for a successful seal. Tests of bipolar stacks at Gould have shown very promising early results.

(2) The production of all lithium-containing compounds from a feedstock of Li$_2$CO$_3$ is proposed as a method of reducing the manufacturing cost of lithium-alloy/iron sulfide batteries. This procedure requires the fabrication of cells in the discharged state, i.e., with Li$_2$S as the electrochemically active material in the positive electrode. Uncharged cells using a mixture of Li$_2$S and iron powder in the positive electrode have been tested with good results at ANL.(1) The performance of the cells were about the same as for
<table>
<thead>
<tr>
<th>Class</th>
<th>Battery Designation</th>
<th>Battery Design</th>
<th>Energy kWh</th>
<th>Power kW</th>
<th>P/E</th>
<th>Materials</th>
<th>OEM Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Present</td>
<td>Prismatic</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>(1) Li-Al/FeS; BN</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(1) LiCl-KCl</td>
<td></td>
<td></td>
<td>(2) Li-Al-Si/FeS; MgO</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LiBr-LiCl-LIF</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Commuter 3/4 ton van</td>
<td>Prismatic</td>
<td>12</td>
<td>24</td>
<td>2</td>
<td>Li-Al/FeS; MgO</td>
<td>99</td>
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<tr>
<td></td>
<td></td>
<td>Prismatic</td>
<td>23</td>
<td>46</td>
<td>2</td>
<td>LiCl-KCl</td>
<td>99</td>
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<tr>
<td>3</td>
<td>Full-Performance</td>
<td>Bipolar</td>
<td>50</td>
<td>50</td>
<td>1</td>
<td>Li-Al/FeS; MgO</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bipolar</td>
<td>50</td>
<td>50</td>
<td>1</td>
<td>LiCl-KCl</td>
<td>99</td>
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<tr>
<td>4</td>
<td>Hybrid</td>
<td>Bipolar</td>
<td>15</td>
<td>50</td>
<td>3.3</td>
<td>Li-Al-Si/FeS; MgO</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LiBr-LiCl-LIF</td>
<td>1725</td>
</tr>
</tbody>
</table>
cells built in the charged state. Precautions need to be taken in uncharged cell fabrication because of the sensitivity of Li$_2$S to the moisture content in the atmosphere. Also, work at ANL showed that charging the cell must commence as soon as the electrolyte is molten to maximize cell lifetime. Considerable work remains in developing the uncharged cell fabrication technology to the present level of charged cell construction. Based upon the experience with uncharged cell fabrication at ANL, the prospects for the successful development of this approach for post 1990 vehicle batteries appears good.

V. ENERGY BALANCE

An energy balance for vehicle operating on the JPL modified FUD cycle was developed based upon the data supplied by JPL and assumptions given below.

Basis:

(1) Battery Weight = 488 kg
(2) Vehicle Test Weight = 1660 kg
(3) Ave Speed for Cycle 3 = 19.6 mph
(4) Time for Cycle 3 = 463/3600 = 0.121 h
(5) Cycle 3 Distance = 19.6 x .121 = 2.37 mile
(6) Distance/Day = 12 x 2.37 = 28.4 mile
(7) Battery Heat Loss at Operating Temp. = 150 W

A diagram showing the energy input/output for each major component that occurs during the performance of cycle 3 is given in Fig. 2.
Fig. 2. Energy Balance for JPL/FUD Cycle.

**Basis**

Cycle Segment - Cycle 3  
Time/cycle 0.121 h (463 sec)  
Distance/cycle 2.37 mile  
Charger Efficiency 85% (DC out/AC in)  
Battery Efficiency 70% (DC out/DC in)  
Battery Weight 488 kg  
Vehicle Test Weight 1660 kg  

![Energy Balance Diagram](image-url)
A summary of energy consumption and selected energy performance coefficients is given in Table 5.

Table 5. Energy Consumption

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Heat Loss/24 h = 150 W x 24 = 3600 Wh</td>
<td>1</td>
</tr>
<tr>
<td>I2R heating/24 h = 262 Wh x 12 cycles = 3144 Wh</td>
<td>2</td>
</tr>
<tr>
<td>Energy Required to Maintain Temperature = 456 Wh</td>
<td>3</td>
</tr>
<tr>
<td>AC energy required = 949 Wh/2.37 mile = 400 Wh/mile</td>
<td>4</td>
</tr>
<tr>
<td>Battery DC Output = 612 Wh/2.37 mile = 258 Wh/mile</td>
<td>5</td>
</tr>
<tr>
<td>Vehicle Efficiency = 258/1.66 tonnes = 155 Wh/tonne mile</td>
<td></td>
</tr>
<tr>
<td>Overall Energy Efficiency = 258/400 = 0.65</td>
<td></td>
</tr>
</tbody>
</table>

The estimates of In-Use Energy Consumption is given in Table 6.

Table 6. Estimates of In-Use Energy Consumption

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Segments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-up and shut-down</td>
<td>None required; battery kept at constant temperature</td>
</tr>
<tr>
<td>Self-Discharge</td>
<td>Negligible; Ah efficiency 98-99+%</td>
</tr>
<tr>
<td>Shunt Current</td>
<td>None</td>
</tr>
<tr>
<td>Parasitics</td>
<td>None</td>
</tr>
<tr>
<td>Thermal Loss</td>
<td>0 24 Wh 0 14 Wh 0</td>
</tr>
<tr>
<td>Charge Eff. (DC Out/DC In)</td>
<td>- - - - 70%</td>
</tr>
</tbody>
</table>
VI. LIFE CONSIDERATIONS

A. Cycle Life

Engineering-sized cells are currently achieving from 500 to >1000 cycles with prospects for achieving 1500 cycles MTTF in the next few years considered very good.

Modules of 5 to 10 cells have been tested with the lifetimes obtained generally following that expected from the life time obtained in single cell tests. (2) One module failed after only a few cycles when defects in one or more cells allowed electrolyte leakage.

The present status and projected cycle life of cells, modules, and batteries is discussed in Appendix D.

As discussed in the Appendix, a battery comprised of cells having a MTTF of 1500 cycles with a failure distribution characterized by a Weibull slope of 5 would achieve 1000 cycles with a replacement of 5 cells.

B. Life Effects

The effect of cycle life on specific energy has already been noted (Table 1, Appendix D). Capacity loss of cells has been progressively reduced from about 8%/100 cycles to present values of about 2%/100 cycles.

The resistance of the cells do not appear to change significantly with cycle life, hence the specific power is expected to be unchanged with battery life.

The coulombic efficiency of new cells range between 98-99+% with only slight decreases in coulombic efficiency occurring until cell failure, at which point the efficiency drops drastically. Failed cells, however, have been shown to contribute to battery power for part of the discharge cycle even when partially shorted.

The effect of cycle life on the thermal characteristics of the cells has not been measured. No potentially adverse effects have come to our attention.
VII. OTHER OPERATIONAL CHARACTERISTICS

A. Special Charge Requirements

The normal charge and discharge reactions in the Li-Al/FeS cell result in the formation of solid products without gaseous side-reactions, which permits the cell to be sealed and eliminates the need for electrolyte replacement. Information on the effects of overcharging and overdischarging Li-Al/FeS cells has been obtained from thermodynamic data, laboratory-scale cell experiments, full-scale cell tests, and post-test examinations of cells. The normal charge cutoff voltage (IR-included) is 1.55V and the reversible (IR-free) voltage is 1.33V. When the charge cutoff voltage is exceeded, the first significant overcharge reaction, which occurs at about 1.8 V (IR-free),

$$\text{Fe} + 2\text{LiCl} + 2\text{Al} \rightarrow \text{FeCl}_2 + 2\text{LiAl}$$

This reaction involves (1) anodic oxidation of the iron current collector in the FeS electrode to form FeCl₂ (complexed as KFeCl₃ or K₂FeCl₄) and (2) the deposition of additional lithium in the Li-Al electrode. Corrosion of the iron current collector by this mechanism can be reduced by the addition of iron powder to the FeS electrode.

The normal IR included discharge cutoff voltage for Li-Al/FeS cells is 1.0 or 0.9V. The principal overdischarge reaction is

$$\text{Al} + 3\text{LiCl} \rightarrow \text{AlCl}_3 + 3\text{Li}$$

This reaction occurs at -1.5V (IR-free). Aluminum in the LiAl electrode undergoes anodic oxidation to form AlCl₃, which is soluble in the electrolyte, and metallic lithium is deposited on the iron sulfide electrode. The cell under these conditions is in a state of reversal. Continuing to overdischarge eventually causes a short circuit due to the deposition of metallic aluminum in the separator or the formation of liquid lithium at the iron sulfide electrode.
The reaction at -1.5V (IR-free) is consistent with the maximum voltage observed (-1.6) during cell reversal tests that were performed at ANL.

Individual cell charge balancing (equalization) is required with Li-Al/FeS cells because small differences in the coulombic efficiency of the cells when cycled will produce a cell-to-cell charge imbalance. The cell to cell variation of coulombic efficiency is small and 10-cell series-connected modules have been operated with "equalization" charging being performed on a once-per-week basis. This observation suggests that van fleets could operate with an inexpensive bulk charger dedicated to each van (for overnight charging) while rotating a charger-equalizer unit among as many as seven or more vans. Concepts for inexpensive charger/equalizers for this battery system are under investigation in the EPRI program.

Periodic complete discharge is not necessary for this system.

B. Maintenance Requirements

Regular maintenance is not required because the battery is sealed and requires no electrolyte replacement. The battery temperature is controlled automatically to the proper operating temperature by the built-in heat exchanger (heating and cooling capability). The bulk charger (used for overnight charging) can also have a separate AC circuit that provides the power to the battery heaters for temperature maintenance for periods of intermediate storage (1-2 weeks). For longer term storage, the battery can be allowed to cool to room temperature and reheated to restore it to service. Periodic equalization (every 1-2 weeks) by a charger-equalizer unit is required. Equalization can be accomplished overnight.

The ANL van battery design(3) developed for the EPRI program packages individual cells into 9-cell module trays. Individual cells can be replaced in a planned maintenance step that provides a cool-down of the
battery to room temperature. An example that was described earlier (see Appendix C - Life Considerations) suggested that replacement of 5 cells in a 100 cell battery would significantly extend the battery life and be cost-effective.

VIII. PACKAGING FLEXIBILITY

A. Volumetric Considerations

The van battery design\(^{(3)}\) which uses SOA Li-Al/FeS cells and is based upon the use of an electric Chrysler T-van provides a reference for volumetric considerations. The van battery is designed to fit the maximum space available under the deck, 75 x 30 x 12 inches. The energy output for this battery is projected at 36 kWh which yields a volumetric energy density of 82 Wh/l. A conservative packaging design was employed because space was available under the deck which did not infringe upon usable space within the vehicle. With refined packaging, values expected for the commuter car or van battery produced in the 1990's would be 100-125 Wh/l. Specific designs have not been attempted for the bipolar battery. A preliminary estimate puts the bipolar batteries in the range of 125-175 Wh/l.

B. Size Limitations

Cells have been built with two to seven electrode plates with the plate sizes ranging from 3 x 5 inches to 12 x 12 inches. The system as developed allows a great deal of flexibility in the size and capacity of the cells. The larger plate designs (i.e., 12 x 12 inches) have current distribution and heat removal requirements somewhat more demanding than the 5x7 inch size currently being developed for EV batteries.
C. Special Considerations

The battery design includes a high-efficiency insulating case, a heat-exchanger, voltage and temperature instrumentation taps packaged as a single unit. A small blower will be mounted adjacent to the battery to circulate the cooling air.

D. Scale Effects

Scaling factors for batteries in the range of interest i.e., 10-50 kWh have not been developed. Based upon the flexibility available in the cell design, i.e., size, thickness, and number of plates, efficient cell designs can be developed for batteries that span the 10-50 kWh range.

The battery shape, which is determined by the application, influences the surface/volume ratio of the battery and has an important effect upon volumetric energy density because of the need for an insulating case. The impact of shape upon the gravimetric energy density is less important. For the prismatic battery designs that have been studied thus far discount factors of 0.5 to 0.6 have been obtained that convert cell volumetric energy density to battery volumetric energy density. The discount factors developed by design studies for the gravimetric energy density have ranged from 0.75-0.8. Preliminary cell design studies have been completed for bipolar cells. Scaling factors and discount factors for bipolar cells packaged as a battery unit have not as yet been developed.
ACKNOWLEDGEMENT

This report was prepared in support of the Jet Propulsion Laboratory Electric and Hybrid Vehicle Project, Contract NASA NIPR No. WO-8756.

REFERENCES


APPENDIX A - PRISMATIC BATTERY PERFORMANCE PROJECTIONS

I. Specific Energy Projections

The specific energy as a function of constant power discharge was obtained from an estimate based upon a high-power cell built and tested by T. Kaun.

The values projected by T. Kaun(1) are given in Table A-1.

Table A-1 Specific Energy with Constant Power Discharge

<table>
<thead>
<tr>
<th>Discharge Rate (W/kg)</th>
<th>Specific Energy (Wh/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>111</td>
</tr>
<tr>
<td>11</td>
<td>107</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>47</td>
<td>93</td>
</tr>
<tr>
<td>82</td>
<td>82</td>
</tr>
<tr>
<td>126</td>
<td>63</td>
</tr>
</tbody>
</table>

The state-of-the-art and projected specific energy for cells having P/E ratio = 2 was obtained from modeling studies.(2) These values are given in Table A-2.

(1) T. Kaun, Private communication, Argonne National Laboratory, March 1981.
(2) E. Gay, Private communication, Argonne National Laboratory, Jan. 1984.
Table A-2 Specific Energy, Wh/kg

<table>
<thead>
<tr>
<th>Technology State</th>
<th>Cells</th>
<th>Batteries*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOA</td>
<td>87</td>
<td>65 @ 16 W/kg</td>
</tr>
<tr>
<td>Projected (1990)</td>
<td>115</td>
<td>86 @ 21 W/kg</td>
</tr>
</tbody>
</table>

*Derating factor of 0.75 (from cells to batteries).

These values are plotted on Fig. A-1 which provides the basis for the SOA and projected values for the specific energy of Li-Al/FeS batteries as a function of constant power discharge rates.

11. Peak Power Projections

The peak power estimates are based upon a shape factor obtained from the estimates based upon an experimental high-power cell and modeling studies for cells with a P/E ratio of 2.

These values are plotted in Fig. A-2.
Fig. A-1. Specific Energy of Prismatic Li-Al/FeS Batteries.
Fig. A-2. Peak Power of Prismatic Li-Al/FeS Batteries.
APPENDIX B - BIPOLAR BATTERY PERFORMANCE PROJECTIONS

A study was made to characterize the projected performance of the bipolar type Li-Al/FeS batteries. The study was focused on the following:

1) Specific energy of a battery when discharged at a constant specific power.

2) 30-second specific power capability of the battery as a function of the state-of-charge (SOC) as defined for the standard C/3 rate.

I. Description of Bipolar Type Li-Al/FeS Cell Batteries

The cell considered in the study employs Li-Al/LiCl-KCl/FeS operating at about 460°C with open circuit voltage of 1.35 V at the fully charged state. The bipolar cell discussed in this study comprises stacked layers of circular electrodes, 0.2 cm thick ceramic (MgO powder) separators, a ceramic (MgO) ring insulator, and a 0.018 cm thick stainless steel can. The bipolar plates are made of 0.018 cm thick stainless steel. As we will discuss later, an electrode diameter of 17.78 cm (thick) with a three bipolar plates was found to satisfy the requirements.

II. Methodology

For the analysis, a conceptual cell design was developed by first selecting mechanical dimensions and a theoretical capacity and applying key design parameters including loading densities and the negative/positive ratio. The cell design was then used to calculate 1) specific energies at different rates of discharge, and 2) 30-second peak specific powers at different states of charges as defined. Flow charts of the computer programs used to carry out the analysis are shown in Fig. B1 and B2.
Fig. B-1. Computer Flow Chart for Specific Energy.
Fig. B-2. Computer Flow Chart for Peak Power.
In calculating the specific energies, the utilization of the active material in the cell at the desired discharge rate must be determined. For this, the following formula which is derived from experimental data on an advanced prismatic cell was used.\(^{(1)}\)

\[
U(\text{current}) = 1 - 1.67 \cdot i
\]

where \(i\) is in A/cm\(^2\).

The utilization is also known to be affected by the electrode thickness although its effect diminishes as the thickness decreases particularly below 0.15 cm. The effect is analytically expressed by the following formula based on an experimental correlation.\(^{(2)}\)

\[
U(\text{thickness}) = 1.15 - t_c
\]

where \(t_c\) is the positive electrode thickness in cm. Two values of the above utilizations were then compared and the smaller value was taken to determine the discharge capacity of the cell at the selected rate. For determining the average cell voltage, the following equation was used.

\[
V_{av} = 1.35 - R \cdot i
\]

where \(V_{av}\) is in volt, \(R\) is cell resistance in ohm·cm\(^2\), and \(i\) is current density in A/cm\(^2\). The cell resistances were taken as 0.8 for advanced and 1.2 for the SOA cells. These values are similar to those found for the prismatic cells. The energy and power outputs of the cell can be calculated by multiplying the average voltage by the cell capacity and current, respectively.

For the calculation of the peak power, one needs to know the peak-power flux, W/cm\(^2\). Data for 30-sec peak power are available for SOA and

an advanced prismatic cell\(^{(4)}\) as a function of the SOC. The values are listed below:

<table>
<thead>
<tr>
<th></th>
<th>80% SOC</th>
<th>50% SOC</th>
<th>30% SOC</th>
<th>10% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced, W/cm²</td>
<td>0.57</td>
<td>0.41</td>
<td>0.32</td>
<td>0.25</td>
</tr>
<tr>
<td>SOA, W/cm²</td>
<td>0.40</td>
<td>0.25</td>
<td>0.17</td>
<td>0.10</td>
</tr>
</tbody>
</table>

These values are observed for the prismatic cells, and even higher values are expected for a bipolar type cell because of its intrinsically low cell resistance. The cell values obtained were multiplied by 0.75 to allow for the weight of the battery case and other battery components.

III. Summary of Results

A series of computations were made for both the advanced and SOA designs with the electrode diameter varying from 3 in. (7.62 cm) to 7 in. (17.78 cm), the cell capacity varying from 100 to 300 Ah, and the number of bipolar plates varying from 1 to 3. For both the advanced and SOA design, the cells having 7 inch electrodes, 3 bipolar plates and theoretical capacity of 180 Ah were selected because they provided the best P/E match to the requirements. The results are summarized below and also presented in Fig. B3 and B4.

1. Specific energy of a battery when discharged at a constant specific power

<table>
<thead>
<tr>
<th></th>
<th>20 W/kg</th>
<th>60 W/kg</th>
<th>80 W/kg</th>
<th>100 W/kg</th>
<th>200 W/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced, Wh/kg</td>
<td>136</td>
<td>115</td>
<td>103</td>
<td>90</td>
<td>30</td>
</tr>
<tr>
<td>SOA, Wh/kg</td>
<td>121</td>
<td>97</td>
<td>83</td>
<td>69</td>
<td>-</td>
</tr>
</tbody>
</table>

2. 30-second specific power capability as a function of the SOC.

<table>
<thead>
<tr>
<th></th>
<th>80% SOC</th>
<th>50% SOC</th>
<th>30% SOC</th>
<th>10% SOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced, W/kg</td>
<td>242</td>
<td>187</td>
<td>146</td>
<td>114</td>
</tr>
<tr>
<td>SOA, W/kg</td>
<td>167</td>
<td>104</td>
<td>71</td>
<td>42</td>
</tr>
</tbody>
</table>

\(^{(4)}\) Redey, L., Private communication (1982).
Fig. B-3. Specific Energy as a Function of Constant Power Discharge.

**CELL DIMENSIONS:**
- CELL CAPACITY: 180 Ah
- ELECTRODE DIA: 17.76 cm
- BIPOLAR PLATES: 3
Fig. B-4. Specific Power (30-sec) as a Function of State of Charge.
The cell design parameters and cell dimensions used in the analysis are summarized in Tables B1 and B2.

Table B1. Cell Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Advanced</th>
<th>SOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cell Electrode Dia</td>
<td>17.78 cm</td>
<td></td>
</tr>
<tr>
<td>Electrode Area</td>
<td>744.5 cm²</td>
<td></td>
</tr>
<tr>
<td>No. of Bipolar Layers</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Theoretical Capacity</td>
<td>180 Ah</td>
<td></td>
</tr>
<tr>
<td>Neg Loading Density, Ah/cm³</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Pos Loading Density, Ah/cm³</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>Neg/Pos Ratio</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Cell Resistance, ohm cm²</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Cell Thickness, cm</td>
<td>1.94</td>
<td>2.21</td>
</tr>
<tr>
<td>Cell Weight, kg</td>
<td>1.23</td>
<td>1.34</td>
</tr>
</tbody>
</table>

Table B2. Cell Dimensions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Advanced</th>
<th>SOA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Dia, cm</td>
<td>17.78</td>
<td>17.78</td>
</tr>
<tr>
<td>No. of Bipolar Layers</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Electrode Area, cm²</td>
<td>744.5</td>
<td>744.5</td>
</tr>
<tr>
<td>Electrode Thickness Positive, cm</td>
<td>0.151</td>
<td>0.173</td>
</tr>
<tr>
<td>Negative, cm</td>
<td>0.266</td>
<td>0.332</td>
</tr>
<tr>
<td>Separator, cm</td>
<td>0.200</td>
<td>0.200</td>
</tr>
<tr>
<td>Can, cm</td>
<td>0.018</td>
<td>0.018</td>
</tr>
<tr>
<td>Total Thickness, cm</td>
<td>1.941</td>
<td>2.21</td>
</tr>
<tr>
<td>Total cell volume, cm³</td>
<td>733</td>
<td>833</td>
</tr>
<tr>
<td>Total cell weight, kg</td>
<td>1.228</td>
<td>1.344</td>
</tr>
</tbody>
</table>
APPENDIX C - BATTERY MANUFACTURING COST PROJECTIONS

I. INTRODUCTION

The potential for low-cost battery manufacture is explored here by (1) the use of the Gould cell technology (powder MgO separators) (2) manufacture of all the required lithium containing compounds from a $\text{Li}_2\text{CO}_3$ feedstock (3) use of low-carbon steel* for the cell container, electrode structure, and particle retainers (mechanically perforated sheet), and (4) manufacture of the cell in a discharged state, i.e., use of $\text{Li}_2\text{S}$ as the source of electro-chemically active lithium.

The cost impact of the LiBr-LiCl-LiF electrolyte versus the LiCl-KCl electrolyte is examined by choosing the Li-Br containing salt for a high-power battery and the LiCl-KCl electrolyte for a high-energy battery.

II. MATERIALS COST

The market price of materials of interest for this analysis is given in Table C1.

Starting with a feedstock of $\text{Li}_2\text{CO}_3$, $\text{H}_2\text{S}$, HF, HCl, $\text{H}_2\text{SO}_4$, and NaBr, the feedstock costs to make a pound of $\text{Li}_2\text{S}$, LiBr, LiCl, and LiF (as required for the high-power cell) is listed and compared with market prices in Table C2.

*LiAl was chosen as the negative active material to permit the use of low-carbon steel for the negative electrode housing.
### Table C1. Market Price of Materials* (1983)

<table>
<thead>
<tr>
<th>Material</th>
<th>Market Price, $/lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium metal</td>
<td>31.00</td>
</tr>
<tr>
<td>Li₂CO₃</td>
<td>1.48</td>
</tr>
<tr>
<td>LiCl</td>
<td>3.00</td>
</tr>
<tr>
<td>LiF</td>
<td>4.72</td>
</tr>
<tr>
<td>KCl</td>
<td>0.105</td>
</tr>
<tr>
<td>HCl</td>
<td>0.27</td>
</tr>
<tr>
<td>HF</td>
<td>0.68</td>
</tr>
<tr>
<td>H₂S</td>
<td>0.11</td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>0.04</td>
</tr>
<tr>
<td>NaBr</td>
<td>1.04</td>
</tr>
<tr>
<td>MgO</td>
<td>0.50</td>
</tr>
<tr>
<td>Al</td>
<td>0.60</td>
</tr>
<tr>
<td>Iron powder</td>
<td>1.00</td>
</tr>
<tr>
<td>Low Carbon Steel</td>
<td>0.33</td>
</tr>
<tr>
<td>KCl</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*Chemical Marketing Reporter, Nov. 11, 1983.

### Table C2. Feedstock/Market Price Comparison

<table>
<thead>
<tr>
<th>Compound</th>
<th>Feedstock Cost, $/lb of Compound</th>
<th>Market Price* of Compound, $/lb</th>
<th>Feedstock Cost as % of Market Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li Metal</td>
<td>9.29</td>
<td>31.00</td>
<td>30</td>
</tr>
<tr>
<td>Li₂S</td>
<td>2.48</td>
<td>**</td>
<td>-</td>
</tr>
<tr>
<td>LiBr</td>
<td>1.88</td>
<td>6.50</td>
<td>29</td>
</tr>
<tr>
<td>LiCl</td>
<td>1.52</td>
<td>3.00</td>
<td>51</td>
</tr>
<tr>
<td>LiF</td>
<td>2.63</td>
<td>4.72</td>
<td>56</td>
</tr>
</tbody>
</table>

*Chemical Marketing Reporter, Nov. 11, 1983.

**Not made in commercial quantities.

†Includes Li₂CO₃ plus all reactants to convert Li₂CO₃ to the compound listed.
III. COST OF CONVERTING LiCO_3 TO THE DESIRED COMPOUNDS

The feedstock cost for the conversion of Li_2CO_3 to the desired compounds Li_2S, LiBr, LiCl, and LiF is given in Table C3.

Table C3. Feedstock Cost for a High-Power Battery

Basis
1. 5 lb of electrolyte per kWh
2. Electrolyte composition, wt.%
   LiBr, 68; LiCl, 22; LiF, 10.
3. 0.67 lb elemental Li req'd per kWh in 2.2 lb Li_2S

<table>
<thead>
<tr>
<th>Compound</th>
<th>Cpd Wt 1b/kWh</th>
<th>Feedstock Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$/lb Cpd</td>
</tr>
<tr>
<td>Li_2S</td>
<td>2.2</td>
<td>2.48</td>
</tr>
<tr>
<td>LiBr</td>
<td>3.4</td>
<td>1.88</td>
</tr>
<tr>
<td>LiCl</td>
<td>1.1</td>
<td>1.52</td>
</tr>
<tr>
<td>LiF</td>
<td>0.5</td>
<td>2.63</td>
</tr>
<tr>
<td>Totals</td>
<td>7.2</td>
<td></td>
</tr>
</tbody>
</table>

The conversion cost of the feedstock was estimated using the following assumptions.

1. The equipment cost, depreciation base, total investment, rent and labor costs are 1/2 of that estimated for the battery plant in ANL-79-59 p. 15 (ADL Method, Table 11). The values for the chemical conversion part of the plant are:

   Equipment Cost, $x10^6 2.33, $2.03/kWh (1979 $)
   Depreciation Base, $x10^6 4.68, $4.07/kWh
   Total Investment, $x10^6 8.68, $7.55/kWh
   Total Labor, $/kwh 2.13
2. Inflation rate = 1.099 \times 1.096 \times 1.062 = 1.28.

3. Battery size = 24 kWh

4. Plant size $1.15 \times 10^6$ kWh/year

The conversion cost of $\text{Li}_2\text{CO}_3$ to the desired lithium compounds is shown in Table C4.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Item</th>
<th>$/Battery</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Materials Cost</td>
<td>356</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Materials OH</td>
<td>35</td>
<td>10% of materials cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>391</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Direct Labor</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Labor OH</td>
<td>182</td>
<td>280% of direct labor</td>
</tr>
<tr>
<td></td>
<td></td>
<td>247</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Equipment Depreciation</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rent</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>4</td>
<td>Factory Cost</td>
<td>655</td>
<td>Item 1 + 2 + 3</td>
</tr>
<tr>
<td>5</td>
<td>ROI + Taxes</td>
<td>70</td>
<td>30% of total investment</td>
</tr>
<tr>
<td>6</td>
<td>Production Cost, $/battery</td>
<td>725</td>
<td></td>
</tr>
<tr>
<td></td>
<td>, $/kWh</td>
<td>30.21</td>
<td></td>
</tr>
</tbody>
</table>

The cost of the non-lithium-containing materials is given in Table C5.
### Table C5. Non-Lithium-Containing Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Wt/kWh</th>
<th>$/lb</th>
<th>$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.5</td>
<td>0.60</td>
<td>1.50</td>
</tr>
<tr>
<td>Iron Powder</td>
<td>3.5</td>
<td>1.00</td>
<td>3.50</td>
</tr>
<tr>
<td>MgO</td>
<td>1.9</td>
<td>0.50</td>
<td>.95</td>
</tr>
<tr>
<td>L.C. Steel</td>
<td>7.0</td>
<td>0.33</td>
<td>2.31</td>
</tr>
<tr>
<td>Feedthru Parts</td>
<td>-</td>
<td>-</td>
<td>4.80</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>14.9</strong></td>
<td>-</td>
<td><strong>13.06</strong></td>
</tr>
</tbody>
</table>

The feedstock cost for producing Li\textsubscript{2}S and LiCl for the high-energy battery is given in Table C6.

### Table C6. Feedstock Cost for Producing Li\textsubscript{2}S and LiCl for the High-Energy Battery

<table>
<thead>
<tr>
<th>Compound</th>
<th>Cpd Wt/kWh, lb</th>
<th>Feedstock Cost $/lb cpd</th>
<th>$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li\textsubscript{2}S</td>
<td>2.2</td>
<td>2.48</td>
<td>5.45</td>
</tr>
<tr>
<td>LiCl*</td>
<td>2.2</td>
<td>1.52</td>
<td>3.34</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>4.4</strong></td>
<td>-</td>
<td><strong>7.79</strong></td>
</tr>
</tbody>
</table>

*5 lbs of electrolyte with 44 wt.% LiCl-56 wt.% KCl
The production cost of Li$_2$S and LiCl from the feedstock is given in Table C7.

Table C7. Production Cost of Li$_2$S and LiCl From Feedstock

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost Item</th>
<th>$/Battery</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Materials Cost</td>
<td>187</td>
<td>10% of materials costs</td>
</tr>
<tr>
<td></td>
<td>Materials Overhead</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>206</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Direct Labor</td>
<td>33</td>
<td>280% of direct labor</td>
</tr>
<tr>
<td></td>
<td>Labor Overhead</td>
<td>92</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Equipment Depreciation</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rent</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Factory Cost</td>
<td>340</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>ROI + Taxes</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Production Cost</td>
<td>375</td>
<td>($15.60 kWh)</td>
</tr>
</tbody>
</table>

IV. OEM SELLING PRICE

A summary of the costs leading to the estimation of the OEM selling price is given in Table C8. A comparison is made between a high-power battery that employs LiBr-LiCl-LiF electrolyte with a high-energy battery using LiCl-KCl electrolyte.
### Table C8. OEM Selling Price for Lithium-Metal Sulfide Batteries

*(Battery Size - 24 kWh)*

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>High-Power</th>
<th>High-Energy</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium Bearing Compounds</td>
<td>725</td>
<td>375</td>
<td>Table C4 (High-P); Table C7 (High-E)</td>
</tr>
<tr>
<td>Other Materials</td>
<td>313</td>
<td>320</td>
<td>Table 5; Table C5 + $7 for KCl</td>
</tr>
<tr>
<td>Insulating Enclosure</td>
<td>650</td>
<td>650</td>
<td>Consiglio/Symons estimate</td>
</tr>
<tr>
<td><strong>Material Overhead</strong></td>
<td>1,688</td>
<td>1,345</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,857</td>
<td>1,480</td>
<td></td>
</tr>
<tr>
<td>Direct Labor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell</td>
<td>131</td>
<td>131</td>
<td>AML-79-59 x inflation</td>
</tr>
<tr>
<td>Cell/Battery</td>
<td>33</td>
<td>33</td>
<td>25% of cell labor</td>
</tr>
<tr>
<td><strong>Direct Labor Overhead</strong></td>
<td>164</td>
<td>164</td>
<td>(Consiglio/Symons)</td>
</tr>
<tr>
<td></td>
<td>459</td>
<td>459</td>
<td>280% of direct labor</td>
</tr>
<tr>
<td></td>
<td>623</td>
<td>623</td>
<td></td>
</tr>
<tr>
<td>Equipment Depreciation</td>
<td>25</td>
<td>25</td>
<td>ANL-79-59 x inflation</td>
</tr>
<tr>
<td>Rent</td>
<td>8</td>
<td>8</td>
<td>ANL-79-59 x inflation</td>
</tr>
<tr>
<td><strong>Factory Cost</strong></td>
<td>2,513</td>
<td>2,136</td>
<td></td>
</tr>
<tr>
<td>Capital Investment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working Capital</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Investment</td>
<td>464</td>
<td>464</td>
<td>AML-79-59 x inflation</td>
</tr>
<tr>
<td><strong>ROI + Taxes</strong></td>
<td>139</td>
<td>139</td>
<td>30% of total investment</td>
</tr>
<tr>
<td>Warranty</td>
<td>100</td>
<td>100</td>
<td>Consiglio/Symons study</td>
</tr>
<tr>
<td><strong>OEM Selling Price</strong></td>
<td>2,752</td>
<td>2,375</td>
<td></td>
</tr>
<tr>
<td>($115/kWh)</td>
<td>($99/kWh)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
V SUMMARY

1. The main objective of this study was to show that by the use of \( \text{Li}_2\text{CO}_3 \) as a feedstock for the production of all the required lithium-containing compounds, it may be possible to reduce the battery OEM price to about $100/kWh.

2. The ADL costing methodology was followed except where modified by the Consiglio/Symons study. The capital values for equipment, depreciation, and total investment as well as rent were taken from the ANL-79-59 study on cost.

3. Based upon this approach, a trade-off analysis for a high-power system (using the \( \text{LiBr} \) containing electrolyte) shows a 15% higher cost compared to the system using \( \text{LiCl-KCl} \) electrolyte ($115/kWh compared to $99/kWh).

4. It seems likely that the power and energy requirements for the commuter car and van can be met using prismatic cell designs optimized for power using \( \text{LiCl-KCl} \) electrolyte, a Li-Al electrode (to permit use of low-carbon steel for the negative electrode structure) and low-carbon steel for the cell can. By addition of iron powder (a 30% stoichiometric excess) to the positive electrode mix, it would be possible to use low-carbon steel for the positive electrode structure. Mechanically perforated steel sheet in series with the MgO powder separator can probably be used successfully as a particle retainer.

   As indicated in Table C8, the OEM cost for such a battery would be $99/kWh.

5. A cost analysis for the bipolar battery was not attempted. For purposes of this study, no distinction between prismatic or bipolar battery manufacturing cost was made.
APPENDIX D - LIFE CONSIDERATIONS

A. Cells

A summary of the cycle-life tests for the Gould and Eagle-Picher status cells is presented in Table D1. For the purposes of cycle-life testing, a deep cycle was defined as 80% or greater of the theoretical cell capacity, and end of cell life was defined as either a 20% loss of the initial capacity or a drop in the coulombic efficiency to 95%. Groups of at least 12 cells of identical design were cycle-life tested to provide statistical data on the time to failure. The highest mean time to failure (MTTF) was 410 cycles for the Eagle-Picher Group I cells and 330 cycles for the second group of Gould powder separator cells. The Weibull Slope, which defines the distribution of failures, ranged from 1.4 to 3.2. The average capacity loss rate ranged from 2.5 to 8% per 100 cycles.

Significant lifetime improvement was demonstrated by a group of five cells built by Eagle-Picher in a program for the U.S. Army (MERADCOM). The cycle life of the five cells is plotted against the voltage at cut-off at 80% depth of discharge (see Fig. D1). The testing of this group continues with two of the cells having exceeded 1000 cycles. The average capacity loss rate for a cell in this group has been measured at 2%/100 cycles.

Life limiting mechanisms for the cells have been studied extensively by the post-test examination of hundreds of cells. The cells fail by shorting caused by the extrusion of active material from the negative or positive electrode due to ruptures in the electrode containment structures or by shorting caused by the formation of Li-Al protrusions that penetrate the BN separator.*

*This failure mechanism has been experienced only in the Eagle-Picher cells.
Table D1. Summary of Li/FeS Cell Performance Tests at ANL

<table>
<thead>
<tr>
<th></th>
<th>Gould Status Cells</th>
<th>Eagle-Picher Status Cells</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I</td>
<td>II</td>
</tr>
<tr>
<td>No. of Cells in Group</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Theo. Capacity, Ah</td>
<td>194</td>
<td>194</td>
</tr>
<tr>
<td>Av. Operating Temperature, °C</td>
<td>465</td>
<td>a</td>
</tr>
<tr>
<td>Av. Peak Capacity, Ah</td>
<td>158</td>
<td>157</td>
</tr>
<tr>
<td>Std. Deviation in Peak</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacity, ± %</td>
<td>4.5</td>
<td>3.2</td>
</tr>
<tr>
<td>Av. Specific Energy, Wh/kg</td>
<td>74</td>
<td>80</td>
</tr>
<tr>
<td>Peak Specific Power, W/kg</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

Cycle Life\(^b\)

|                          |                    |                           |         |           |          |          |
| High/Low, Cycles         | 307/14             | 467/121                   | 542/158*| 1031/238  | 908/23   | 201/100  |
| Mean Time-to-Failure,    |                    |                           |         |           |          |          |
| Cycles                   | 218/26\(^c\)       | 268                       | 330     | 410       | 362      | 138      |
| Weibull Slope            | 2.0/3.4            | 3.1                       | 2.9     | 2.9       | 1.4      | 2.1      |

Av. Capacity Loss Rate, Z per cycle

|                          | 0.08               | 0.06                      | 0.032   | 0.027     | 0.045    | 0.024    |

\(^a\)Temperature was 455°C until 20% capacity loss, then raised in 5°C increments to 455-475°C.

\(^b\)End of life defined as 20% capacity loss or coulombic efficiency decrease to <95%.

\(^c\)Correlated as five- and seven-cell groups. Single group correlation not possible.

* Gould Status Cells, Group II, showing the improved performance obtained by raising the temperature to 475°C.
**FIG. D-1**

**CYCLE LIFE OF MERADCOM CELLS**

Legend
- △ CELL 211
- × CELL 206
- ○ CELL 209
- × CELL 210
- × CELL 207

![Graph showing cycle life of Meradcom cells](image-url)
The Gould cells which employ a MgO powder separator fail by the gradual degradation of the separator which allows the electrodes to contact or by the gradual buildup of iron particles in the separator that eventually bridge and cause a short.

An analysis relating the MTTF and the failure distribution of cells on the expected battery life is given in Section C.

B. Modules

The cycle life achieved by Li-Al/FeS modules tested under deep discharge conditions at ANL and Eagle-Picher, Industries is given in Table D2. In general, the cycle life obtained was that expected based upon cell life results obtained from tests of individual cells. The exception occurred in the test of the 30 cell module which failed early in life due to electrolyte leakage from hairline cracks which developed in several of the cells. The cell cans are at negative potential and fail rapidly when the electrolyte bridges cells in a closely packed cell array. This condition causes an electrolysis reaction resulting the transfer of iron accompanied by rapid discharge of the cells.

Module testing at ANL is continuing in the Electric Power Research Institute (EPRI) program. A 9-cell array of Gould cells will be tested in a fully-engineered system that includes heating and cooling units in a high-efficiency thermal insulated case.

C. Batteries

Test work at ANL has shown that a series-connected module can continue to operate for many cycles with a small percentage of failed cells. (1) Tests were also performed on individual cells with a procedure that simulated

(1) ANL Report, ANL-81-65 pp. 42-46 (February 1982).
### Table D2. Module Tests

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of Cells</th>
<th>Battery Voltage V</th>
<th>Battery Capacity kWh</th>
<th>Thermal Insulation</th>
<th>Cycle Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>1977</td>
<td>6</td>
<td>8.8</td>
<td>1.0</td>
<td>Vac-Foil</td>
<td>11</td>
</tr>
<tr>
<td>1979</td>
<td>10</td>
<td>5.9</td>
<td>3.7</td>
<td>Conventional</td>
<td>34</td>
</tr>
<tr>
<td>1979</td>
<td>5</td>
<td>5.6</td>
<td>1.6</td>
<td>Vac-Foil</td>
<td>70</td>
</tr>
<tr>
<td>1980</td>
<td>9</td>
<td>10.6</td>
<td>3.0</td>
<td>Conventional</td>
<td>72</td>
</tr>
<tr>
<td>1981</td>
<td>10</td>
<td>12</td>
<td>2.5</td>
<td>Vac-Foil</td>
<td>71</td>
</tr>
<tr>
<td>1981</td>
<td>10</td>
<td>12</td>
<td>2.5</td>
<td>Vac-Foil</td>
<td>79</td>
</tr>
<tr>
<td>1981</td>
<td>10</td>
<td>11.6</td>
<td>3.8</td>
<td>Conventional</td>
<td>270</td>
</tr>
<tr>
<td>1981</td>
<td>10</td>
<td>11.8</td>
<td>4.0</td>
<td>Conventional</td>
<td>150</td>
</tr>
<tr>
<td>1983</td>
<td>30</td>
<td>36</td>
<td>12</td>
<td>Conventional</td>
<td>12*</td>
</tr>
</tbody>
</table>

*Module failed early in life due to electrolyte leakage from several defective cells (see text).
the behavior of a failed cell in a series-connected string. Cells that had developed a short as a result of lifecycle testing were tested using a timed cycle in which 284 Ah were passed through the cell both on charge and discharge with the voltage and heating rates monitored. The voltage history of such a cell is given in Fig. D2. The main points to be noted are that the shorted cell provides useful voltage for a number of cycles (30-40 cycles) as shown by the curve labeled 2 until it deteriorates to the condition shown by curve 3 where the cell exhibits its peak negative voltage of -1.6 V and its maximum heat generation of 90-100 W on discharge. The duration of this peak negative voltage state was 15-30 cycles when it then tended to a terminal state shown by curve 4. Voltage conditions for the terminal state are -0.4 V on discharge and +0.4 V on charge with heat evolution of 35-40 W on discharge and 15-20 W on charge.

The main conclusion that has been drawn from these tests is that it may be possible to operate a series-connected battery containing a small number of failed cells if provision is made to handle the extra heat generated by the failed cells. This conclusion provides the rationale for considering maintenance schemes that allow the battery to operate until the number of failed cells in the battery drops the capacity below an acceptable level at which time the battery is shut down and the failed cells are replaced.

A battery life analysis for Li-Al/FeS cells with a projected MTTF of 1500 and a Weibull slope of 5 was developed. The assumptions made were (1) initial capacity of 20 kWh delivered by a 100 cell battery (2) 2%/100 cycle capacity loss rate (3) average voltage loss per failed cell of 2.4 V and (4) 80 miles/discharge.

Fig. D2. Typical Voltage of a Short-Circuited Cell on Continued Cycling.
The distribution of failures with cycle-life is given in Fig. D3. Using this data, the battery output as a function of cycles was derived and is shown plotted on Fig. D4. The results show that a battery life of 1000 cycles is possible with the replacement of 5 cells.

Whether it is economical to repair the battery after the first few cells fail will depend upon the cost of repair and the lifetime extension obtained compared to the cost of purchasing a new battery. An example developed in Table D3 suggests that maintenance for an additional 16,000 miles (200 cycles) obtained by replacing 5 cells would be cheaper; that is, amortizing battery first cost over 64,000 miles (800 cycles) results in a cost of 4.7¢/mile while the $600 spent for maintenance provides an additional 16,000 miles and results in a cost of 3.75¢/mile.

To summarize:

1. State-of-the-art cells at the engineering level have shown the potential for achieving >1000 cycles MTTF.

2. Statistical distribution for cells as determined by Weibull analysis show distributions characterized by slopes of 2-3. The potential for improvement to distributions characterized by a Weibull slope of 5 appears good.

3. Typical module tests resulted in obtaining module lifetimes that could be projected from consideration of single cell lifetime data. One module test was abruptly terminated due to electrolyte leakage from cells.

4. Experimental work at ANL with cells and modules has demonstrated the operation of a module with several failed* cells. Individual cells were tested in a mode simulating the operation of a failed cell in a series-connected

*Failure defined by the single cell test criteria of (1) less than 80% of initial capacity or (2) less than 95% coulombic efficiency.
FIG. D-3

FAILURE RATE FOR CELLS WITH MTTF OF 1500 CYCLES

Legend

Δ WEIBULL SLOPE 1
X WEIBULL SLOPE 2
□ WEIBULL SLOPE 5
Fig. D-4. Effect of Cell Replacement on Battery Life.

Drops From 20 kWh to 18 kWh in 500 Cycles

Minimum Acceptable Capacity (80% of initial 20 kWh)
### Table D3. Battery Maintenance Cost for an Electric Automobile

<table>
<thead>
<tr>
<th>Cycle No.</th>
<th>Cumulative Miles</th>
<th>Maintenance Work</th>
<th>Costa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-800</td>
<td>64,000</td>
<td>none</td>
<td>$3,000 (Battery purchase)</td>
</tr>
<tr>
<td>800-870</td>
<td>69,600</td>
<td>2 cells replaced</td>
<td>210</td>
</tr>
<tr>
<td>870-910</td>
<td>72,800</td>
<td>1 cell replaced</td>
<td>130</td>
</tr>
<tr>
<td>910-975</td>
<td>78,000</td>
<td>1 cell replaced</td>
<td>130</td>
</tr>
<tr>
<td>970-1000</td>
<td>80,000</td>
<td>1 cell replaced</td>
<td>13C</td>
</tr>
</tbody>
</table>

aBattery cost to consumer taken as $150/kWh. Cell cost at $30/cell and labor at $50/hr.
string. These tests showed that the voltage behavior of a failed cell passed through a voltage maximum of -1.6 V during discharge and then stabilized at -0.4 V. The conclusion drawn from the single-cell work was that the operation of a module with a small percentage of failed cells might be feasible if provisions for the excess heat removal from failed cells were made in the design of the thermal management system.

5. An analysis of battery life that was based upon a hypothetical cell population that had a MTTF of 1500 cycles, a Weibull slope of 5, and a capacity loss rate of 2%/100 cycles was made. The analysis suggests that a battery lifetime of 1000 cycles is achievable with a replacement of 5 cells.
APPENDIX G

PERFORMANCE AND COST PROJECTIONS
FOR LITHIUM-IRON SULFIDE BATTERIES
Prepared for
Jet Propulsion Laboratories
4800 Oak Grove Drive
Pasadena, CA 91109

Contract No.: 956761
Subject: Performance and Cost Projections for Lithium-Iron Sulfide Batteries

Prepared by
Gould Research Center
Materials and Devices Laboratory
Gould Defense Systems Inc.
Rolling Meadows, Illinois 60008

Date: March 1984
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</thead>
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<tr>
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<td>2</td>
</tr>
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I. INTRODUCTION

This report has been prepared under JPL Contract No. 956761 in support of the Jet Propulsion Laboratory Electric and Hybrid Vehicle Project.

Research and development on lithium alloy-metal sulfide, molten salt electrolyte rechargeable batteries has been ongoing at Gould since the mid-1970s until the present time. This effort was initially supported by DOE contracts via the National Laboratories (ANL, SNL, LBL) and more recently by contracts from the Air Force and EPRI in addition to funds from Gould.

The lithium-sulfur system is generic in nature, in that there are a number of choices possible for both the negative and positive electrode active materials. The most energetic electrochemical couple would be that of elemental lithium and elemental sulfur. However, since both these electrodes would be molten at the battery operating temperature, it is extremely difficult to engineer a practical cell design. Consequently the technology has evolved by sacrificing some of the specific energy offered by the elemental lithium and sulfur electrodes and employing lithium-alloy negative electrodes and metal-sulfide positive electrodes. These latter type electrodes permit practical engineering cells to be built since the electrodes are solid at the cell operating temperatures of 350-475°C; the melting point of the salt electrolyte dictates the operating temperature range. The lithium alloys which have received greatest attention are lithium-aluminum (e.g. 20 w/o Li:80 w/o Al) and lithium-silicon (e.g. 43 w/o Li:57 w/o Si); each of which offers particular advantages in terms of properties and cell performance. Most of the early engineering cell development was performed with Li-Al negative electrodes, however, more recently the Gould development effort has chosen to use a physical mixture of the two binary alloys Li-Al and Li-Si in order to take advantage of the characteristics of each alloy.

Similarly, there are a number of possible alternatives that can be considered for the positive electrode from the metal chalcogenides. In particular, the sulfides of iron have received the greatest attention since they are plentiful and hence relatively inexpensive. Although iron disulfide is more energetic
than the monosulfide it has not been considered in this study since its use necessitates the employment of relatively exotic and therefore expensive materials (e.g., molybdenum) for the positive electrode current collection system. The cost of such a current collection system is prohibitive to be considered in the near term for the electric vehicle application. Consequently for this study iron monosulfide (FeS) has been considered exclusively since the material is inexpensive and can readily be incorporated into practical cell designs in the time-frame relevant to this study re-early 1990s.

To date, the Li-MS work at Gould has been devoted primarily to cell development, rather than the complete battery system and therefore, we have limited knowledge to fully address all aspects of the battery system design. However, this report has been prepared in close collaboration with fellow Li-MS developers at ANL and it is the intention of the Gould report to corroborate the ANL projections where possible by experimental data and relevant studies performed at Gould under various contracts.

II. PERFORMANCE MODELING

In performing this study, two basic cell configurations have been considered. These are a conventional monopolar prismatic cell design, in which electrodes of the same polarity are connected in parallel within the cell and a bipolar configuration in which the electrode elements are stacked in series. The monopolar prismatic design is the current "state-of-the-art" which has been developed extensively during the DOE programs at ANL, Gould and Eagle Picher and is currently being pursued for a 9-cell battery demonstration in the EPRI van battery program. With minor improvements to existing technology this prismatic design is well capable of meeting the commuter car and van requirements (see Table 1).

The bipolar design which is currently being developed at Gould and the Admiralty Materials Technology Establishment (AMTE) in the UK, has the potential for significant performance improvement over the monopolar design particularly in terms of power and energy density since the current path
within the electrodes is significantly reduced and the current collection system is greatly simplified with a concomitant reduction in weight. Hence, a bipolar design is desirable for the hybrid and full performance EV where high power and high energy densities are required respectively (see Table 1).

The specific energy and peak power projections for the Li alloy - FeS system, for the various classes of batteries in Table 1, are given in Tables 2 and 3 respectively.

For the prismatic-monopolar cell, calculations have been based on a seven plate design, (i.e. 3 positive electrodes and 4 negative electrodes). The negative and positive electrodes are pressed plaques of a 80 w/o LiAl-20 w/o LiSi mixture and iron monosulfide (FeS) respectively. The separator is a high surface area magnesium oxide powder. Each of these three components also contain the alkali-halide salt electrolyte. The prismatic design has been selected for the commuter car and van applications since the performance requirements for these can be met with minor improvements in the current technology.

The bipolar design was selected for the full-performance EV and the hybrid vehicle since such a design offers the best promise of achieving the high energy and power densities required in these applications.

The methodology used in projecting the performance of the monopolar and bipolar batteries are discussed in Appendices A and B respectively.
Table 1

Battery Energy and Power Requirements for Electric and Hybrid Vehicles

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Specific Energy</th>
<th>Peak Power</th>
<th>Power: Energy Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total kWh</td>
<td>Battery Wh/kg</td>
<td>Vehicle Wh/kg</td>
</tr>
<tr>
<td>Commuter</td>
<td>12</td>
<td>67</td>
<td>12</td>
</tr>
<tr>
<td>General Purpose EV or Commercial Van</td>
<td>25</td>
<td>50</td>
<td>12</td>
</tr>
<tr>
<td>Hybrid</td>
<td>15</td>
<td>50</td>
<td>9</td>
</tr>
<tr>
<td>Full-Performance EV</td>
<td>50</td>
<td>155</td>
<td>30</td>
</tr>
</tbody>
</table>
### Table 2  Specific Energy with Discharge Rate for Li Alloy-FeS Batteries

<table>
<thead>
<tr>
<th>Class</th>
<th>Battery Designation</th>
<th>Battery Design</th>
<th>Battery Specific Energy (Wh/kg)* at Various Discharge Rates (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>1</td>
<td>Present Monopolar</td>
<td>Monopolar</td>
<td>54</td>
</tr>
<tr>
<td>2</td>
<td>Commuter &amp; 3/4 Ton Van</td>
<td>Monopolar</td>
<td>74</td>
</tr>
<tr>
<td>3</td>
<td>Full-Performance Bipolar</td>
<td>Bipolar</td>
<td>116</td>
</tr>
<tr>
<td>4</td>
<td>Hybrid Bipolar</td>
<td>Bipolar</td>
<td>108</td>
</tr>
</tbody>
</table>

* The battery specific energy has been calculated by derating the cell specific energy by 25-30%.

### Table 3  Peak Power at Various States of Charge for Li Alloy-FeS Batteries

<table>
<thead>
<tr>
<th>Class</th>
<th>Battery Designation</th>
<th>Battery Design</th>
<th>30 Sec Power Capability (W/kg) at Various States of Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>80%</td>
</tr>
<tr>
<td>1</td>
<td>Present Monopolar</td>
<td>Monopolar</td>
<td>155</td>
</tr>
<tr>
<td>2</td>
<td>Commuter &amp; 3/4 Ton Van</td>
<td>Monopolar</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>Full-Performance Bipolar</td>
<td>Bipolar</td>
<td>272</td>
</tr>
<tr>
<td>4</td>
<td>Hybrid Bipolar</td>
<td>Bipolar</td>
<td>234</td>
</tr>
</tbody>
</table>
III. COST PROJECTIONS

The projected OEM price for lithium alloy-iron monosulfide batteries for the different classes of vehicles is shown in Table 4.

The basis for these cost projections is given in Appendix C.

IV. TECHNICAL SUPPORT FOR PROJECTIONS

The main departures from the state-of-the-art technology that were considered in making the performance and cost projections were as follows:

(i) A bipolar battery design was chosen for the hybrid and full-performance electric vehicles since this has the potential for the high-power and high-energy outputs required by these classes of vehicle.

The feasibility of success of a bipolar design depends on eliminating stray conductive paths, both electronic and ionic, between the cells in the battery stack which would otherwise allow shunt currents to discharge the stack. One of the main sources for these stray conductive paths is electrolyte bridging between cells and to the battery case. However, the immobilised electrolyte-powder separator concept being developed at Gould and AMTE in the UK is an approach which could lead to a solution to this problem and therefore greatly simplify the design of peripheral seals required to isolate cells in the stack. Initial tests on bipolar stacks at Gould have produced very promising results and this work is to be pursued under our present EPRI contract.

The other advantage of a bipolar design is that the current collection system is less complex than a monopolar design, and therefore the part count, weight and cost are all reduced.

(ii) The materials considered in the costing of both the monopolar and bipolar batteries are those presently used in the Gould technology. However, some cost reductions could be readily brought about by
### Table 4  Projected Cost of Lithium-Metal Sulfide Batteries

<table>
<thead>
<tr>
<th>Battery Designation</th>
<th>Battery Design</th>
<th>Energy kWh</th>
<th>Power kW</th>
<th>P/E</th>
<th>Materials</th>
<th>OEM Selling Price $/kWh</th>
<th>$/Battery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>Monopolar</td>
<td></td>
<td></td>
<td></td>
<td>LIA1: LiS1-FeS; MgO; LICI-KCl</td>
<td>154</td>
<td>1848</td>
</tr>
<tr>
<td>Commuter</td>
<td>Monopolar</td>
<td>12</td>
<td>25</td>
<td>2.08</td>
<td>LIA1: LiS1-FeS; MgO; LICI-LiF-LiBr</td>
<td>154</td>
<td>3850</td>
</tr>
<tr>
<td>Gen. Purpose EV or Commercial Van</td>
<td>Monopolar</td>
<td>25</td>
<td>60</td>
<td>2.40</td>
<td>LIA1: LiS1-FeS; MgO; LICI-LiF-LiBr</td>
<td>154</td>
<td>3850</td>
</tr>
<tr>
<td>Hybrid</td>
<td>Bipolar</td>
<td>15</td>
<td>50</td>
<td>3.33</td>
<td>LIA1: LiS1-FeS; MgO; LICI-LiF-LiBr</td>
<td>127</td>
<td>1905</td>
</tr>
<tr>
<td>Full-Performance EV</td>
<td>Bipolar</td>
<td>50</td>
<td>50</td>
<td>1.0</td>
<td>LIA1: LiS1-FeS; MgO; LICI-LiF-LiBr</td>
<td>127</td>
<td>6330</td>
</tr>
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</table>
utilising less expensive materials if one is willing to accept some modest loss in performance in either specific energy and/or power.

The cell and electrode containment hardware and the current collection system which are currently fabricated from stainless steel and nickel respectively could be made from a low carbon steel. The consequence of such a change would be a heavier cell (i.e. lower specific energy) if the strength of the containment hardware at the battery operating temperature and the conductivity of the current collection system are to be maintained. Alternatively, some relaxation in the conductivity of the current collection system would probably result in a cell with reduced power capabilities especially at low states of charge. The life of the battery may be affected also if less expensive alloys are chosen for the hardware since their corrosion resistance is more than likely to be inferior at the elevated operating temperatures, (i.e. 450-5000C). Similarly, the selection of the negative active material may govern the choice of alloy for the hardware, especially the current collector.

From the cost analysis summarized in Appendix C however, it can be seen that the cost of the lithium bearing compounds are a major portion of the battery cost (i.e. ~40%). If a significant reduction is to be made therefore in the cost of lithium-metal sulfide batteries it is in this area which the greatest savings could be realized.

The two obvious ways in which the lithium bearing material cost can be reduced are:

1) Reduce the quantity of lithium bearing compounds or replace with cheaper alternatives.

ii) Identify a low cost source of lithium and develop inexpensive manufacturing processes to produce the required lithium compounds.

Examples of these would be to build cells which are negative electrode limited and starved in electrolyte. In addition a change in electrolyte composition
from the ternary lithium halide salt to the binary LiCl-KCl electrolyte would significantly reduce the electrolyte cost since lithium bromide is the major constituent in the ternary salt electrolyte.

A low cost source of lithium is lithium carbonate which is currently available as an item of commerce. The conversion of lithium carbonate into other lithium compounds suitable for building lithium-metal sulfide batteries has been explored to some depth by Chilenskas et al. at ANL. I refer you to their report\(^1\) and analysis in which they have shown the potential for reducing the cost of lithium-iron sulfide batteries below the $154-127/kWh range projected in this report.

V. ENERGY BALANCE

An energy balance for a vehicle operating on a JPL modified FUD schedule (see Figure 1) has been developed based on data from JPL and the following assumptions:

1) Vehicle test weight 1660 kg.
2) Battery weight 488 kg.
3) Average speed for cycle 3, 46.5/8 x 60/88 = 19.6 mph.
4) Time for cycle 3, 436/3600 = 0.111 h.
5) Distance covered in cycle 3, 19.6 x 0.121 = 2.37 miles.
6) Total distance per day 12 x 2.37 = 28.4 miles.
7) Battery heat loss at operating temperature = 150 W.
8) Charger efficiency 85% (D.C. out/A.C. in).
9) Battery efficiency 80% (D.C. out/D.C. in).
10) Battery Heat Capacity 0.25 Wh/kg OC.
11) Battery Specific Energy 75 Wh/kg.

An energy balance diagram is shown in Figure 2 for performing the JPL/FUD driving schedule over a period of 24 hours. Each of the major components in the system are identified along with the input/output energy.
Figure 1  JPL modified Federal Urban Driving Schedule for 24 hour period.
Figure 2
Energy Balance Over 24 Hours for JPL/FND Schedule

AC Power Supply 3641 Wh (AC) Charger (85% Eff.) 1296 Wh (Heat Loss)

Battery Electric Energy (80% Eff.)

7347 Wh (DC) 6828 Wh (DC)

Motor/Controller 5640 Wh (Drivetrain)

(Regenerative Braking) 1188 Wh

1707 Wh (Battery I^2R Heating)

Battery Heat Energy 3600 Wh (Heat Loss Through Insulation)

1891 Wh (AC Power to Battery Heater)
A summary of the overall energy consumption and efficiency coefficients are given in Table 5 while estimates for the in-use energy consumption are given in Table 6.

Table 5  Energy Consumption Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Battery heat loss per 24h.</td>
<td>3600 Wh</td>
</tr>
<tr>
<td>Battery I^2R heating during operation over 24h</td>
<td>1707 Wh</td>
</tr>
<tr>
<td>External heating required to maintain battery temperature over 24h.</td>
<td>1893 Wh</td>
</tr>
<tr>
<td>Total A.C. Energy Required</td>
<td>363 Wh/mile</td>
</tr>
<tr>
<td>Battery D.C. Output</td>
<td>235 Wh/mile</td>
</tr>
<tr>
<td>Vehicle Energy Consumption</td>
<td>142 Wh/tonne mile</td>
</tr>
<tr>
<td>Overall Energy Efficiency</td>
<td>65%</td>
</tr>
<tr>
<td>Battery heat energy generated during segment 1 of JPL/FUD cycle.</td>
<td>854 Wh</td>
</tr>
<tr>
<td>Maximum temperature rise of battery during segment 1 of JPL/FUD cycle.</td>
<td>70°C</td>
</tr>
<tr>
<td>Energy required to raise battery temperature from R.T. to 450°C.</td>
<td>53 kWh</td>
</tr>
<tr>
<td>Total Battery Energy</td>
<td>36.6 kWh</td>
</tr>
<tr>
<td>Depth of Discharge to drive JPL/FUD cycle</td>
<td>19%</td>
</tr>
</tbody>
</table>
Table 6  Estimates of In-Use Energy Consumption

<table>
<thead>
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<th>Parameters</th>
<th>Segments</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Start up and Shut down</td>
<td>None required: Battery capable of maintaining its operating temperature</td>
</tr>
<tr>
<td>Self-Discharge (Wh)</td>
<td>22</td>
</tr>
<tr>
<td>Shunt Current</td>
<td>none</td>
</tr>
<tr>
<td>Parasitics</td>
<td>none</td>
</tr>
<tr>
<td>Thermal Loss (Wh)</td>
<td>110</td>
</tr>
</tbody>
</table>
| Charge Eff. (Battery AC in /DC out) | 79%
VI. LIFE CONSIDERATIONS

A. Cycle Life

The cycle life of Gould engineering-size cells (i.e. theoretical capacity based on the positive electrode in the range of 120-240 Ah) is currently around 500 cycles with a number of cells having exceeded 800 cycles. The prospects for achieving 1000 cycles mean-time-to-failure (MTTF) therefore in the next few years is reasonably high.

Gould has limited experience in testing small battery modules (i.e. 3 to 10 cells connected in a series string), however results from this work indicate that generally one would expect similar lifetimes from modules as from individual cells provided that the series string of cells is periodically balanced. The current status of cycle life for engineering size cells is discussed in Appendix D.

B. Life Effects

The degradation in specific energy with cycling has been progressively reduced during the development of lithium alloy-iron monosulfide cells from approximately 0.07% per cycle to 0.02% per cycle for cells discharged at the C/3 rate. Data generated under the Air Force contract indicates that the degradation in specific energy with cycling is dependent on the discharge rate and the depth of discharge. As would be expected the higher the discharge rate or greater the depth of discharge the faster is the decline in specific energy with cycling.

The coulombic efficiency of new cells after formation can be as high as 99%, however, this can be somewhat lower (64%) depending on the overall charge-discharge cycle time since the cells have a finite leakage current in the range of 150-300mA. With cycling there is a very gradual decline in coulombic efficiency until the point of cell failure when it drops dramatically.
In small battery module tests, cells which have developed a partial short have been found to contribute to the battery capacity for a portion of the discharge cycle.

The thermal characteristics of cells during operation over many cycles has not been thoroughly investigated. However, from the extensive number of cell tests performed there is little evidence of a substantial change in the cell charge-discharge temperature profile with cycling. The largest increases in cell temperature above the normal operating temperature of \(-450^\circ C\) occur when cells are discharged at very high rates (e.g. \("3C\)), in such cases cell temperatures have been observed in excess of \(520^\circ C\) at the end of discharge.

**C) Failure Modes**

As indicated in the previous two sections, the main failure modes identified for lithium alloy-iron monosulfide cells are i) loss in capacity and ii) decrease in coulombic efficiency. Initially, loss in capacity was the predominant mode of failure, but the most recent series of cell tests indicate that the decline in coulombic efficiency is now the primary failure mode. The mechanism by which the decline in coulombic efficiency occurs has not yet been elucidated, other than that it is attributed to the development of a conductive path or paths between the electrodes. Metallographic examination, performed by J. Battles of ANL, on some earlier Gould cells indicate that the conductive paths are due to the deposition of iron within the powder separator layer and positive active material exudation, however there have been a number of changes in the more recent Gould cells and these have not yet been examined.

**VII. OTHER OPERATIONAL CHARACTERISTICS**

**A. Special Charge Requirements**

The normal charge and discharge reactions in lithium alloy-iron monosulfide cells result in the formation of solid products without gaseous side reactions. This permits the cells to be hermetically sealed and eliminates the need for electrolyte additions.
Information on the effects of overcharging and overdischarging Li alloy-FeS cells has been obtained from thermodynamic data, cell tests and metallographic examination of cells after cycling.

The upper cut-off voltage on charge normally used for LiAl-FeS cells is 1.55 V (IR-included) and 1.65 V for LiAl:LiSi-FeS cells. When these upper charge cut-off voltages are exceeded, the first major overcharge reaction which occurs at approximately 1.8 V (IR-free) is as follows:

\[ \text{Fe} + 2\text{LiCl} + 2\text{Al} + \text{FeCl}_2 + 2\text{LiAl} \]

This reaction involves any free iron in the FeS electrode to form FeCl\(_2\) and the deposition of additional lithium in negative electrode. On extended overcharge the FeCl\(_2\) can leave the positive electrode and permeate the separator where it is reduced to iron and thus cause a short. In the case of the negative electrode the lithium concentration can become sufficiently high that it forms a liquid metal phase in the electrode which can also ultimately lead to a short.

The normal lower cut-off voltage on discharge for Li alloy-FeS cells is in the range 1.0-0.9 volts (IR-included). The principal overdischarge reaction is:

\[ \text{Al} + 3\text{LiCl} \rightarrow \text{AlCl}_3 + \text{Li} \]

which occurs at -1.5 V (IR-free). In this case, aluminum in the negative electrode is oxidized to form AlCl\(_3\), which is soluble in the electrolyte, and metallic lithium is deposited on the positive electrode. The cell under these conditions is in a state of reversal. If discharging is continued then the cell eventually short circuits due to the deposition of metallic aluminum in the separator or the formation of liquid lithium at the iron sulfide electrode.

Experience has shown that cells are much more forgiving after being subjected to overdischarge than to overcharge. Indeed a number of cells which have been driven into reversal have fully recovered their initial capacity after being
subjected to a slow rate charge. In the case of severely overcharged cells no recovery has been possible.

In order to maintain the full capacity of the Li alloy-FeS battery during operation it will be necessary to periodically equalize the individual cells in the battery. The imbalance in the battery is brought about by the small variation in coulombic efficiency of the cells. Tests at Gould on 10-cell series-string batteries have shown that it takes a number of cycles before a significant amount of capacity is unavailable due to imbalance in the cells and therefore it is anticipated that the equalization charging would be required at most on a weekly basis. This suggests that fleet vehicles could be operated with an inexpensive battery charger dedicated to each vehicle for most of the overnight charging and that one more expensive charger-equalizer unit could be rotated among a minimum of seven vehicles. Concepts for charging and equalization of Li alloy-FeS batteries are under investigation by ANL in the EPRI program.

It is anticipated that periodic complete discharge will not be necessary for Li alloy-FeS batteries.

B. Maintenance Requirements

Regular maintenance, other than a periodic charge and equalization, will not be required for a Li alloy-FeS battery since the cells are sealed; therefore no electrolyte addition is necessary. The cell equalization can be readily accomplished overnight.

The operating temperature range of the battery will be controlled automatically by a sophisticated thermal management system which is capable of heating and cooling the battery on demand. It is envisaged that a separate AC circuit will be incorporated into the charging units to provide power to the resistive battery heaters. This arrangement will maintain the battery temperature during charging or for periods of intermediate standing. For longer term storage and major overhaul, the battery can be cooled to room temperature and then brought back into service by reheating to operating
temperature. The advantage in overhauling the battery at room temperature is that it will be electrically safe which is not the case with ambient temperature battery systems.

An electric vehicle battery will comprise a number of multi-cell submodule units. Hence, one refurbishment scenario would be to replace the complete submodules in which there are failed cells by either new or reconditioned submodules. The submodules removed from the battery could then be dismantled and rebuilt with the appropriate number of new cells for a future refurbishment of the battery. Replacement of a few cells (<10% of total number in battery) would no doubt be more cost effective than replacing the complete battery and should extend the life of the battery substantially (see ANL Analysis in Appendix D of their report).

VIII. PACKAGING FLEXIBILITY

A. Volumetric Considerations

At Gould we have not yet designed a full-size EV battery for a specific application and therefore can only address the volumetric requirements of a battery in general terms. There are, however, a number of design criteria which have to be satisfied in order to maximize the volumetric energy density of the battery; these are:

1) Minimize the battery surface area: volume ratio and thus minimize the heat losses. Obviously a battery in the form of a cube would best satisfy this condition, but vehicle design usually dictates that the length of the battery is at least a factor of two greater than the width or the height.

ii) The insulated battery enclosure need only be large enough to hold the desired number of battery submodules, the intermodule connectors, charge control wires and the heat exchanger system which will heat and cool the battery to maintain the desired operating temperature range.
iii) The wall thickness of the insulative enclosure should be as thin as possible. However, the thickness depends on the thermal conductivity value of the insulation and the heat loss which is tolerable in order to operate the battery. The lowest conductivity insulation is the most expensive and hence there is an economic trade-off to be considered between the various types of insulation available.

In order to obtain an approximate range for the volumetric energy density of Li alloy-FeS batteries the following assumptions have been made:

(i) Density of Li alloy-FeS cells $\approx 2 \text{ g/cm}^3 \text{ (kg/l)}$

(ii) Wall thickness of insulative enclosure $\approx 2.5 \text{ cm}$

(iii) Thickness of insulative and plug $\approx 7.5 \text{ cm}$

(iv) Heat exchanger occupies $\approx 15\%$ of insulative enclosure

(v) From assumptions (i)-(iv) density of battery (including enclosure) $\approx 1.3 \text{ g/cm}^3 \text{ (kg/l)}$

(vi) Volumetric energy density (Wh/l) = Gravimetric energy density (Wh/kg) x density (kg/l)

Hence from the cell and battery densities plus the gravimetric energy density values calculated in Appendix A and tabulated in Table 2 a range of volumetric energy densities can be derived which range from 1.3 to 2 times the gravimetric energy density. It should be noted that the smaller the battery size in terms of capacity (kWh), the greater will be the volume fraction of the insulative enclosure, and hence the volumetric energy density will be lower the smaller battery size even though identical battery submodules can be used in different size batteries.
B. Size Limitations

The Li alloy-FeS electrochemical system permits great flexibility in the design of both monopolar-prismatic cells and bipolar batteries. In the development of the system a number of different electrode sizes have been used in engineering calls from 7.5 cm x 12.5 cm to as large as 30 cm x 30 cm. The choice of electrode size, thickness and number will greatly depend upon the battery requirements in terms of power and energy. In general the high power battery would comprise many small, thin electrodes whereas the high energy battery would comprise few, large, thick electrodes. However, it is usually necessary to make compromises in both power and energy to obtain optimum battery performance. The larger electrode designs tend to have non-uniform current distribution on the electrodes which result in reduced active material utilization and increased thermal problems, consequently an electrode size of ~200 cm² is presently being considered for the EV application. A typical EV monopolar call design is shown in Figure 3. The one feature of the design which permits a significant reduction in the cell volume is the height of the terminals, particularly the positive, above the main body of the cell. A substantial portion of the positive terminal length is devoted to the feedthrough seal which electrically isolates the terminal from the cell container. Hence if a low profile ceramic-to-metal seal is developed for the positive feedthrough then the length of the terminals could be significantly reduced with the consequential improvement in volumetric energy density.

C. Special Considerations

The complete Li alloy-FeS battery comprises a high-efficiency insulating enclosure, a heating and cooling system, current, voltage and temperature leads and control instrumentation packaged as an integral self-contained unit. The cooling media will be circulated to the heat exchanger by a small electric fan mounted adjacent to the battery.
Theoretical Capacity: 240 Ah
Cell Weight: 2.5 kg
Volume: 1.36 l

Figure 3 Lithium-Metal Sulfide Cell
D. Scale Effects

Detailed scaling factors have not yet been derived for batteries in the range of 10-50 kWh. However, since the Li alloy-FeS system permits great flexibility in design parameters (i.e. size, thickness and number of electrodes) it should be possible to develop high performance batteries over the range of interest.

Batteries of a monopolar prismatic design will be used first to demonstrate the feasibility of high temperature lithium-metal sulfide batteries in electric vehicles, but the ultimate performance of the system in this application will be realized in a bipolar battery design.
ACKNOWLEDGEMENT

This report was prepared in support of the Jet Propulsion Laboratory Electric and Hybrid Vehicle Project, under Contract No. 956761 and in collaboration with fellow Li-MS battery developers at Argonne National Laboratory who have also written a similar report for the JPL Project.

References

Appendix A

PRISMATIC-MONOPOLAR BATTERY PERFORMANCE PROJECTIONS

I. Specific Energy

The current technology data presented in Table 2 has been generated from recent tests on prismatic-monopolar-multiplate cells which have a theoretical capacity of ~240 Ah and a height:width aspect ratio of ~0.7. This particular cell design has evolved over several years during a DOE contract with ANL and more recently a contract with the Air Force. The cell developed for the Air Force had a theoretical capacity of ~120 Ah and an aspect ratio of ~0.7. However, many of the design features employed in the Air Force cell have now been incorporated into a larger capacity cell (i.e. 240 Ah) for an electric van application under our current contract with EPRI.

Battery specific energy data at various discharge rates are plotted in Figure A-1. These plots have been obtained by derating the cell specific energy data by 25%. This is an average derating factor one might expect when the weight of all the ancillary battery hardware and thermal management system are accounted for in a high temperature battery design.

The "projected" performance of a monopolar battery also shown in Figure A-1 has been derived from a second iteration of the cell design currently being evaluated under the EPRI program. By optimizing the first design it has been possible to significantly reduce the weight of the cell, particularly the hardware, without making any change to the quantity of electrochemically active materials. Hence it is projected that this cell will exhibit a significant improvement in performance. The projected cell performance, again has been derated by 25% in order to obtain the battery specific energy.

II. Peak Power

The peak power data for the current technology and the "projected" prismatic-monopolar battery are plotted in Figure A-2. The current technology data are
Figure A.1 Specific energy of a prismatic monopolar lithium alloy-iron sulfide battery as a function of constant power discharges.
Figure A-2 Peak power (30 sec pulse) of prismatic monopolar lithium-iron sulfide batteries at various states of charge.
experimental results from the same cells as were used for the specific energy measurements. The "projected" data was generated from the second iteration cell design mentioned previously. All cell data was derated by 25% in order to estimate the battery peak power performance.
Appendix B

BIPOLAR BATTERY PERFORMANCE PROJECTIONS

An analysis has been performed in order to project the performance that could be expected from a bipolar type lithium-iron monosulfide battery which utilizes the immobilized electrolyte-powder separator concept that Gould has been actively pursuing since 1980. This preliminary analysis has been limited to projecting:

i) The specific energy profile of a battery discharged at constant power in the range 20-200 W/kg.

ii) The peak power performance of the battery as a function of the state-of-charge as defined for a nominal C/3 discharge rate.

I. The Bipolar Design

The electrochemical couple proposed in the bipolar design is the same as that employed in the prismatic-monopolar design. This is a LiAl:LiSi alloy negative electrode and an iron monosulfide positive electrode operated in a ternary lithium halide electrolyte (Li:Br, F, Cl) in the temperature range of 450-500°C. The separator is also the magnesium oxide powder type.

A conceptual design of the proposed bipolar battery is shown in Figure B-1. The basic components of the battery are the bipolar element, the current collector-terminal-feedthrough system and the container for the stack. The bipolar element comprises one positive and one negative electrode placed either side of a thin metal current collector membrane. In addition a separator layer has been included in the bipolar element in order to simplify the battery calculations. The battery is assembled by stacking the required number of bipolar elements in order to obtain the desired battery energy.

The advantages offered by a bipolar design over that of a monopolar design are:
Prepared for Jet Propulsion Laboratories
Pasadena, CA 91109
Contract No. 956761

Gould Research Center
Materials & Devices Laboratory
March 12, 1984

Figure 8-1 Bipolar cell stack design

\[ n = \text{NO. OF BIPOLAR ELEMENTS} \]
\[ C = \text{CAPACITY OF POSITIVE ELECTRODE (Ah)} \]
\[ U = \text{UTILIZATION OF POSITIVE ACTIVE MATERIAL} \]
\[ W_1 = \text{WEIGHT OF BIPOLAR ELEMENT} \]
\[ W_2 = \text{WEIGHT OF COVER-TERMINAL-DISTRIBUTOR ASSEMBLY} \]
\[ V = \text{CELL VOLTAGE OF BIPOLAR ELEMENT (VOLTS)} \]

\[
\text{SPECIFIC ENERGY} = \frac{(n + 1) \text{CVU}}{(n + 1) W_1 + 2W_2} \quad (\text{Wh/kg})
\]
i) The weight of the current collection system can be considerably reduced since the current path is perpendicular to the face of the electrodes, i.e., bus bars and distribution plates necessary in a monopolar design can be eliminated.

ii) A more uniform current distribution can be obtained on the electrodes and therefore the active material utilization is improved particularly at the higher rates of discharge.

II. Methodology for Bipolar Design Calculations

The first step in designing the conceptual bipolar battery proposed in Figure B-1 is to assign physical and electrochemical parameters to the various components in the battery. The values assigned to these parameters are based on data that has been obtained from engineering and experimental pellet cells. The facial area of the electrodes has been maintained the same as in the prismatic-monopolar design (i.e., ~214 cm²) so that the performance between the two batteries can be directly compared. However, for the bipolar battery we have opted for a circular electrode instead of a rectangular electrode.

From these key parameters and empirical relationships that have been derived for utilization, voltage against current density and depth of discharge for the Li-MS system it is possible to calculate the specific energy and sustained power. The parameters assigned to the various components are listed in Table B-1.

In order to calculate the available energy from the battery at various discharge rates it is necessary to know the relationship between active material utilization and current density. The following, empirical equation has been derived from experimental data on advanced cell work performed both at ANL1 and Gould2.

2. S. Misra private communication.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrode Diameter</td>
<td>16.51 cm</td>
</tr>
<tr>
<td>Electrode Area</td>
<td>214.08 cm²</td>
</tr>
<tr>
<td>No. of Bipolar Elements</td>
<td>24</td>
</tr>
<tr>
<td>Theoretical Capacity of Positive Electrode</td>
<td>40.78 Ah</td>
</tr>
<tr>
<td>Positive Plaque Loading Density</td>
<td>1.5 Ah/cm³</td>
</tr>
<tr>
<td></td>
<td>0.45 Ah/g</td>
</tr>
<tr>
<td>Negative Plaque Loading Density</td>
<td>1.0 Ah/cm³</td>
</tr>
<tr>
<td></td>
<td>0.63 Ah/g</td>
</tr>
<tr>
<td>Separator Density</td>
<td>2.35 g/cm³</td>
</tr>
<tr>
<td>Negative:Positive Capacity Ratio</td>
<td>1.3:1</td>
</tr>
<tr>
<td>Positive Electrode Thickness</td>
<td>0.127 cm</td>
</tr>
<tr>
<td>Negative Electrode Thickness</td>
<td>0.248 cm</td>
</tr>
<tr>
<td>Separator Thickness</td>
<td>0.152 cm</td>
</tr>
<tr>
<td>Bipolar Membrane Thickness</td>
<td>0.008 cm</td>
</tr>
<tr>
<td>Weight of Bipolar Element</td>
<td>300 g</td>
</tr>
<tr>
<td>Weight of Terminal/Collector/Battery End Cover</td>
<td>300 g</td>
</tr>
<tr>
<td>Total Battery Weight</td>
<td>8.1 kg</td>
</tr>
<tr>
<td>Total Battery Volume</td>
<td>4.27 liters</td>
</tr>
</tbody>
</table>
where $i$ is current density in A/cm². This equation has been plotted in Figure 3-2. Another factor which affects the utilization of an electrode is the thickness (i.e., the thicker the electrode the poorer the utilization). However, for electrodes with a thickness of <0.15 cm the variation in utilization with thickness is insignificant and therefore, since we have chosen for this analysis a positive electrode thickness of 0.127 cm, we have ignored this effect.

The average voltage on discharge for a Li alloy-FeS cell as a function of the discharge rate has been integrated from experimental data measured on a pellet cell, since this type of cell closely approximates to the electrode arrangement in a bipolar stack. This data, plotted in Figure B-3, shows the average discharge voltage as a function of current density for a single cell. The bipolar battery voltage is assumed to be $n+1$ times the single cell voltage, where $n$ is the number of bipolar units in the battery. Hence the battery energy and sustained power can be calculated by multiplying the average bipolar stack voltage by the cell capacity and average discharge current, respectively. The specific energy versus discharge rate is plotted in Figure 3-4 for the bipolar battery, including a derating factor of 25% to take into account all other ancillary hardware.

In order to calculate the peak power for the bipolar battery it is necessary to know the peak power flux, W/cm². Again, such data are available from 30 sec. peak power pulse tests performed on advanced design pellet cells and higher power prismatic cells with lithium alloy and iron monosulfide electrodes. The peak power flux data are plotted in Figure B-5 as a function of state-of-charge for both state-of-the-art and advanced design cells. The 30 sec peak power for the bipolar battery was then calculated by multiplying the flux values by the area of electrode in the battery. These values were derated by a multiplying factor of 0.75 to compensate for the ancillary battery hardware. The results of these computations are presented in Table B-2 which are the 30 sec. specific peak power capability at various states-of-charge for the complete battery.
Figure B-2  Positive electrode utilization as a function of current density for lithium alloy-iron monosulfide cells.
Figure B-3  Average discharge voltage for a lithium alloy-iron sulfide cell as a function of current density.
Figure B-4  Specific energy of bipolar lithium alloy-iron monosulfide battery as a function of constant power discharge rate.
Figure 8-5  The peak power flux for lithium alloy-iron monosulfide electrodes as a function of state-of-charge.
## Table B-2

### Peak Power of Bipolar Battery at Various States-of-Charge

<table>
<thead>
<tr>
<th>Specific Peak Power (W/kg) at State of Charge (%)</th>
<th>80</th>
<th>50</th>
<th>30</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Advanced</strong></td>
<td>272</td>
<td>233</td>
<td>188</td>
<td>129</td>
</tr>
<tr>
<td><strong>State-of-the-Art</strong></td>
<td>213</td>
<td>163</td>
<td>114</td>
<td>49</td>
</tr>
</tbody>
</table>
Appendix C

BATTERY MANUFACTURING COST PROJECTIONS

I. Introduction

The cost projections are based on existing technology at Gould for the monopolar-prismatic battery and have assumed some modest improvements in this technology for estimating the cost of the bipolar battery.

The present technology at Gould utilizes a lithium-aluminum-silicon negative electrode and an iron monosulfide positive electrode. The separator is magnesium oxide powder and the electrolyte is a ternary lithium halide salt of 22 w/o LiCl-68 w/o LiBr-10 w/o LiF. The current collection system is fabricated from Nickel 200 in order to provide good electrical conductivity. All other hardware is made from Grade 304 stainless steel.

The plant for manufacturing these batteries at the rate of 100,000 units/year is assumed to be highly automated and hence manual labor is minimal. All the processing steps involved in manufacturing Li-MS batteries are typical of present-day battery and powder metallurgy establishments. The only special feature of a Li-MS battery plant would be that a number of the processing steps have to be performed in a dry-room atmosphere since the negative active material and electrolyte are highly moisture sensitive. It has been assumed that most of the cell hardware components will be bought-in items since they can be readily made by conventional metal stamping and forming operations. Many of the cell components are already made this way even for our present needs.
II. Cost Analysis

The following cost analysis has been performed as per the ADL guidelines* except where indicated in the following and noted in the tables of this appendix.

The main assumptions in the ADL costing methodology and deviations proposed are:

i) Overhead Rates

The labor overhead rate is 150% of the direct labor and the materials overhead is 10% of the materials cost. It should be noted that in the Consiglio/Symons costing, (see Table C-2) they applied a 280% labor overhead rate. In their report they reference this overhead rate to Gould. However, it should be pointed out that when this rate is applied it includes equipment depreciation, rent and warranty costs. Therefore their analysis will be somewhat high since they have included these costs twice, but figured in two different ways.

ii) Direct Labor

In this analysis we have chosen to figure the direct labor as 9% of the materials cost, instead of at a fixed hourly rate.

iii) Equipment and Depreciation

The capital equipment costs have been figured on the basis of $20/kWh for the theoretical capacity within the battery. The capital equipment has been amortized linearly over a ten-year period, hence a 10% depreciation factor is used in the calculation.

iv) Rent

This has been figured at $6/ft² for the conceptualized plant.

v) Working Capital Requirements

The working capital requirements are assumed to be equal to 30% of the value of annual production based on the factory cost.

vi) After-Tax Return on Investment and Taxes

Each of these two items are assumed to be equal to 15% of the total investment on an annual basis. The total investment is the sum of the equipment cost plus the working capital.

The basic raw material prices used in the calculations are listed in Table C-1 and a summary of the costs leading to the estimates for the OEM selling price for both monopolar prismatic and bipolar batteries are given in Table C-2. For comparison, the costing performed by Consiglio and Symons is listed also in Table C-2. However, it should be noted that their costs are based on an annual production rate of 20,000 batteries whereas the Gould estimates are for a rate of 100,000 units per year.
### Table C-1  Market Price of Materials* 1984

<table>
<thead>
<tr>
<th>Material</th>
<th>Market Price $/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lithium Metal</td>
<td>47.74</td>
</tr>
<tr>
<td>Lithium Bromide</td>
<td>14.32</td>
</tr>
<tr>
<td>Lithium Chloride</td>
<td>6.60</td>
</tr>
<tr>
<td>Lithium Fluoride</td>
<td>10.38</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2.38</td>
</tr>
<tr>
<td>Silicon</td>
<td>1.45</td>
</tr>
<tr>
<td>Iron Sulfide</td>
<td>0.90</td>
</tr>
<tr>
<td>Magnesium Oxide</td>
<td>1.76</td>
</tr>
<tr>
<td>Potassium Chloride</td>
<td>0.12</td>
</tr>
<tr>
<td>Nickel</td>
<td>14.48</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>3.01</td>
</tr>
<tr>
<td>Iron Powder</td>
<td>0.62</td>
</tr>
<tr>
<td>Low Carbon Steel</td>
<td>0.73</td>
</tr>
</tbody>
</table>

*Sources: Chemical Marketing Reporter, February 84; American Metal Market, March 84.
Table C-2. OEM Selling Price for Lithium-Metal Sulfide Batteries  
(Battery Size - 25 kWh delivered at C/3 rate)

<table>
<thead>
<tr>
<th>Cost Item</th>
<th>1984 Dollars/Battery</th>
<th>Remarks on Gould Costing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Consiglio/Symons</td>
<td>Gould</td>
</tr>
<tr>
<td></td>
<td>20,000 Batts/yr</td>
<td>100,000 Batts/yr</td>
</tr>
<tr>
<td>Monopolar</td>
<td>Prismatic</td>
<td>Bipolar</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lithium Bearing Compounds</td>
<td>1552</td>
<td>1405</td>
</tr>
<tr>
<td>Other Materials</td>
<td>690</td>
<td>600</td>
</tr>
<tr>
<td>Insulating Enclosure</td>
<td>650</td>
<td>290</td>
</tr>
<tr>
<td>Material Overhead</td>
<td>289</td>
<td>229</td>
</tr>
<tr>
<td></td>
<td>3181</td>
<td>2524</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Labor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell</td>
<td>241</td>
<td>207</td>
</tr>
<tr>
<td>Cell/Battery</td>
<td>60</td>
<td>52</td>
</tr>
<tr>
<td>Direct Labor Overhead</td>
<td>843</td>
<td>389</td>
</tr>
<tr>
<td></td>
<td>1114</td>
<td>648</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Depreciation</td>
<td>100</td>
<td>58</td>
</tr>
<tr>
<td>Rent</td>
<td>63</td>
<td>48</td>
</tr>
<tr>
<td>Factory Cost</td>
<td>6488</td>
<td>3278</td>
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<tr>
<td>Capital Investment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working Capital</td>
<td>1346</td>
<td>983</td>
</tr>
<tr>
<td>Equipment</td>
<td>1000</td>
<td>580</td>
</tr>
<tr>
<td>Total Investment</td>
<td>2346</td>
<td>1563</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ROI + Taxes</td>
<td>704</td>
<td>469</td>
</tr>
<tr>
<td>Warranty</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>OEM Selling Price</td>
<td>5292</td>
<td>3847</td>
</tr>
<tr>
<td>($212/kWh)</td>
<td>($154/kWh)</td>
<td>($127/kWh)</td>
</tr>
</tbody>
</table>
III. Summary Remarks

It can be seen from Table C-2 that the cost per kWh for lithium alloy-metal sulfide batteries employing existing technology are substantially more expensive than the desired $100/kWh target for the advanced battery systems in electric vehicle applications. However, a major portion of the cost is attributed to the lithium bearing compounds (i.e. ~40%). Therefore, if the cost goal is to be attained, this area should receive greatest attention. In the report submitted by ANL under this contract, Chilenskas and Shimotake have proposed a number of feasible ideas which can be shown to significantly reduce the price of lithium-metal sulfide batteries. In particular they have suggested using lithium carbonate as an inexpensive feed stock for manufacturing all the required lithium bearing compounds necessary for the battery. It may be possible also to use a LiCl-KCl electrolyte in place of the all-lithium-halide electrolyte in the less demanding vehicle applications.

The OEM selling price from this and the ANL report is projected to be in the range of $154-99 per kWh. The upper end of the range relates to existing technology whereas the lower end can probably be realized in a second generation plant.
LIFE CONSIDERATIONS

I. Cells

A summary of the cycle-life tests performed on Gould immobilized-electrolyte-powder separator type cells (see Figure 2) at both ANL and Gould is presented in Table D-1. The tests performed at ANL were on cells specifically designed for the EV application. These cells were cycled on a 12 hour regime (i.e. 8h charge/4h discharge) to 100% DOD or 1.0 V lower cut-off voltage. The end of life was defined as either a 20% loss in the initial capacity or a decline in the coulombic efficiency below 95%. The highest mean-time-to-failure for these cells was 330 cycles; with a Weibull Slope, which defines the distribution of failures of 2.9. The average capacity loss was 0.06% per cycle.

The tests performed at Gould were on cells designed for a high rate application and consequently the specific energy is substantially reduced due to the heavier current collection system. The electroactive materials, electrolyte and separator, however, were essentially the same as those in the Group II EV cells. Two different test regimes were examined, one was a 6h regime (5.25h charge, 0.75h discharge) the other a 24h regime (22.8h charge, 1.2h discharge). The cells were discharged also to different depths-of-discharge between 40% and 80%. The end of life for these cells was when the leakage current exceeded 1000 mA.

It was concluded from the Gould tests that the cell life is somewhat dependent upon depth of discharge (i.e. longer life for lower depths of discharge) but this is a second order effect and the primary factor limiting the life of the Gould cells is the time at operating temperature. This time is in the region of 150 days and is arrived at by dividing the number of cycles by the cycles per day of the test regime.
Table D-1. Summary of Gould Li Alloy-FeS Cell Performance in Tests at ANL and Gould

<table>
<thead>
<tr>
<th>Status Cells Tests (ANL)</th>
<th>Gould Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>No. of Cells in Group</td>
<td>12</td>
</tr>
<tr>
<td>Theo. Capacity, Ah</td>
<td>174</td>
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<tr>
<td>Av. Operating Temp., °C</td>
<td>465</td>
</tr>
<tr>
<td>Av. Peak Capacity, Ah</td>
<td>150</td>
</tr>
<tr>
<td>Std. Dev. in Peak</td>
<td>4.5</td>
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<tr>
<td>Capacity, %</td>
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<tr>
<td>Av. Specific Energy, Wh/kg</td>
<td>74</td>
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<tr>
<td>Peak Specific Power, W/kg at 50% DOD</td>
<td>70</td>
</tr>
<tr>
<td>Cycle Life, to 1 DOD</td>
<td>100</td>
</tr>
<tr>
<td>High/Low, Cycles</td>
<td>307/14</td>
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<tr>
<td>Mean Time to Failure Cycles</td>
<td>218/26</td>
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<tr>
<td>Weibull Slope</td>
<td>2.0/3.4</td>
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<tr>
<td>Av. Capacity Loss Rate, % per Cycle</td>
<td>0.06</td>
</tr>
<tr>
<td>Charge/discharge cycle, h</td>
<td>8/6</td>
</tr>
</tbody>
</table>

*Temperature was 455°C until 20% capacity loss, then raised in 5°C increments to 455-475°C.
*End of life defined as 20% capacity loss or coulombic efficiency decrease to <93%.
*Correlated as five- and seven-cell groups. Single group correlation not possible.
*Gould Status Cells, Group II, showing the improved performance obtained by raising the temperature to 475°C.
*Cells still cycling.
The failure mechanism which is limiting the life of these most recent cells has not yet been investigated. Post-test examination of earlier cells, however, has shown the failure to be due to shorts which develop as the positive active material is exuded through the particle retainer basket into the separator and eventually this material comes into contact with the negative electrode, or other conductive material that with time becomes deposited in the separator layer (i.e. iron particles).

Recent Eagle-Picher cell tests, performed under a program for the U.S. Army, have demonstrated a life in excess of 1000 cycles and 500 days of operation to 80% DOD. Therefore, there is no reason to believe that with modification the Gould immobilized electrolyte-powder separator cells cannot achieve a similar lifetime at temperature.

II. Battery Modules

Within Gould minimal lifetime information has been generated on Li alloy-MS battery modules since only three have been assembled and tested. One of these was a three cell module and the other two were ten-cell 2.5 kWh modules. However, a reasonable amount of operational experience and information was gathered during the testing of these latter two modules. The early performance of the modules were as expected with the battery capacity declining steadily with cycling as the cell imbalance increased due to minor differences in the coulombic efficiency of the cells. The full battery capacity, however, could be restored by performing an equalization after 14 cycles. It was possible to repeat this cycling-equalization routine at least 5 times before problems arose with the batteries. These problems were partially attributable to electrolyte leakage from the positive feedthrough seals and the subsequent "wicking-action" along the insulation on the intercell connectors. In general the life of the two battery modules was in line with the cycle life of the individual cells from which they were constructed. The thermal management systems used in these battery modules were capable of maintaining the cells within their operating temperature range during both charge and discharge and it was concluded that a minimal cooling system will be required.
As part of the current EPRI program, Gould is to build 9-cell battery modules that are to be tested at ANL in a high-efficiency thermal insulated housing fitted with an integrated thermal management system. This system will provide both heating and cooling during operation of the battery.
APPENDIX H

BATTERY DESIGN ANALYSIS
BATTERY DESIGN ANALYSIS

FEBRUARY 1984

Prepared for
Jet Propulsion Laboratory
California Institute of Technology

Prepared by
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<td>3</td>
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<td>Cost Projections</td>
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SUMMARY

A brief design analysis was performed which confirms that sodium-sulfur (Na/S) batteries can be designed to match a wide range of mobile application requirements. These missions range from low-power commuter EVs to full performance SUVs to very high power hybrid vehicles. In spite of the need for high temperature operation, the projected specific energy, power density and energy efficiency of the complete Na/S battery system are excellent, enabling all the missions to be considered technically viable. Economic estimates are less certain, but indicate that battery initial cost is likely to be relatively high. Economic viability would depend on alternate fuel costs as well as on attaining the projected cycle life and high-rate production.

It would appear that the appropriate next step should include demonstration of hardware and validation of projections for both performance and cost.
INTRODUCTION

The applicability of sodium-sulfur batteries to a wide range of mobile missions was addressed in this brief analysis. The influence of battery size and power-to-energy ratio was determined at a system level through a series of four point designs, each targeted at a representative application. These include three EV vehicles and a battery hybrid vehicle. In all cases, the exceptional efficiency and high specific energy of individual cells lead to practical performance projections for the complete battery systems. Obviously, larger batteries are favored as a consequence of the weight and volume requirements for thermal control, but even the small commuter battery has a specific energy of about 90 Wh/kg.

These analyses addressed issues of thermal and charge control, packaging, overall energy balance, aging, maintenance and cost estimates. For this study, the design guidelines supplied by JPL were followed with few exceptions in order to facilitate battery comparisons. As a result, some performance parameters are lower than could otherwise be claimed with a more detailed design. In areas of battery reliability, maintenance and cost, the state of Na-S technology development does not support firm projections.
1.0 PERFORMANCE MODELLING

Four candidate missions were specified along with their energy and power requirements. These are listed in Table 1.1. Using assumptions specified in the guidelines and augmented by the others discussed with the JPL Program Manager, sodium-sulfur batteries were designed for each of the four missions. The principal assumptions are listed in Table 1.2.

The sizing (initial rating) of each battery is increased by 10% in both energy and power to approximately offset deterioration during life. The balance between credits for providing excess capability in early life and penalties for having inadequate performance in later life is poorly quantified. The issue is clouded by the probable spread in customer tolerance to performance shortfall and willingness to follow recommended maintenance schedules. The fixed 10% factor for all missions is considered more appropriate than trying to estimate separate life-cycle averages for each mission. Small additional adjustments are made to the power and energy goals of each mission to compensate for controller limitations. The performance ratings of the batteries are estimated in accordance with the guidelines (i.e., 1-year battery), and battery outputs over life are projected Section 5.

1.1 BATTERY DESIGN

In this study, it is assumed that cells are connected in long series strings to provide either full- or half-battery voltage. Full battery capacity is obtained by paralleling the appropriate number of strings. The response of long strings is to average (sum) the individual cell resistances, thus reducing the effect of cell variability. However, the effective string capacity is determined by that of the weakest cell since it blocks further current. Based on present modelling studies, this long string interconnection topology appears to provide best battery reliability.
Table 1.1. Candidate Missions

<table>
<thead>
<tr>
<th>APPLICATIONS</th>
<th>RANGE</th>
<th>ENERGY CONSUMED</th>
<th>MAXIMUM PULSE POWER DEMAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Commuter EV</td>
<td>128 km</td>
<td>12 kWh</td>
<td>25 kW</td>
</tr>
<tr>
<td>II. Hybrid Vehicle</td>
<td>80 km</td>
<td>15 kWh</td>
<td>50 kW</td>
</tr>
<tr>
<td>III. General Purpose EV/Van</td>
<td>160 km</td>
<td>25 kWh</td>
<td>60 kW</td>
</tr>
<tr>
<td>IV. Full Performance EV</td>
<td>400 km</td>
<td>50 kWh</td>
<td>50 kW</td>
</tr>
</tbody>
</table>

Table 1.2. Assumptions for Performance Modelling

1. Controller Voltage Range Fixed Over Life
   - Nominal 240 V battery (except 120 V for commuter)
   - Allowable range: OCV±0.54 OCV
   - No provision for regeneration voltage
   - Controller limits removed for charge

2. Mission Requirements Considered "Mid-Life"
   - 110% used to size "new" battery
   - 1-year old battery used to project performance
   - 1-year old battery used for "energy balance"

3. Battery Aging Model (circa 1990)
   - \( \frac{dN}{N} = -0.00 \) per freeze-thaw cycles \((N = \text{number of good cells})\)
   - \( \frac{dN}{N} \): Weibull statistics \((\alpha = 1500 \text{ cycles}, \beta = 3.0)\)
   - \( \frac{dR}{R} = +(1.0 \pm 0.5) \times 10^{-4} \) per electrical cycle \((R = \text{resistance})\)
   - \( \frac{dC}{C} = -(1.0 \pm 0.5) \times 10^{-4} \) per electrical cycle \((C = \text{capacity})\)
   - Failed cells have 1 m\(\Omega\) resistance

4. Balance of System Components
   - Structural support weight proportional to cell weight.
   - Thermal enclosure size & losses scale as \((\text{volume})^{2/3}\)
   - Thermal control proportional to square of sustained power.
For Na/S cells, the principal design factors are the capacity (both theoretical and rated) and internal resistance (both pulsed and steady). The resistance values are nearly constant throughout a cycle except at the extreme ends of the charge or discharge. The common convention in Na/S technology is to define theoretical capacity between "sulfur" as charged and "Na₂S₃" as discharged. At Ford Aerospace, a linear chemical state-of-charge scale is used which conveniently represents the relative Ah content for a sulfur-limited design. Using the F-scale (corresponding to composition Na₂FS₃), the theoretical capacity ranges from sulfur (F=0) to Na₂S₃ (F=1). A value F₁ represents the end of charge defined by the dynamics of the recharge processes which are affected principally by the charge rate, voltage limit and temperature. Similarly, F₂ represents the dynamic end of discharge. The utilization (U) of the sulfur electrode is F₂ - F₁ and thus depends on operating conditions.

It may be desirable for other system considerations to limit the range of cathode operation and define "design" or "rated" values for F₁R, F₂R and U_R. In this present study, the design F₂R is chosen between 0.6 and 0.8 for reasons related to improving the constancy of pulse power, for reduction of entropic heating, and in order to retain more voltage swing at the end of discharge (EOD) to offset additional battery deterioration thereby extending the interval before maintenance. The 100% state-of-charge (SOC) condition corresponds to the design point F₁R, and the 0% SOC corresponds to F₂R. With this convention, the battery can operate beyond the 0% - 100% range in SOC. The relationships of these notations to cell voltage are depicted in Figure 1.1.

In other EV analyses, it was often desirable to provide some "limp-home" range at less than specified power. To do this with Na/S technology,
Figure 1.1. Relationship of State of Charge and $F$ Values.
the battery is designed to meet or exceed specified power out to its rated discharge condition, $F_{2R}$, until it reaches its defined end-of-life. By increasing the cells' sodium content slightly, additional range capability at lower power is provided at very low incremental weight and volume. Furthermore, with its higher performance early in life, the battery can deliver the specified power throughout the additional range as well. However, in keeping with this study's guidelines, no "limp-home" provision is included.

1.1.1 INITIAL SIZING

Throughout most of its discharge cycle, the Na/S cell is well represented as a fixed linear resistor in series with a voltage source which varies slightly with SOC, as shown in Figure 1.1. Because part of the voltage loss results from concentration polarization which is nearly linear with current, the effective resistance for pulse operation is somewhat lower than for steady operation (e.g., $R_p/R_s \sim 0.8$ to 0.95). This is beneficial in meeting the peak power specifications.

With the simple linear electrical circuit, the relationships between energy, power, efficiency, voltage, current, capacity and time are straightforward. The voltage range set by the motor/controller interacts with the battery characteristics to limit the deliverable energy and power. In this study, the voltage ratio $K_1 = V_{\text{min}}/V_{\text{max}} = 0.54$ was selected to correspond to the hardware under development at JPL and the DOE-Ford ETX program. These controllers operate between 265 V and 143 V. By removing provisions for regeneration in a new battery, the battery OCV is taken as large as possible: thus $K_2 = \text{OCV (SOC = 100%)}/V_{\text{max}} = 1.0$. For convenience, several other ratios were defined. The cell's OCV varies with SOC as shown in Figure 1.1, with $K_3 = \text{OCV (SOC = 0%)}/\text{OCV (SOC = 100%)}$ varying from 0.85 to unity as a
function of the selected $F_2$ value for the cathode. The delivered energy is related to the average cell voltage, hence to the average OCV. The ratio, $K_4 = \frac{OCV}{OCV(\theta \text{ SOC} = 100\%)}$, is very nearly unity. Although the sulfur electrode response to pulse loads differs appreciably from its steady operation, the ratio of cell resistances, $K_5 = \frac{R_p}{R_s}$, varies with design and is seldom less than 0.8.

Using these normalizing factors, the response of a new battery can be approximated as follows:

$$E_{DEL} = (OCV = I_D R_S) \cdot C$$

$$= V_{\text{max}} \cdot K_2 \cdot K_4 \cdot C \cdot \frac{1}{T_D}$$

$$E_{DEL} = \frac{P_{AVG}}{T_D}$$

$$P_{DEL}(\text{SOC} = 0) = \frac{I_p \cdot V_{\text{MIN}}}{T_D}$$

$$= V_{\text{MAX}}^2 \left( K_2 \cdot K_3 - K_1 \right) \frac{K_1}{R_p}$$

$$P_{BAT}(\text{SOC} = 0) = V_{\text{MAX}}^2 \left( K_2 \cdot K_3 \right)^2 / 4 R_p$$

where $\frac{1}{T_D} = 1 - \left( I_D R_S / OCV \right)$ is average discharge efficiency;

$V_{\text{MAX}}$ and $V_{\text{MIN}}$ are controller voltage limits;

$R_p$, $R_s$, and $C$ are pulse and steady resistance, and capacity of the t

$T_D$ and $I_D$ are effective time and average current during motorin;

and $K_1 \ldots K_5$ are ratios defined in text.

The initial capacity of the battery must be oversized by a factor

$(1/\pi_D)$ to account for voltage losses. The peak battery power at SOC = 0 must exceed the vehicle demand by a factor $K_2^2 K_3^2 / 4 K_1 (K_2 K_3 - K_1)$ to offset the controllers' voltage range limitation. The resulting beginning-of-life goals
for the four missions are adjusted by the appropriate factors and are summarized in Table 1.3. A representative cell design for each mission is then generated. Salient features of each cell are listed in Table 1.4, along with the resulting initial battery characteristics.

1.1.2 ONE YEAR OLD BATTERY

The effect of cell deterioration and cell (electrolyte) failures on the response of the Na/S battery is strongly influenced by cell interconnection topology. Present analyses indicate a preference for several long "strings" of cells, paralleled at the battery terminals. Under these assumptions, the battery characteristics decay gracefully.

Three modes of cell deterioration are assumed: electrolyte fracture, resistance rise, and capacity decline. Present experience indicates that some failures occur with the freeze-thaw phase change, and other electrolyte failures follow a Weibull statistic. The effect of cell loss is to reduce the OCV by an amount proportional to the fraction of failed cells in the battery. (Unsymmetrically distributed failures cause temporary unbalance in string currents, but these generally average out when the cell OCV begins to fall near the end of discharge.) The effect of 1-year service (<10,000 miles/year or ~250 partial cycles) is modelled as an equivalent number of full cycles which provides the same range.

Cell performance deteriorates continuously with service with resistance and capacity worsening at an average fraction rate of $1 \times 10^{-4}$ per cycle. The present average rate and width of distribution of decay rates are projected to improve by 1990 technology (Table 1.2).
<table>
<thead>
<tr>
<th></th>
<th>I (Commuter)</th>
<th>II (Hybrid)</th>
<th>III (EV/VAN)</th>
<th>IV (Full Perf.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range (km)</td>
<td>128</td>
<td>80</td>
<td>160</td>
<td>400</td>
</tr>
<tr>
<td>Discharge Time (h)</td>
<td>2.0</td>
<td>1.25</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Charge Time (h)</td>
<td>8.0</td>
<td>8.0</td>
<td>8.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Average Power (kW)</td>
<td>6.0</td>
<td>12.0</td>
<td>8.33</td>
<td>10.0</td>
</tr>
<tr>
<td>Sustained Power* (kW)</td>
<td>12.5</td>
<td>25.0</td>
<td>25.0</td>
<td>25.0</td>
</tr>
<tr>
<td>Nominal Volts (V)</td>
<td>120</td>
<td>240</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>13.2</td>
<td>16.5</td>
<td>27.5</td>
<td>55.0</td>
</tr>
<tr>
<td>Peak Power** (kW)</td>
<td>27.9</td>
<td>55.4</td>
<td>67.1</td>
<td>56.8</td>
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</tbody>
</table>

* for 20 minutes
**at SOC = 0%
### Table 1.4. Initial Characteristics - Cells and Batteries

<table>
<thead>
<tr>
<th>Cells</th>
<th>Commuter</th>
<th>Hybrid</th>
<th>EV/VAN</th>
<th>Full Perf.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OD (cm)</strong></td>
<td>3.02</td>
<td>2.74</td>
<td>3.18</td>
<td>3.78</td>
</tr>
<tr>
<td><strong>Length (cm)</strong></td>
<td>31.9</td>
<td>29.6</td>
<td>35.4</td>
<td>35.1</td>
</tr>
<tr>
<td><strong>Weight (g)</strong></td>
<td>473</td>
<td>380</td>
<td>582</td>
<td>755</td>
</tr>
<tr>
<td><strong>Volume (cm³)</strong></td>
<td>229</td>
<td>175</td>
<td>280</td>
<td>394</td>
</tr>
<tr>
<td><strong>Capacity (Ah)</strong></td>
<td>37.8</td>
<td>23.7</td>
<td>38.4</td>
<td>77.8</td>
</tr>
<tr>
<td><strong>Energy (Wh)</strong></td>
<td>73.6</td>
<td>46.2</td>
<td>76.7</td>
<td>153</td>
</tr>
<tr>
<td><em><em>PP</em> (W)</em>*</td>
<td>155</td>
<td>154</td>
<td>186</td>
<td>158</td>
</tr>
<tr>
<td><strong>Dis. Eff. (-)</strong></td>
<td>0.943</td>
<td>0.938</td>
<td>0.968</td>
<td>0.957</td>
</tr>
<tr>
<td><em><em>Pulse Resistance</em> (m²)</em>*</td>
<td>6.36</td>
<td>6.91</td>
<td>5.30</td>
<td>5.73</td>
</tr>
<tr>
<td><strong>SE (Wh/kg)</strong></td>
<td>156</td>
<td>121</td>
<td>132</td>
<td>202</td>
</tr>
<tr>
<td><strong>ED (Wh/l)</strong></td>
<td>322</td>
<td>264</td>
<td>274</td>
<td>387</td>
</tr>
<tr>
<td>*<em>SPP</em> (W/kg)**</td>
<td>328</td>
<td>405</td>
<td>320</td>
<td>209</td>
</tr>
<tr>
<td><em><em>PPD</em> (W/l)</em>*</td>
<td>678</td>
<td>880</td>
<td>664</td>
<td>400</td>
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</table>

<table>
<thead>
<tr>
<th>Batteries</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of Cells (-)</strong></td>
<td>180</td>
<td>360</td>
<td>360</td>
<td>360</td>
</tr>
<tr>
<td><strong>OCV (SOC = 100%) (V)</strong></td>
<td>124</td>
<td>249</td>
<td>249</td>
<td>249</td>
</tr>
<tr>
<td><strong>Capacity (Ah)</strong></td>
<td>113</td>
<td>71</td>
<td>115</td>
<td>233</td>
</tr>
<tr>
<td><strong>Resistance - steady (m²)</strong></td>
<td>137</td>
<td>296</td>
<td>224</td>
<td>247</td>
</tr>
<tr>
<td><strong>Energy (kWh)</strong></td>
<td>13.3</td>
<td>16.6</td>
<td>27.7</td>
<td>54.9</td>
</tr>
<tr>
<td><em><em>PP</em> (kW)</em>*</td>
<td>27.9</td>
<td>55.4</td>
<td>67.0</td>
<td>56.8</td>
</tr>
</tbody>
</table>

*At SOC = 0%
The effect of resistance rise is determined principally by the average rise rate since long series strings average the distribution. However, capacity decline rate is established by that of the worst cell in the string. Thus a \((\bar{X} - 3\sigma)\) value is appropriate for the worst cell in a 360-cell battery. Extreme capacity loss (e.g., >20%) would be prevented (eliminated) by a maintenance operation which shorts out the cell.

The projected deterioration factors for a 1 year old "1990" battery are listed in Table 1.5, along with resulting battery characteristics for the four missions.

1.1.3 STRUCTURAL AND PACKAGING

Each cell must be electrically insulated to prevent shorting to its neighbors. Sixty-cell groups are then assembled into modules and supported by an enamelled steel enclosure. Provisions for cell interconnections, bus bar connections, heaters, and thermal control are included within the module structure. The modules are enclosed within a vacuum thermal insulation enclosure. The thermal control system and battery are supported on a tray bolted onto the vehicle frame.

The weight of the module hardware is modelled as proportional to cell weight and estimated by analogy to Ford Aerospace's CARBAT-1 experience. The weight of the thermal enclosure is scaled as the 2/3 power of battery size. Weight of the thermal control system is taken proportional to the square of sustained power which reflects the heat rejection requirements.

Estimates of the packaging requirements include: 5-mm allowance between modules and around the outside of the module pack; 3-cm allowance for internal support platforms including heating/cooling ducts; a 2.5-cm thick evacuated
### Table 1.5. Characteristics of 1-Year Old Battery

<table>
<thead>
<tr>
<th></th>
<th>I Commuter</th>
<th>II Hybrid</th>
<th>III EV/VAN</th>
<th>V Full Perf.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cumulative Range (km)</strong></td>
<td>12000</td>
<td>16000</td>
<td>16000</td>
<td>24000</td>
</tr>
<tr>
<td><strong>Equivalent Cycles (-)</strong></td>
<td>100</td>
<td>150</td>
<td>100</td>
<td>60</td>
</tr>
<tr>
<td><em><em>Deterioration Factors</em> (1990 Technology)</em>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte Failures</td>
<td>0.0033</td>
<td>0.0040</td>
<td>0.0031</td>
<td>0.0031</td>
</tr>
<tr>
<td>Resistance Rise</td>
<td>1.010</td>
<td>1.015</td>
<td>1.010</td>
<td>1.006</td>
</tr>
<tr>
<td>Capacity Decline</td>
<td>0.976</td>
<td>0.964</td>
<td>0.976</td>
<td>0.984</td>
</tr>
<tr>
<td><strong>Battery Characteristics</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of Cells (-)</td>
<td>179</td>
<td>358</td>
<td>359</td>
<td>359</td>
</tr>
<tr>
<td>OCV (SOC=100%) (V)</td>
<td>123.8</td>
<td>247.5</td>
<td>248.2</td>
<td>248.2</td>
</tr>
<tr>
<td>Capacity (Ah)</td>
<td>110.6</td>
<td>68.6</td>
<td>112.2</td>
<td>229.8</td>
</tr>
<tr>
<td>Energy (kWh)</td>
<td>12.86</td>
<td>15.90</td>
<td>26.88</td>
<td>53.91</td>
</tr>
<tr>
<td>Peak Power (SOC=0%) (kW)</td>
<td>27.47</td>
<td>54.24</td>
<td>66.14</td>
<td>56.24</td>
</tr>
<tr>
<td>Peak Power (@ V min*, SOC=0%) (kW)</td>
<td>26.98</td>
<td>53.77</td>
<td>65.01</td>
<td>54.40</td>
</tr>
<tr>
<td>Average Dis Eff. (-)</td>
<td>0.942</td>
<td>0.937</td>
<td>0.968</td>
<td>0.957</td>
</tr>
</tbody>
</table>

*Multiplicative Factor
enclosure, and a 12.5-cm long bottom superinsulating end plug which provides space for the air blowers, fuses, connecting plugs, and microprocessor-based charging control. The charger is off-board and not included in this analysis.

A summary of the weights and sizes of the battery components and for the total system is given in Table 1.6.

1.1.4 BATTERY DISCHARGE CHARACTERISTICS

For each 1-year old battery, the energy delivered at various discharge rates is calculated. These calculations are based on the "steady" resistance value and average OCV and result in a Ragone curve. The discharge characteristics are summarized in Table 1.7.

The variation in deliverable peak pulse power throughout the discharge cycle is calculated by using the batteries' pulse resistance and the voltage difference between the battery OCV and controller limit, \( V_{\text{MIN}} \), to determine maximum pulse current at the controller voltage. The results are presented in Table 1.8, and are very flat as a consequence of limiting the design depth of discharge and avoiding the normal voltage droop associated with a deeper depth of discharge.
Table 1.6. Size & Weight of Battery System

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Commuter</td>
<td>Hybrid</td>
<td>EV/VAN</td>
<td>Full Perf.</td>
</tr>
<tr>
<td><strong>60-Cell Module</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Width (cm)</td>
<td>14.4</td>
<td>13.1</td>
<td>15.1</td>
<td>17.8</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>40.3</td>
<td>36.8</td>
<td>42.2</td>
<td>49.8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>33.9</td>
<td>31.6</td>
<td>37.4</td>
<td>37.1</td>
</tr>
<tr>
<td>Volume (l)</td>
<td>19.6</td>
<td>15.2</td>
<td>23.8</td>
<td>32.8</td>
</tr>
<tr>
<td><em>Cell Wt.</em> (kg)</td>
<td>28.4</td>
<td>22.8</td>
<td>34.9</td>
<td>45.3</td>
</tr>
<tr>
<td>Total Weight (kg)</td>
<td>34.6</td>
<td>27.8</td>
<td>42.6</td>
<td>55.3</td>
</tr>
<tr>
<td><strong>Module Pack with Support &amp; Thermal Manifolds</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Module Arrangement</td>
<td>3 x 1</td>
<td>3 x 2</td>
<td>3 x 2</td>
<td>3 x 2</td>
</tr>
<tr>
<td>Width (cm)</td>
<td>45.1</td>
<td>43.0</td>
<td>48.7</td>
<td>56.7</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>42.1</td>
<td>75.0</td>
<td>86.0</td>
<td>101.0</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>36.9</td>
<td>34.6</td>
<td>40.4</td>
<td>40.1</td>
</tr>
<tr>
<td>Volume (l)</td>
<td>70.1</td>
<td>111.5</td>
<td>169.1</td>
<td>228.8</td>
</tr>
<tr>
<td>Manifold &amp; Support Tray (kg)</td>
<td>5</td>
<td>7</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Weight of Modules (kg)</td>
<td>103.9</td>
<td>116.9</td>
<td>255.6</td>
<td>331.6</td>
</tr>
<tr>
<td>Total Weight (kg)</td>
<td>109</td>
<td>174</td>
<td>266</td>
<td>345</td>
</tr>
<tr>
<td><strong>Thermal Enclosure</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer Dimensions (cm)</td>
<td>50.2</td>
<td>48.0</td>
<td>53.8</td>
<td>61.6</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>47.2</td>
<td>80.1</td>
<td>91.1</td>
<td>106.1</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>52.1</td>
<td>49.8</td>
<td>55.6</td>
<td>55.3</td>
</tr>
<tr>
<td>Volume (l)</td>
<td>124</td>
<td>192</td>
<td>272</td>
<td>362</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>21</td>
<td>28</td>
<td>35</td>
<td>42</td>
</tr>
<tr>
<td><strong>Blowers &amp; Ducts</strong> (kg)</td>
<td>5.0</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td><strong>Misc. Weight</strong> (kg)</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td><strong>Total Battery Weight (kg)</strong></td>
<td>145</td>
<td>227</td>
<td>326</td>
<td>412</td>
</tr>
<tr>
<td><strong>Total Battery Volume (l)</strong></td>
<td>124</td>
<td>192</td>
<td>272</td>
<td>362</td>
</tr>
</tbody>
</table>
### Table 1.7. Discharge Characteristics after 1-Year Service

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Specific Power (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Present</td>
<td>85.8</td>
</tr>
<tr>
<td>Commuter</td>
<td>91.5</td>
</tr>
<tr>
<td>Hybrid</td>
<td>73.1</td>
</tr>
<tr>
<td>EV/VAN</td>
<td>83.4</td>
</tr>
<tr>
<td>Full Performance</td>
<td>131.9</td>
</tr>
</tbody>
</table>

*May require increased heat exchange for prolonged operation.

### Table 1.8. Specific Pulsed Power After 1-Year Service

Limited by Controller Voltage

<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Sp. Pulsed Power (W/kg) vs State of Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOC = 80%</td>
</tr>
<tr>
<td>Present</td>
<td>122</td>
</tr>
<tr>
<td>Commuter</td>
<td>211</td>
</tr>
<tr>
<td>Hybrid</td>
<td>247</td>
</tr>
<tr>
<td>EV/VAN</td>
<td>227</td>
</tr>
<tr>
<td>Full Performance</td>
<td>167</td>
</tr>
</tbody>
</table>
2.0 COST PROJECTIONS

Funding did not permit a detailed cost analysis to be performed for this study. Estimates of OEM cost were derived by extrapolation and revision of prior (1980) costing studies that had been performed as part of Department of Energy Contract No. DE-AM04-79CH10012.

A number of modifications were incorporated into the 1980 study to generate the present estimates. These include:

a) Allowance for balance of system costs ranging from $600 to $1000
b) Use of recommended scaling factors for high production rates:
   - materials \( \sim (\text{Production Rate})^{0.9} \)
   - labor \( \sim (\text{PR})^{0.6} \)
   - capital equipment \( \sim (\text{PR})^{0.6} \)
c) The electrolyte assembly was costed at $0.015/cm\(^2\) of electrolyte surface (at 10\(^7\)/year) on the basis of purchase from a supplier, rather than internal manufacture.
d) Capitalization only for cell assembly and battery fabrication

The results of these price projections are presented in Table 2.1 which gives battery selling price to vehicle OEM manufacturers for each of the four missions. In addition, the cost of incremental cell production is estimated for each cell type. No information is listed for "present design" since it is at the first engineering prototype stage.

The conductive ceramic electrolyte is the dominant cost item in the cell, accounting for \( \sim 80\% \) of its material costs. A sensitivity analysis to the cost of electrolyte was made. For a 10% increase in electrolyte cost, the incremental cell price increased by 6% and battery price increased by 3%.
<table>
<thead>
<tr>
<th>Battery Design</th>
<th>Battery Selling Price</th>
<th>Cell Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Commuter</td>
<td>$2430.</td>
<td>$4.92</td>
</tr>
<tr>
<td>II. Hybrid</td>
<td>3128.</td>
<td>4.13</td>
</tr>
<tr>
<td>III. EV/Van</td>
<td>3802.</td>
<td>5.63</td>
</tr>
<tr>
<td>IV. Full Performance</td>
<td>4059.</td>
<td>6.13</td>
</tr>
</tbody>
</table>
3.0 TECHNICAL SUPPORT FOR PROJECTIONS

A number of improvements are under development in the laboratories of Na/S developers, or have been identified as critical needs. R&D efforts are being initiated to establish the technical base for resolution of these present shortcomings, none of which appear to be of fundamental nature.

Improvements in cell components are expected for nearly every element in the cell, especially in regard to cost reduction and quality control. Manufacturing development will overcome many present difficulties associated with lack of reproducibility. The anticipated modifications to the battery and balance-of-system components relate to engineering refinements of the structural, thermal and charge control designs. A listing of probable changes is provided in Table 3.1.
<table>
<thead>
<tr>
<th>B-30</th>
<th>ORIGINAL PAGE IS POOR QUALITY</th>
</tr>
</thead>
</table>

**Table 3-1. Technical Support for Projections**

### A. Cell

<table>
<thead>
<tr>
<th>Present Status</th>
<th>Design Change</th>
<th>Performance Change</th>
<th>Cost Change</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolyte</td>
<td>High quality Balkovski a-alumina starting powder</td>
<td>Low cost powders</td>
<td>0-20% resistance increase</td>
<td>&lt;$2/kg vs. $15/kg</td>
</tr>
<tr>
<td>Zeta processing</td>
<td>Spray dried powders</td>
<td>Thinner, lower resistance electrolytes</td>
<td>Faster, automatic green forming, eliminates calcining and bisqueing steps</td>
<td></td>
</tr>
<tr>
<td>Batch sintering</td>
<td>Continuous sintering</td>
<td>More uniform product</td>
<td>Reduced energy consumption and higher throughput</td>
<td></td>
</tr>
<tr>
<td>Manual inspection &amp; QC</td>
<td>Automated QC</td>
<td>Eliminate defective parts</td>
<td>Improved yield</td>
<td></td>
</tr>
<tr>
<td>Sodium Electrode</td>
<td>High purity sodium</td>
<td>Selective impurity control</td>
<td>Reduced touch labor</td>
<td></td>
</tr>
<tr>
<td>Sulfur Electrode</td>
<td>Rayon precursor graphite</td>
<td>Pitch based fibers</td>
<td>$1/kg vs. $10/kg</td>
<td></td>
</tr>
<tr>
<td>Positive Current Collector</td>
<td>Chromium-based corrosion protection layer</td>
<td>Improved chromium</td>
<td>$10/kg vs. $250/kg</td>
<td></td>
</tr>
<tr>
<td>Steel substrate</td>
<td>Conductive glass, oxides or other layers</td>
<td>Aluminum cladding</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>Cell Assembly</td>
<td>Manual</td>
<td>Automated</td>
<td>Reproducible product</td>
<td></td>
</tr>
<tr>
<td>Cell Characteristics</td>
<td>3% freeze-thaw failures, Fail shorted.</td>
<td>Stress relief design</td>
<td>&lt;0.3% freeze-thaw failures</td>
<td></td>
</tr>
<tr>
<td>String/Module</td>
<td>Under development</td>
<td>Modified design</td>
<td>No penalty</td>
<td></td>
</tr>
<tr>
<td>Thermal Enclosure</td>
<td>Initial units</td>
<td>Evacuated enclosure</td>
<td>Improved load share</td>
<td></td>
</tr>
<tr>
<td>Thermal Control</td>
<td>Radiation/indirect</td>
<td>Evacuated end plugs</td>
<td>Reduced deterioration rate</td>
<td></td>
</tr>
<tr>
<td>Support Structure Cells/Modules</td>
<td>Enamelled sheetmetal with insulated cells</td>
<td>Combined radiation/convection</td>
<td>Some volume increase</td>
<td></td>
</tr>
<tr>
<td>Battery/Vehicle</td>
<td>Fitted to existing vehicle</td>
<td>Reduced control power</td>
<td>150 W vs. 300 W</td>
<td></td>
</tr>
<tr>
<td>Charge Control and Monitoring</td>
<td>Many instrumentation leads</td>
<td>Status calculated from string response</td>
<td>Linde projects &lt;$300 cost</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- Battery developers are working with alumina suppliers to provide control on specific impurities in low cost powders.
- Permits high rate dry bag process.
- Adaptable to single step sinter/anneal process.
- Single furnace supports high rate production.
- Improved battery reliability by providing better component uniformity.
- Combines with automated filling & sealing.
- Eliminates occasional defective coating.
- Enamelling operation is in common commercial use.
- Permits larger cells, reduces cell wt. substantially. Concerned with long-term intermetallic diffusion.
- Requires extensive capitalization.
- Ensures good startup and maintenance of battery.
- Ensures operation of long series strings.
- Designed for periodic maintenance.
- Battery performance not critically affected by individual cell failures.
- EV requires evacuated insulation. Single location necessary to minimize heat loss.
- Heat exchange sized for sustained power.
- Design easy maintenance.
- T.B.D.
- Eliminates extraneous faults.
4.0 ENERGY BALANCE

The Na/S battery is very energy efficient during use because of 100% coulombic efficiency and good voltage efficiency during both charge and discharge. Thermal losses are minimized by incorporating the advanced evacuated insulation currently under development at Linde Division, Union Carbide Corporation. In addition, the large thermal mass and wide permissible range of operating temperature permit most of the electrical losses during operation to be retained to offset thermal losses during idle. During sustained high-power operation, heat must be rejected from the battery to restrict the temperature rise. In this mode of operation, thermal efficiency is lower; however, the thermal penalty is small compared to the energy consumption at high power. Since JPL-Driving Cycle #3 does not incorporate a sustained load, it does not apply to this study.

Calculations of energy balance throughout a 24-hour period were made for the general purpose EV/Van battery with a nominal 1500-kg test weight vehicle. For these calculations, a 1-year old battery condition is assumed. The recommended cycle, JPL Profile #3, was modified in two aspects for the energy balance calculations. The extreme high-power demand, 89 W/kg, (133 kW peak) is not real. The 4-second period was extended to 8-seconds to lower its average power to 47 W/kg, equal to the subsequent demand. Secondly, all power levels were reduced by a factor 1.5 to bring the maximum power demand down to more nearly proper levels (47 kW). Even with this reduction factor, the energy consumed per mile with regeneration is 398 Wh/mile, a value that is still about 1.4 times too large based on the Ford ETX projections. The modified profile used in these calculations is given in Table 4.1.

The thermal response of the battery is summarized in Table 4.2. The final temperature during each segment is estimated. The 17°C rise during
Table 4.1. Modified JPL Profile #3

<table>
<thead>
<tr>
<th>Segment</th>
<th>Guidelines</th>
<th>Modified</th>
<th>1500 kg Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Segment</td>
<td>Time W/kg</td>
<td>Time W/kg kW</td>
</tr>
<tr>
<td>I. 1.</td>
<td>0-26 12</td>
<td>1. 0-22 8</td>
<td>0-22 8 13</td>
</tr>
<tr>
<td></td>
<td>26-30 89</td>
<td>22-30 31</td>
<td>22-30 31 47</td>
</tr>
<tr>
<td></td>
<td>30-74 33</td>
<td>30-74 22</td>
<td>30-74 22 32</td>
</tr>
<tr>
<td></td>
<td>74-76 47</td>
<td>74-76 31</td>
<td>74-76 31 47</td>
</tr>
<tr>
<td></td>
<td>76-171 -3</td>
<td>76-171 -2</td>
<td>76-171 -2 -3</td>
</tr>
<tr>
<td>2.</td>
<td>171-196 0</td>
<td>2. 171-196 0</td>
<td>171-196 0 0</td>
</tr>
<tr>
<td></td>
<td>196-211 33</td>
<td>196-211 22</td>
<td>196-211 22 33</td>
</tr>
<tr>
<td></td>
<td>211-236 7</td>
<td>211-236 5</td>
<td>211-236 5 7</td>
</tr>
<tr>
<td></td>
<td>236-251 -10</td>
<td>236-251 -7</td>
<td>236-251 -7 -10</td>
</tr>
<tr>
<td>3.</td>
<td>Same as 2</td>
<td>3. Same as 2</td>
<td>Same as 2</td>
</tr>
<tr>
<td>4.</td>
<td>Same as 2 plus idle</td>
<td>4. Same as 2 plus idle</td>
<td>Same as 2 plus idle</td>
</tr>
</tbody>
</table>
Table 4.2. Thermal Response

<table>
<thead>
<tr>
<th></th>
<th>Temperature Variation (°C)</th>
<th>Net Heat Generation (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/Regen</td>
<td>W/O Regen</td>
</tr>
<tr>
<td>Start of Drive</td>
<td>To</td>
<td>To</td>
</tr>
<tr>
<td>End of Segment 1</td>
<td>To +17.39</td>
<td>To +17.30</td>
</tr>
<tr>
<td>2</td>
<td>To -7.43</td>
<td>To -7.52</td>
</tr>
<tr>
<td>3</td>
<td>To +9.96</td>
<td>To +9.77</td>
</tr>
<tr>
<td>4</td>
<td>To -4.14</td>
<td>To -4.33</td>
</tr>
<tr>
<td>5</td>
<td>requires supplemental heat</td>
<td></td>
</tr>
</tbody>
</table>

Battery Heat Capacity ~59.7 Wh/°C

Battery Heat Loss Rate ~160 Watts

Required Supplemental Heat

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Regen</td>
<td>1820 Wh</td>
</tr>
<tr>
<td>W/O Regen</td>
<td>1870 Wh</td>
</tr>
</tbody>
</table>
the morning use is well within the acceptable operating range. No blower power is required. For this drive cycle, no heating or cooling is required during the daytime. About 2 kWh is required overnight to restore the battery temperature.

Calculations of the electrical battery parameters, with and without regeneration, are summarized in Table 4.3. The average electrical discharge efficiency is high, even with the peaked driving cycle. Because daily range is small, the Na/S battery operates on its voltage plateau at a high state of charge which also is the region of low entropy. The overall daily efficiency, including thermal makeup energy, is about 75%. These data are transcribed onto the guideline format in Table 4.4.
### Table 4.3. 24-Hour Energy Balance

<table>
<thead>
<tr>
<th>Segment I</th>
<th>Energy At Terminals (Wh)</th>
<th>Capacity (Ah)</th>
<th>Average Efficiency (%)</th>
<th>Heat Generation (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Regen</td>
<td>5774</td>
<td>27.32</td>
<td>85.1</td>
<td>1156</td>
</tr>
<tr>
<td>W/O Regen</td>
<td>6990</td>
<td>32.11</td>
<td>87.7</td>
<td>1151</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Recharge</th>
<th>Energy kWh</th>
<th>kWh</th>
<th>Efficiency (%)</th>
<th>Heat Generation (Wh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Regen</td>
<td>13642</td>
<td>54.64</td>
<td>99.3</td>
<td>-292</td>
</tr>
<tr>
<td>W/O Regen</td>
<td>16050</td>
<td>64.22</td>
<td>99.3</td>
<td>-332</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overall Cycle</th>
<th>Disch Energy kWh</th>
<th>Chg Energy kWh</th>
<th>DC-DC Efficiency (%)</th>
<th>Thermal Makeup kWh</th>
<th>Overall Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/Regen</td>
<td>11.55</td>
<td>13.64</td>
<td>84.7</td>
<td>1.82</td>
<td>74.7</td>
</tr>
<tr>
<td>W/O Regen</td>
<td>13.98</td>
<td>16.05</td>
<td>87.1</td>
<td>1.87</td>
<td>78.0</td>
</tr>
</tbody>
</table>
Table 4.4. Estimates of In-Use Energy Consumption

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Startup &amp; shutdown</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Self Discharge</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Shunt Current</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Parasitics</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Thermal Loss W/0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.82</td>
</tr>
<tr>
<td></td>
<td>W/O</td>
<td></td>
<td></td>
<td></td>
<td>1.87</td>
</tr>
<tr>
<td>Delivered Energy W</td>
<td>5.77</td>
<td>-</td>
<td>5.77</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>W/O</td>
<td>6.99</td>
<td>-</td>
<td>6.99</td>
<td>-</td>
</tr>
<tr>
<td>Recharge Energy W</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>13.64</td>
</tr>
<tr>
<td></td>
<td>W/O</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16.05</td>
</tr>
<tr>
<td>Charge Eff* (%) W</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>.993</td>
</tr>
<tr>
<td></td>
<td>W/O</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>.993</td>
</tr>
</tbody>
</table>

*Uses Standard Charger
5.0 LIFE CONSIDERATIONS

The service life of an EV battery is dominated by the failure modes and deterioration rates of individual cells. Some of these factors were discussed in Section 1.1.2. The selected cell interconnection topology, control strategy and maintenance procedure generally reduce the influence of cell degradation on battery response. However, certain cell failure modes could be enhanced by the battery configuration and lead to worsened life statistics for the battery than for the cell.

At this point in technology development, system reliability is one of the principal active areas of analysis. Response to the following topics is mostly qualitative and tentative.

5.1 PRESENT LIFE STATUS

Cell durability is affected by electrical operating conditions, mechanical abuse and design features in addition to the manufacturing variables. Although several thousands of cells have been tested, actual life data from carefully controlled tests are meager. Few modules have been evaluated, and only one full size EV battery has been fabricated for test.

5.1.1 CELL LIFE

For a population of 384 load-leveling cells operating about 5 cycles per week, the failure statistics give fair fit to a Weibull curve with $\alpha = 1400$ days (~1000 cycles), $\beta = 2.0$ [Ref. 1]. This on-going test began in January 1981 and has progressed to a condition in which about 20% of the cells have failed. A previous 20-cell test (circa 1980) of load-leveling cells gave a similar time projection with a shape factor near unity.

We have not undertaken a statistically significant test to determine life of our EV cells. Although many have been on test for considerable time, the test conditions are frequently varied to explore response to other variables.
The longest cycle life of an EV cell presently on test is 1100 cycles, 16 months.

The effect of depth of discharge on cell life appears minor, although excessive overdischarge is likely to damage the cell. The life limiting mechanisms were discussed in Section 1.1.2.

5.1.2 MODULE AND BATTERY LIFE CONSIDERATIONS

Many concept strategies for cell interconnection and battery maintenance are being analyzed. No thorough validation of models or optimization of design exists to date.

5.2 PROJECTED LIFE IMPROVEMENTS

The planned approach to attain improved cell life consists of incorporating more manufacturing QC with more extensive NDE, coupled with continued basic R&D efforts to identify causes of cell failure. Control of specific impurities and defects could extend life significantly and be cost effective.

A list of expected technical improvements within the cell was presented in Section 3. These improvements apply to cells of either high-power or high-energy designs.

5.3 PERFORMANCE DETERIORATION

The basic effects of resistance rise, capacity decline and cell failure during life were described in Section 1.1.2. Initial response is expected to show a linear decrease in all battery performance parameters with cycling. The linear resistance rise model produces a corresponding linear fall in peak power capability. The linearly modelled capacity decline produces a linear drop in energy. Since the efficiency is high under steady loads, the interaction of increased resistance with lower capacity does not cause further reduction in energy.
As the battery ages significantly, cell failures become more frequent. The accelerating rate of cell failures causes the battery voltage to drop at an increasing rate. Energy varies about linearly with voltage, although efficiency also begins to fall. Most significantly, the peak power delivered at the controller's minimum voltage drops quickly. The peak current is determined by the voltage spread between battery OCV and the controller $V_{\text{MIN}}$. Since $V_{\text{MIN}}$ is greater than half of the initial voltage, the fractional loss of peak current is more than twice the fractional loss of cells.

An illustration of the decrease of battery performance over the early portion of life including the first maintenance operation is given in Table 5.1. In this example, the battery designed for the general purpose EV/Van mission is assumed, along with the assumptions listed in Table 1.2 for deterioration and failure rates of cells.

5.4 RELIABILITY

At present, the battery is imagined to consist of six 60-cell modules for purposes of packaging and support. However, it is assumed that individual cells can be replaced during a "cool-down" repair.

As seen in the previous example of battery aging, Table 5.1, the time-to-first-repair is long but the time between failures becomes much shorter as the battery ages. A crude estimate of a possible repair schedule calls for replacement of about 15 cells after 5, 6¼, 7¼, 8¼, 9, and 9½ years. This schedule suggests replacement of ¼1/4 of the cells to obtain a 10-year battery.
### Table 5.1. Deterioration of Battery Performance

<table>
<thead>
<tr>
<th>In Service Years</th>
<th>Cycles</th>
<th>Deterioration Factors</th>
<th>Battery Output</th>
<th>Energy @ 8.33 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No. of Good Cells</td>
<td>Resistance Factor</td>
<td>Capacity Factor</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>359</td>
<td>0.997</td>
<td>1.0</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>359</td>
<td>1.008</td>
<td>0.9757</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td>358</td>
<td>0.992</td>
<td>0.9514</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>356</td>
<td>1.021</td>
<td>0.9272</td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td>352</td>
<td>1.022</td>
<td>0.9029</td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>345</td>
<td>1.017</td>
<td>0.8786</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Repaired - Replaced 15 Cells</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>500</td>
<td>359</td>
<td>1.046</td>
<td>0.8895</td>
</tr>
<tr>
<td>6</td>
<td>600</td>
<td>350</td>
<td>1.035</td>
<td>0.8674</td>
</tr>
</tbody>
</table>
6.0 OTHER OPERATIONAL CHARACTERISTICS

The sodium-sulfur battery has a number of distinctive operating characteristics. Many of these are incompletely characterized or are significantly affected by details of design. The following responses are provided based on our present preferred cell interconnection topology and state-of-art cell design.

6.1 SPECIAL CHARGE REQUIREMENTS

Special charge control requirements are discussed below.

6.1.1 OVERCHARGE OR OVERDISCHARGE EFFECTS

At the end of charge, the cell exhibits a high polarization related to loss of electrochemically active area. As the available polysulfide (Na$_2$S$_5$) decreases and is replaced by insulating sulfur, the charging current is focused onto smaller areas of the electrolyte. Current densities can become large, and gradients of current density can become extremely high. Ultimately, cell voltage rises until limited by the power source or until the electrolyte fractures.

At rated current, the cells normally withstand ~5 V repeatedly without failure. At low currents (1/10 rated), most cells withstand 10 V and frequently withstand 20 V without apparent damage. All electrolytes have been failed by 40 V.

Following electrolyte fracture, cell failure goes to completion in a benign mode as a consequence of the safety devices incorporated into the sodium reservoir. A possible exception occurs if the conditions prior to failure have caused excessive cell heating, and fracture occurs when the cell is already above about 450°C. Cell rupture then becomes possible.

Overdischarge of a cell with excess sodium causes the polysulfide to solidify (Na$_2$S$_2$) and either rupture the casing due to expansion, or develop high internal resistance with accompanying voltage reversal and copious heat.
generation. Overdischarge of a cell with limited sodium leads to a loss of active anode area, high current densities and extreme gradients of current density.

These characteristics are not well quantified. Most cells withstand overdischarge to below 1 V. Not many cells survive voltage reversal at rated current. Following voltage reversal failure, completion of cell failure is generally benign.

6.1.2 CELL BALANCING REQUIREMENTS

With long series string connections, it is not necessary to adjust the individual cells' SOC since each functional cell is 0.99999 faradaic. Should a cell become nonfaradaic due to electrolyte deterioration, that cell is expected to be driven to failure by becoming out of balance, hence overdischarged.

6.1.3 PERIODIC DISCHARGE REQUIREMENTS

Sodium-sulfur cells do not require complete discharge cycles.

6.1.4 EQUALIZING REQUIREMENTS

As discussed above in Section 6.1.2, each string does not require internal equalization. As cell failures occur and strings become unbalanced, the ability to recharge each string to equal SOCs depends on the charging algorithm. A moderate duration of taper charge could be required each cycle to restore full capacity. This taper period is easily contained within the 8-h recharge time allotment.

6.2 MAINTENANCE REQUIREMENTS

Some maintenance options are discussed below.

6.2.1 REGULAR MAINTENANCE

Ford Aerospace has limited experience in operation of full-scale batteries. Conceptual maintenance strategies have been generated but not validated.
A plausible strategy is described below. With a 10% initial margin in battery performance, a significant number of cell failures can occur before performance falls below specifications. Deterioration is graceful. Maintenance can be scheduled at operator's convenience. During a 1-day repair, the battery would be cooled, and most defective cells replaced (perhaps cell packs or modules would be substituted and then restored ex situ). The interval between such required maintenance operations would be large at first and then shorten near end-of-life. Maintenance should not be more frequent than 6 months.

Between scheduled repairs, occasional brief maintenance could become necessary if a cell fails "open" and blocks its string current. This repair, at temperature, involves shorting out the defective cell and could be accomplished quickly if access into the thermal enclosure is provided.

6.2.2 REFURBISHMENT OPTIONS

A number of options for refurbishment have been proposed. The practicality of any of these will likely be determined by the state of health of the remaining "good" cells, and the characteristics of the cells after the refurbishment function. Some preliminary experience at Ford Aerospace is encouraging. The cost benefits of such refurbishment cannot be estimated at this time.
7.0 PACKAGING FLEXIBILITY

The sodium-sulfur battery offers good energy density provided that the system can be packaged into a single volume with reasonable aspect ratios.

7.1 VOLUME REQUIREMENTS

For the design developed for each mission in Section 1, the resulting battery volumes are listed in Table 7.1.

Table 7.1. Volume Requirements

<table>
<thead>
<tr>
<th>Mission</th>
<th>Volume</th>
<th>ED*</th>
<th>PD*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Present</td>
<td>285 (l)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2. Commuter</td>
<td>124 (l)</td>
<td>103</td>
<td>216</td>
</tr>
<tr>
<td>3. Hybrid</td>
<td>192 (l)</td>
<td>82</td>
<td>279</td>
</tr>
<tr>
<td>4. EV or Van</td>
<td>272 (l)</td>
<td>98</td>
<td>239</td>
</tr>
<tr>
<td>5. Full Performance</td>
<td>362 (l)</td>
<td>148</td>
<td>150</td>
</tr>
</tbody>
</table>

*After 1 year service

7.2 SIZE LIMITATIONS

There is no absolute limit to cell dimensions. Present technology is based on "single-electrolyte tube" cells. To maximize active area (power) per unit seal perimeter, cell length is usually extended toward maximum manufacturability limits. At short lengths, SE, ED, and cost per unit performance are degraded because of the relatively large weight of the seals and ends and reduced energy per cell. At present, a "soft" limit of about 20 cm length applies to EV applications. Advanced cell concepts (e.g., multitube) would permit shorter cells to be developed which retain good performance characteristics.

7.3 PLACEMENT OF AUXILIARIES

Sodium-sulfur cells are self-contained and do not require external storage, pumps or crystalizers. All components are enclosed within a single thermal enclosure, except for the thermal control system and battery disconnects.
The air blower and ducting must be located near the battery and have access to the outside (preferably underneath) of the vehicle to exhaust the high-temperature air when cooling is required. The battery disconnect devices are to be mounted near the enclosure to minimize copper losses.

7.4 SCALE EFFECTS

A major feature of Na/S cells is that power and energy are separately adjustable by design of the cathode and electrolyte. The resulting scale effects for a battery are determined by both the power and energy levels.

7.4.1 SCALING FACTORS FOR FIXED P/E RATIO

When the specified power-to-energy ratio remains fixed while the size of the battery is varied, the individual cell design remains fixed. The number of cells would be varied to meet the battery output. With a smaller battery-core, the thermal enclosure and auxiliaries are reduced, but their weights and volumes do not decrease in proportion to the energy or power. Hence the resultant specific energy and energy density are degraded as size is reduced.

An example of the scaling factor effects was generated by using the commuter mission battery as base design and comparing it to 2X and 4X designs. The results are indicated in Table 7.2.

<table>
<thead>
<tr>
<th></th>
<th>25 kW/12 kWh</th>
<th>50 kW/24 kWh</th>
<th>100 kW/48 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE (Wh/kg)</td>
<td>88.2</td>
<td>91.4</td>
<td>99.9</td>
</tr>
<tr>
<td>ED (Wh/l)</td>
<td>103</td>
<td>110</td>
<td>116</td>
</tr>
<tr>
<td>( T_D ) (h)</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

7.4.1 SCALING FACTORS AT FIXED POWER

When power is fixed, the area of electrolyte is about constant. Additional energy is incorporated into the cell by increasing the reactant volumes and weights. To utilize the additional energy at fixed power, discharge time must be increased accordingly.
An example of the scaling factors applicable to this case was generated by taking the EV/Van battery design as base, and comparing to half-energy and double-energy batteries at fixed power. The resultant effects on SE and ED are indicated in Table 7.3.

Table 7.3. Scale Factors at Constant Power

<table>
<thead>
<tr>
<th></th>
<th>60 kW/12.5 kWh</th>
<th>60 kW/25 kWh</th>
<th>60 kW/50 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>SE (Wh/kg)</td>
<td>55.5</td>
<td>82.7</td>
<td>116.0</td>
</tr>
<tr>
<td>ED (Wh/l)</td>
<td>65.1</td>
<td>99.0</td>
<td>137.3</td>
</tr>
<tr>
<td>T_D (h)</td>
<td>1.5</td>
<td>3.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

References

APPENDIX I

CONTRACTOR RESPONSE: ALUMINUM-AIR BATTERY
and
ALUMINUM-AIR POWER CELL
RESEARCH AND DEVELOPMENT
PROGRESS REPORT
CONTRACTOR RESPONSE: ALUMINUM-AIR BATTERY 

by 
John F. Cooper

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March 24, 1984


RESPONSE TO QUESTIONNAIRE

1. Performance Modelling

(a) Performance modelling is based on an equation interrelating battery weight ($W_b$, kg), peak sustainable power ($P$, kW), and peak energy yield ($E$, kWh):

$$W_b = 36(P/p) + 3.5 (E/e)$$

where $p$ is the peak power density ($\text{kW/m}^2$ of cell area) and $e$ is the peak gross energy yield of aluminum ($\text{kWh/kg-Al}$). The coefficients depend on the choice of scale ratios ($P/p = \text{electrode area}$; and $E/e = \text{aluminum}$). The values of the coefficients are derived by dividing the components of a battery into those which scale according to electrode area, and those which scale according to aluminum fuel mass. In Table 1.1 below, component weights are given for (arbitrary) $E = 70 \text{ kWh}$, $P = 31 \text{ kW}$, $e = 5 \text{ kWh/kg}$ and $p = 7 \text{ kW/m}^2$.

Table 1.1

<table>
<thead>
<tr>
<th>Component</th>
<th>Basis</th>
<th>Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Cells</td>
<td>M3 cell design; 1.1 g/cm$^2$; $p = 7 \text{ kW/m}^2$</td>
<td>49</td>
</tr>
<tr>
<td>2. Cyclones</td>
<td>Krebs PC-1; cast in PVC</td>
<td>2</td>
</tr>
<tr>
<td>3. Electrolyte</td>
<td>Crystallizer and cyclone circuit</td>
<td>21</td>
</tr>
<tr>
<td>4. Seed charge</td>
<td>Cell circuit and manifolding</td>
<td>14</td>
</tr>
<tr>
<td>6. Wedge</td>
<td>$30^\circ$ wedge angle</td>
<td>26</td>
</tr>
<tr>
<td>6. Misc.</td>
<td>case, impellers, air-pretreatment, drive motor and start-up battery</td>
<td>30</td>
</tr>
<tr>
<td>7. Aluminum</td>
<td>plates; 5 kWh/kg-Al</td>
<td>14</td>
</tr>
<tr>
<td>8. Water</td>
<td>for reaction and evaporation losses</td>
<td>32</td>
</tr>
<tr>
<td>9. Tankage</td>
<td>water, electrolyte, Al(OH)$_3$</td>
<td>3</td>
</tr>
</tbody>
</table>

Total 209
The first six entries are treated as being proportional to electrode area (P/p); the last three are proportional to aluminum fuel mass (E/e). P and E should not be confused with the integrated energy or power delivered as these quantities depend on drive cycle. However, peak gross and net power yields are the same, as the auxiliary battery provides pumping energy during peak excursions. Net energy yield is equal to 96% of gross energy yield.

Best electrode combinations and cell dimensions indicate a peak energy $e = 4.4$ kWh/kg-Al and a peak power $p = 6.5$ kW/m$^2$ at temperatures of 60-70°C. These values are derived from the polarizations of best electrodes and thin interelectrode gaps. Current electrode research is motivated by the possibility of improvements to $e = 6.0$ kWh/kg-Al and $p = 9$ kW/m$^2$. The latter values may be taken as a difficult but potentially achievable goal, combining successes in anode alloy and air-electrode research with advances in cell design. The former values are those used by Behrin et al. (Design Analysis of an Aluminum-Air Battery for Vehicle Operations; Final report to OVERU; UCRL-53382; March 1983), and are the basis for the present calculation. The latter were revised this year, and are the basis for projections for the full-performance electric vehicle in the 1990's time frame. These values are summarized below.

Table 1.2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Present</th>
<th>Full Perf. EV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak-energy yield of Al</td>
<td>4.4</td>
<td>6.5 kWh/kg</td>
</tr>
<tr>
<td>Peak sustainable surface power</td>
<td>6.5</td>
<td>9 kW/m$^2$</td>
</tr>
<tr>
<td>Open circuit corrosion</td>
<td>0.12</td>
<td>0.01 kA/m$^2$</td>
</tr>
</tbody>
</table>

Table 1.3

Data for Question 1. Battery weights, peak power, and power characteristics for $E = 50$ kWh and $P = 50$ kW.

<table>
<thead>
<tr>
<th>$W_b$ (kg)</th>
<th>Peak Power (W/kg)</th>
<th>Specific energy (Wh/kg) vs Rate (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>317</td>
<td>157 20 60 80 100 157 200 218</td>
</tr>
<tr>
<td>5. Full Perf. EV</td>
<td>229</td>
<td>218 204 196 192 -- 164 145</td>
</tr>
</tbody>
</table>

(b) The 30-second peak specific power capability is independent of the state of charge (i.e., remaining quantity of limiting reactant, aluminum or water). Consistent with current cell and electrode technologies, the peak power is associated with 6.5 kW/m$^2$, and is not decreased by system operation power which is delivered by the auxiliary battery (under peak power conditions only.) Full-performance is consistent with 9 kW/m$^2$. 

I-4
2. Cost Projections

Manufacturing cost of an aluminum-air battery designed for Al-air-only (i.e., non-hybrid) vehicles is estimated to be approximately $32/kW-peak-sustainable-power, for "present" characteristics (6.5 kW/m²). The cost scales with peak power rating, and should become 23 $/kW-peak-power if the Full-Performance value, 9 kW/m² is achieved in practical cells. (That is to say, nearly all battery components scale with electrode area, which is inversely proportional to peak power density.) The cost assumes present battery characteristics as described in the report, "Design Analysis of an Aluminum-Air Battery for Vehicle Operations," E. Behrin, et al., LLNL Report UCRL-53382, March 18, 1983 (Final report of work undertaken for OVERD).

Although design specifics and electrode performance objectives have changed radically since publication Benrin's report, such changes have resulted in simplification of battery subsystems. Specifically, the sealed parallel-plate cell-stack design described in the report has been replaced by the gravity-fed wedge-cells which have no flexing or moving mechanical parts and are unpressurized. The rotating drum filter/separator has been replaced by a single stationary vessel equipped with hydrocyclone separators of commercially-available designs. The essential operating characteristics of wedge cells and hydrocyclones have been verified experimentally and are reported in UCRL-90465.

3. Technical Support for Projections.

Discussion on Cost Projections and Electrode Improvements

Electrode performance estimates. (See also answers to questions 2 and 3, below.) The cost of any fuel cell is generally proportional to the surface area of the cathode and inversely proportional to the surface power density of the cell. Power densities in excess of 10 kW/m² have been achieved using unalloyed aluminum and air-depolarized electrodes in cells tested at Hoppeka Battery Company (Brilon, West Germany) at high temperatures (800°C or above) in the more conductive KOH solutions.

The "present" open circuit corrosion is routinely achieved with unalloyed aluminum; and also with certain alloys developed on a proprietary basis for Eltech Systems by OSU. The "EV" value for open circuit corrosion has been approached with the use of a NaCN corrosion inhibitor (0.01 M NaCN, 4M NaOH, T=40°C) in combination with certain alloys; here o.c. corrosion was 2 mA/cm² and fell below the limit of detection (ca. 0.5 mA/cm²) at -1.6 V vs Hg/HgO; this result and homologous compositions may be patentable and should not be disclosed.

Life-cycle advances in the air electrodes catalyzed with macrocyclic catalysts were reported in UCRL-90455; currently drive-cycle life stands at about 1500 cold startups, an increase by an order of magnitude since the start of the program. Aluminate and aluminum-trihydroxide have been found to be catalysts for peroxide decomposition. Parallel tests in electrolytes bearing aluminate and pure caustic electrolytes indicated longer lives in the former. We believe that 3000 drive cycles (4 year road life) might be a reasonable goal; however, current attention at Eltech Systems, Inc. is focused not on extension of cycle life but on developing continuous processes for cathode mass production.
The standard drive cycle life consists of a series of constant-current plateaus between \(1\) and \(6 \, \text{A/m}^2\) followed by standby at open circuit. Drive-cycles are designed to imitate a typical trip, 750 of which are covered in single year. Failure is associated with processes occurring within the first hour of shut down and hold on open circuit. The deterioration is associated with a loss of catalytic activity, possibly the result of corrosion and isolation of carbon particles. The process apparently is self-inhibiting, and does not continue beyond the first hours of standby. Life extension is being sought through the use of corrosion-resistant carbons, heavier loadings of macromolecular catalysts, self-regenerating catalysts (e.g., sparingly-soluble catalysts), improved wet-proofing agents, and improved mechanical support of the carbon-Teflon matrix.

Beyond any doubt, the area of greatest potential improvement is that of the anode-alloy/electrolyte/operating-temperature combination. With the exception of work performed by Reynolds under subcontract to LLNL, almost no research has been undertaken under DOE sponsorship. This area is being actively pursued by privately-sponsored projects by Eltech (at OSU); Alcan, Ltd. (ca. $1M/y); at Atlantic Richfield (Harvey, IL), ca. $300K/y; and at General Motors (Warren, MI), undisclosed level. A small research program is believed to be conducted at South African National Research Center.

Generic approaches to the modification of energy yield and power include:

1. **Vacancy injection or lattice modifications.** Use of trace (100 ppm) loadings of di-similar-valence metals (Si, V, Ga) to alter the vacancy concentration in either the metal or oxide sublattice of the anodic surface film; hence alteration of the resistance of the film to the mobile ion (either Al or O). Broad classes of lattice expanders or "lattice contractors" have been identified and discussed in the literature; these effect changes in mobility of the aluminum or oxidic species.

2. **Selective inhibition of the water-reduction reaction.** Use of metal-phase or electrolyte-phase poisons for the water-reduction mechanism responsible for hydrogen evolution. Examples here include Sn, CN, P, Tl, and Pb. Often these materials tend to deposit on grain boundaries or inclusions having low overpotentials for \(\text{H}_2\) evolution.

3. **Complexing or segregation of undesirable materials.** Certain materials are used to segregate undesirable impurities common to low-cost smelter-grade aluminum. For example, Mn is used to form intermetallic clusters of Mn, Fe, and Al, which have greatly reduced activities from the standpoint of water reduction. The alloy developed by Reynolds was found to yield 85% of the energy of RX808, yet cost essentially the same as 5A base smelter metal. (See UCRL-90465.)

4. **Alteration of thick surface layers.** The addition of Mg to the alloy has an indirect by profound effect on coulombic efficiency. Surface layers of insoluble, loosely-adherent MgO may entrap electrolyte and create a local electrolyte composition different from that of the bulk. Gallium may effect a reduction in anode surface film adherence. The combination of Mg and Ga is responsible for the high surface power density and coulombic efficiency of RX808. This is currently under investigation by Eltech under subcontract at OSU.
(5) Use of high purity metals. Iron, being deleterious to coulombic efficiency, can be largely removed from Hall-Cell metal through control of coke, alumina, cell lining, and plant practices. (For example, a iron pick is used to break the cryolyte crust each time alumina is added to the cell; it readily dissolves in the melt.) Reynolds assessed the increase of cost associated with achieving 0.04% Fe levels; results are reported in UCRL-90465.

Production of high purity Hall cell metal may be unnecessary. Current processes exist for the partial crystallization of highly pure metal from a molten stream combining the separate outputs from a large array of Hall cells. This "single pass zone refining" might be used to produce highly pure metal for battery fuel applications as a byproduct of a large plant. Currently there is very little market for high purity aluminum other than experimental uses or "sweeteners" for certain aircraft alloys.

Advanced processes for aluminum production (likely to be introduced within the early 1990's) do not have the same impurities or levels of impurities associated with Hall Smelter. The Alcoa Smelting Process utilizes a vapor-phase separation of AlCl₃, and uses no dissolving iron parts; the process incidently consumes only 8.3 kWh/kg-Al. The Mitsui carbothermic reduction process, now in pilot investigations, distills Al from a Al/Pb melt used to extract the metal from alumina/carbon brickets. The iron content is well below that of common smelter-grade aluminum.

In all, it should not be assumed a priori that a cheap aluminum alloy must be based on metal of current commercial purities.

(6) Alterations of electrolyte composition and operating temperature. One-half of the resistance of the aluminum-air cell (3.2 mm spacing) is associated with resistance of the NaOH electrolyte in the interelectrode gap. Electrolytes of higher conductivity (KOH or KOH/NaOH) are being investigated, together with interelectrode gaps below 2 mm to decrease this loss. Cell power increases by 20% per 10 °C increase in temperature—as expected for an electrolyte resistance. Increase of operating temperature from 60 to 80 °C should increase surface power density from typical values of 6 kW/m² to nearly 9 kW/m², when electrolyte resistance and electrode polarizations are taken into account. The limiting factor in temperature increase is water-reduction rate, which also shows an Arrhenius dependence on temperature. The reader is reminded that advances in coulombic efficiency have their primary benefit, not in increased energy yield (coulombic efficiencies are generally above 90%), but in increased power density.

Anode research will receive the major emphasis following successful operation of full-scale, integrated batteries (five-cell modules) at the end of the current calendar year. Alcan has reported to us the existence of a number of new alloys of performance superior to either pure aluminum or 6061 models, including new classes of alloys not requiring electrolyte corrosion inhibitors. A cell operating at 2 V is claimed. This work is not done under DoE auspices and exact compositions were not disclosed to us. Hence, I am unable to independently confirm these claims, although I have no reason to believe that they are exaggerated.

Component Improvements. The use of hydrocyclones of advanced design has resulted in a major simplification of battery design as well as cost reductions. The hydrocyclones were developed by Krebs Engineers for
industrial applications. The units tested in our laboratory with the experiments on integrated cells and crystallizers feature involute-spiral entrance chambers which greatly increases operating efficiency. Two or three units would consume about 1% of gross battery power output; power consumption can be further reduced by placing cyclones in series to stage the particle separation.

Air Electrode Cassettes. The use of air-electrode cassettes which are individually removable and replaceable relax quality control constraints on the air electrodes. Incipient failure or deterioration can be detected, and the electrode may be replaced without loss of the stack. (This is not practical with fuel cells because of the 5-6-fold increase in gas-diffusion electrode area per unit of gross power, and the corresponding increase in the weight of the supporting cassettes.)

Air electrode cost projections of $100/m² assuming large scale production and semi-automated continuous fabrication processes (replacing current small-scale batch processes) and non-precious metal catalysts. This goal is consistent with those of many air-electrode developers. The cost includes a stamped or injection-molded polypropylene holder (cassette). Note that the replaceable unit does not necessarily include electrolyte manifolding as in the Reference Cells. Solution side current collectors need not be replaced along with the cassettes and are expected to last the life of the vehicle.

4. Energy Balance

Startup and shut-down. Current approach to shut down involves draining electrolyte from the cells into the crystallizer, followed evaporation of electrolyte adhering to the anodes. Using the latent heat of the anode mass, this is accomplished in a few seconds. Tests on 50-cm² cells show that the loss approaches a steady-state value of 1.2 g/m²-shutdown. For e = 4.4 kWn/kg, p = 6.5 kW/m² and 730 shutdowns per year, this constitutes a loss of 29 kWh/year; or 40 Wh per shutdown for segments 2 and 4. For e = 0 kWn/kg and p = 9 kW/m², the loss per shutdown is also about 40 Wh. This effect is certainly dependent on alloy composition and electrolyte composition, and passivation of the aluminum cannot a priori be expected to occur. It will be difficult to satisfy this constraint while achieving the high energy yield and high power density levels. Nevertheless flash evaporation and induced passivation is one of the constraints that should be observed in our alloy development project.

Shunt currents are generally not a problem as we are not concerned with redistribution of metal upon prolonged cycling. The resistance of the electrolyte paths between adjacent cells is currently on the order of 6 ohms, and could be reduced further; cell-cell voltage difference is about 1.6 V; current delivered per cell is 120 A. Therefore loss is about 0.2%.

Parasitic losses are associated with the hydrogen evolution reaction. For model electrodes this ranges from 2-25 mA/cm² on open circuit and falls off with increasing current density. Segments 1-3 contain 25 s each of standby, resulting in losses of 1.5-19 Wh/segment, for EV and present calculations. Segment 4 contains 50 s standby, resulting in a loss of 3-36 Wh/segment for EV and present calculations.

Self-discharge. (Answered separately under parasitic and shut-down categories).
Thermal loss. N/A under specified operating conditions and cycles.

Charge efficiency. N/A

5. Life Considerations

As anodes are intended to last only one cycle, life cycle is limited by cathode failure. Current life cycles of 1500 have been achieved, and actual life may be longer: the most recent tests failed because of computer malfunction, not cathode failure. Very little statistical data is available as identical electrodes have been tested in insufficient numbers.

Polypropylene is indefinitely stable in caustic aluminate. PVC is effectively stable as well, and can be extended with alumina.

I am not too concerned that scale formation will be a serious problem in this battery, although we are currently planning experiments to investigated this. If growth mechanisms apply to the development of scale on the inside of the crystallizer, the mass of the scale cannot be more than the annual throughput of hydargillite (ca. 1500 kg) multiplied by the ratio of vessel surface area to seed-surface area (1 m²/1500 m²), which indicates a film growth of 0.4 mm/year; this is trivial. While scale formation may entail agglomeration or porous material at an order of magnitude higher rates, our colleagues at Alcoa and more recently at Alcan, Ltd. tell us that convection, vibration (flexing of walls) and non-stick walls reduce scale formation or adhesion. Coating critical parts (valves and impellers) with Teflon may be necessary. An ice-cream scrapper may be useful in the crystallizer vessel.

Again, air electrode cassettes which form the body of the cell in contact with electrolyte are designed to be individually replaced upon failure or malfunction. Electrolyte residence is to brief in the cells given normal driving patterns for scale buildup to be a problem. We do not expect solution-side current collectors to constitute a failure mechanism, as these are cathodically protected by the aluminum. Pumps and valves are the likely sites of failures.

6. Other Operational Characteristics

(a). Special charge requirements. Over-discharge results in a gradual, non-destructive loss of power. This would be accompanied by the gradual withdrawal anode wedge into the cell. As the anode falls at a rate of about 1.2 micrometers/s at cruise velocities, one would travel 140 miles per cm of fall, accompanied by an 8% loss of power.

Cell equalizing will be required at a frequency which we cannot now estimate. This is accomplished by adding fuel plates of different heights to the various cells. The cells share a common electrolyte through exchange with the crystallizer; hence no individual balancing is required.

Periodic complete discharge is not required.

(b). Maintenance. Refueling is to be accomplished by tap water additions (250 miles) and aluminum additions (at frequencies of 100-3000 miles) by the vehicle owner in his own garage. Aluminum fuel plates could also be vended by machines or service stations. Cells are designed for refueling by adding
plates of appropriate height to a dry chamber above the cell; the wedge is not disturbed by this operation, nor is contact to be expected with electrolyte or electrolyte-wetted components. Hydrargillite withdrawals at frequencies of 250-500 miles are required. The hydrargillite is in water-washed, drained form. Again this may be done either in the owner's garage or at central stations (in a manner commercially analogous to collection of aluminum cans). In the long range, service stations might compete with owner servicing.

Battery refurbishment has not been explored. Possibility of refurbishing the air electrodes by doping with a sparingly soluble macrocyclic catalyst has been discussed. We do not regard this issue as premature.

7. Packaging Flexibility

Overall specific gravity is about 0.6. Nevertheless we do not consider volume to be a limiting factor for three reasons.

(1) Much of the volume of the battery is in the form of water and product tankage, which can be shaped to fit the contours and placed in parts of the vehicle not normally used (e.g., doors, underpan spaces, structural tubes, spaces under the seat, etc.). Without any special care, Alcan was able to fit the entire quarter-scale battery (based on Behrin's 1982 design), motor, and motor controller within a quarter-scale Chrysler for the SAE conference. The only component of rigid design is the cell stack, which occupies 180 liters per 100 cells. An efficient crystallizer/separator design may require a specially allocated volume.

(2) The open spaces required for heat transfer in the aluminum-air battery are located within the cassettes in electrolyte return channels and in air-manifolding channels. Heat transfer interfaces for batteries with exothermic charge or discharge reactions generally coincide with the surface of the battery box; hence the volumes are likewise required but are not counted in specific gravity. For this reason, a volume specification cannot be applied uniformly to these different configurations.

(3) The apparent volume-power density limitation is the consequence of over-constraining the JPL vehicle baseline. If volume were a problem, it is all too easy to buy additional space by raising the hood or choosing a longer car. Raising the hood two inches buys about 140 liters of additional volume (1/3 the volume of the "present" battery!).

(c) Relative placement considerations allow some flexibility in using tankage to absorb collision impact, or to absorb caustic spills.

(d) The battery scales according to power rating. A 10 kWh battery is immaterially different from a 70 kWh battery of the same power: the only differences are size of the water and product tanks and the mass of aluminum.
COMMENTS ON "ADVANCED VEHICLE SUBSYSTEM TECHNOLOGY ASSESSMENT" REPORT: 5030-555 Rev.A

Some updating of this material is warranted. Comments are by section.

Battery Description. Regenerative breaking is quite appropriate for this battery, as it can offset or eliminate the system power requirements which (except under peak power conditions) come from an auxiliary secondary battery. Moreover, some peak shaving power can be supplied by regenerative breaking with an appropriately designed battery which could provide auxiliary power as well. I understand that JPL is taking this into consideration in the revised modeling, this important option should be included.

The hydrargillite is washed and drained to yield Al(OH)₃, not alumina.

The refueling time estimate by Interplan (15 minutes for aluminum plate addition) was not updated for the wedge cells. Here plates are dropped into individual slots on the battery box, and refueling should be comparable to automotive refueling, i.e., about 5 minutes.

Performance characteristics. Possibly, the water of reaction would be stored within the hydrargillite container, as the product powder is about 45% air.

Energy Efficiency. The production of aluminum is not inherently inefficient: aluminum can be electrowon from the melt under conditions approaching reversibility. Most older Hall smelters were designed for maximum production and not energy efficiency. Until the last 10-15 years, the cost of energy did not appear in the equation for economic optimization of cell design (although energy costs dictated geographical location of the cell). Currently, commercial Hall cells have been operated Pechinney St. Lucienne at an average rate of 11.3 kWh/kg. The Alcoa smelting process in large cells consumes 8.3 kWh/kg of electrical energy. Finally, a consortium of Japanese industries is currently developing the Mitsui carbothermic reduction process which consumes no net electricity yet produces a highly pure product. Commercial application of at least one advanced process is highly likely in the 1990's, as the aluminum industry is evolving under the same energy-economy pressures which motivate electric vehicle development.

Advanced electrochemical processes for aluminum production indicate electrical efficiencies (utility to battery terminals) of 51-72%, based on 4.3- and 6 kWh/kg-Al peak yields. Carbothermic reduction processes would reduce energy consumption still further, and result in aluminum being among the most efficient of all uses of primary coal energy in transportation. We believe it is unwarranted to (1) assume major advances in electric vehicle battery technology while (2) assuming no advances in aluminum smelter technology.

There are other differences between secondary battery and electrochemical fuels. Unlike the use of distributed electricity, aluminum smelters pay relatively little electricity "distribution" losses, and energy loss of transporting metal and product is small compared to electrical distribution. Moreover, the practice of locating aluminum smelters in remote power sites
James Bay or N. Australia coal districts) or with very large utilities (Parana River) allow aluminum production to "scavenge" energies of lower than average economic value. There is simply no basis for attempting to cross-compare energy systems based on so radically different energy sources and economics as the aluminum industry and distributed urban electricity.

Charge efficiency The value of 36% for electrical energy generation efficiency does not derive from an assumption of on-site electrical generation and use. Rather it is based on the fact that the industry is a user of base-load energy, the production of which is more efficient than that of distributed urban electricity, which includes contributions of peak-shaving plants. (Despite the mythology, there is no a priori reason for assuming the consumer will charge his vehicle late at night unless he is given an economic incentive for doing so.)

Cost Projections. The estimated cost of the air electrode cassette (electrode and minimum supporting structure) is $100/m^2, assuming a macrocyclic catalyst and continuous fabrication processes. Platinum is not under consideration for a vehicle catalyst because of higher cost, poorer polarization and life-cycle values, and limited availability. On-road cycle-life is not expected to be below two years (1460 cold-startups) and a 1990's projected level of 3000 is a reasonable goal for electrode development.

Conclusions. Again, the apparent problem arising from the low specific gravity of the system is an artifact of JPL vehicle baseline assumptions and the result of Al/Air battery design considerations (which make use of a large internal air volume for heat transfer). With a different choice of vehicle, no problem arises (except for modellers!).
ALUMINUM-AIR POWER CELL RESEARCH AND DEVELOPMENT
PROGRESS REPORT

John F. Cooper

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by
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Department of Chemistry and Materials Science
Lawrence Livermore National Laboratory
ALUMINUM-AIR POWER CELL RESEARCH AND DEVELOPMENT: PROGRESS REPORT*

John F. Cooper

Abstract

An aluminum-air battery is under development with the objective of providing an electric vehicle with the range, acceleration and rapid refueling capability of common automobiles. From tested refuelable cell designs, a wedge-shaped cell was chosen for mechanical simplicity and for its capability of full anode utilization and rapid partial- or full recharge. The cell uses tin-plated copper tracks (triangular cross section) to maintain a constant interelectrode separation and to collect anodic current. Rectangular slabs of aluminum enter the cell under gravity feed and gradually assume the wedge shape during dissolution. The feed is constant and continuous and tin/aluminum junction losses are 7 mV at 2 kA/m². A second generation wedge cell has been developed which incorporates air- and electrolyte manifolding into individually-replaceable air-cathode cassettes.

A prototype wedge cell using replaceable cassettes was operated simultaneously with a crystallizer, which stabilized aluminate concentration and produced a granular aluminum-trihydroxide reaction product. Electrolyte was circulated between cell and fluidized-bed crystallizer, and particles of sizes greater than 0.015 mm were retained within the crystallizer using a hydrocyclone.

Air electrodes have been tested over simulated vehicle drive cycles which include a standby phase in cold, supersaturated electrolyte. Electrodes using advanced sintering and wet-proofing techniques and catalyzed with a non-noble metal catalyst (CoTMP) have been operated for over 1400 drive-cycles (corresponding to a two-year road life).

Fuel costs of $1.72/kg-Al (installed) were estimated on the basis of model alloy production and distribution costs, leading to a projected operating cost of 8-10¢/mile, depending on alloy and vehicle drive-train efficiencies. Unalloyed aluminum yields a peak of 4.5 kWh/kg, while an advanced industrial Hall Process and the pilot-plant Alcoa Smelting Process have electrical energy consumptions of 11.3- and 8.3 kWh/kg, respectively. The significance of energy-use estimates for the 1990's and beyond is discussed.

*Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract no. W-7405-ENG-48.
1.0 Objectives

The refuelable aluminum-air battery is being developed for electric vehicle applications because of its potential for providing the range, acceleration and refuelability of common automobiles.\(^1,2\) Aluminum as a vehicular fuel cannot compete with gasoline derived from conventional sources of petroleum and selling at today's prices. Nevertheless mechanical refuelability, high specific energy and power, and the energetics of aluminum production suggest a route to conserving the quality of transportation in an era of petroleum scarcity and price increases brought about by political or natural causes.

The use of aluminum as a recyclable electrochemical fuel would be roughly comparable in energy use and cost to synthetic liquid fuels derived from coal.\(^3,4\) However, it would avoid the essential dependence on carbonaceous primary resources and the environmental degradation associated with the massive conversion of coal. The production of aluminum as such does not presuppose particular primary energy resource, a strategy for its conversion, or a specific geographical location for industrial production. The metal is light enough to be transported trans-oceanic distances without incurring prohibitive freight costs—thus bringing a national fleet of vehicles access to a world production market.\(^4,5\) The existence of a large aluminum industry is an additional advantage. Projected aluminum demand in the 1990's is large enough—roughly 12 Mtonnes/y—to absorb the gradual introduction of a million aluminum-air vehicles (0.58 Mtonne/y). Finally the aluminum industry will evolve within the time frame of possible vehicle introduction as a result of rising electricity costs. This expectation requires that we consider the impact of new industrial processes that are operating now or likely to be introduced in the next decade.
Figure 1. The aluminum-air battery consists of two essential components: a galvanic cell stack of wedge-shaped cells and a fluidized bed crystallizer. Current collection in the cell is effected by parallel tracts of copper which make contact with the aluminum at the electrolyte interface.
2.0 Background

Two basic components of an aluminum-air battery--cell and crystallizer--are shown in Figure 1. We have developed a wedge-shaped cell (based on a concept proposed to A. Despic)\textsuperscript{6} with the objective of full utilization of the aluminum fuel. The cell consists of two sir-cathode cassettes held at an angle of 3 or 6\textdegree. On the surface of each cassette are metal tracts serving as cell separator and anode current collector. The aluminum dissolves on the faces opposite the cathodes and maintains a wedge shape as it is consumed. Rectangular-slab fuel plates gradually assume the wedge shape as they enter the cell under gravity feed.

Refueling is accomplished by addition of the rectangular plates to a dry chamber above the cell and tap water to a storage tank. Plate addition is simple and safe enough (from the perspective of the refueler and the fragility of the cell) to suggest refueling by the owner in his own garage. A year's supply of aluminum plates would occupy 0.21 m\textsuperscript{3} (7 cu ft), while a month's accumulation of reaction product would occupy about 0.12 m\textsuperscript{3} (i.e., about one standard 35 gallon container).

Individual cassettes (Figure 2) may be removed and replaced upon electrode disfunction or failure. The use of cassettes reduces cost and quality control requirements relative to multiple-cell stacks which cannot easily be disassembled.

The predominant electrochemical reaction in the cell is:

\[
\text{Al} + \frac{3}{2} \text{H}_2\text{O} + \frac{3}{4} \text{O}_2 + \text{NaOH} = \text{NaAl(OH)}_4
\]

Also hydrogen gas is evolved at the anode as a side reaction at a rate depending on composition of the anode alloy, aluminate concentration,
temperature, and the use of corrosion inhibitors (e.g., sodium stannate). This reaction does not generally exceed 5-10% of the rate of aluminum dissolution and coulombic efficiencies exceeding 97% are obtained with unalloyed aluminum under time-averaged discharge rates of 2 kA/m². Catalytic recombination (or controlled combustion) of hydrogen and oxygen in the air stream over the cell will be required for safe vehicle operation.

The crystallizer catalyzes the decomposition of the supersaturated caustic-aluminate to form granular aluminum trihydroxide in the hydrargillite polymorph:

\[
NaAl(OH)_4 \rightarrow Al(OH)_3 + NaOH
\]  
(2)

As hydrargillite is an intermediate feedstock of the aluminum industry, reaction (2) suggests the possibility of recycling to produce either aluminum or alumina products. (Explicit recycling to produce aluminum fuel plates is conceivable but not necessary until the vehicle fleet becomes large enough to seriously perturb the alumina market).

The crystallizer is a fluidized bed charged with about 18 kg of hydrargillite particles of maximum size, 50 micrometers. As shown in the system flow chart of Figure 3, a hydrocyclone has been chosen as the means of separating the relatively clear caustic aluminate electrolyte from the exit stream of the crystallizer. The power required by the hydrocyclone is not more than 1% of the gross battery power for a separation cut point of 15 micrometers. This separation would confine 99+% of the hydrargillite to the crystallizer. The other components are provided for selectively removing, washing, and draining the mature hydrargillite particles (50 micrometers and larger).
Figure 2. Wedge-shaped cells are formed by positioning two air-electrode cassettes at an angle of 3-6°. Individual cassettes can be removed and replaced following disfunction or failure.

Figure 3. Electrolyte is circulated between cell stack and crystallizer. Particles are retained in the crystallizer by means of a hydrocyclone separator, which may also be used to selectively remove mature particles for storage. Numbers indicate approximate volumetric flow rates (ml/s).
3.0 Technical Approach

Early in the program we adopted a development strategy which split the problems of battery process and configuration development from those associated with development of cost-effective and efficient electrodes. This decision reflected the essential independence of the technical problems facing each of these areas. Early phases of the program addressed problems associated with refuelable battery hardware and processes. Model electrodes were used for testing refuelable cell designs, developing precipitation models, and integrating cell and crystallizer processes. The model anode and cathode were taken, respectively, from a torpedo-propulsion battery and an advanced chlor-alkali process using an air-depolarized cathode. (Currently, unalloyed aluminum is used as a model anode.) These are not necessarily advanced as commercially feasible fuels. Progress in the development of the battery is shown in Figure 4. Recently we have integrated a 600-cm² prototype cell (wedge configuration) with crystallizer and hydrocyclone separator, and operated these over conditions anticipated in the vehicle. This allows accurate determination of the weights of a full scale vehicle battery. Currently, support auxiliaries are being developed. A fullscale vehicle prototype battery design will be developed by 1986.

This year we have chosen a prime industrial contractor: Eltech Systems, Inc.—formerly Diamond Shamrock Company—in association with the Aluminum Company of Canada (Alcan, Ltd.). Eltech will pursue development of the battery for commercial applications and place increasing emphasis on the development of commercially attractive alloys. The industrial partner contributes to the support of the program in return for foreground patent rights. In addition, Alcan carries on a larger internal program devoted solely to the proprietary development of alloys meeting the cost-constraints of
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<tr>
<th>Fiscal year</th>
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<th>Activities and milestones</th>
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<tr>
<td>79</td>
<td>Small cells</td>
<td>Small cells (25-cm(^2)) cathode life tests</td>
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<td>80</td>
<td>Large cells and precipitator</td>
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<td>81</td>
<td>Refuelable cells</td>
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<td>M1-3 LMSC (1000-cm(^2) bicell)</td>
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<td>Refuelable cell stacks</td>
<td>M2-LLNL (6-cell)</td>
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<td>M2-3 LMSC (200-cm(^2), 6 cell)</td>
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<td>83</td>
<td>Integration of stack and precipitator</td>
<td>M1-wedge LLNL (600-cm(^2))</td>
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<td>Integration of scalable systems</td>
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<td>84</td>
<td>Support auxiliaries</td>
<td>M3-wedge LLNL (600-cm(^2), 5-cell) and crystallizer, separator</td>
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<td>85</td>
<td>Laboratory prototype battery</td>
<td>Components for removal, post-treatment of mature seed; heat rejection</td>
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<td>Full scale crystallizer, auxiliaries</td>
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<td>Vehicle battery design complete</td>
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Figure 4. The aluminum-air battery technology evolved from single primary cells through rapidly-refuelable cell stacks and integrated cell/crystallizer/hydrocyclone systems. Current efforts include development of auxiliaries for withdrawal and post-treatment of mature hydrargillite.
vehicle applications. LLNL manages the program for DOE, Energy Storage Division. In support of the program we conduct process research focused on the integration of multicells, fluidized bed crystallizers, and hydrocyclone separators.

4.0 Technical Status and Problems

4.1 Cell and Cell Stack Research. The battery technology was developed in stages from small single cells to large refuelable multicell stacks without suffering a degradation of power or voltage, as shown in Figure 5. The voltage and power density curves were obtained with identical pairs of electrodes and operating conditions. The increase in power density attained with the M2 6-cell stack resulted from improvements in air distribution and cathode current collection techniques. Figure 6 shows performance of a low gallium alloy and Diamond Shamrock Standard air electrode in cells with interelectrode separations of 1.5 mm.

A cutaway drawing of the M3-wedge cell tested over the last year is shown in Figure 2. High conductivity copper tracks (with equilateral-triangle cross sections) support the wedge and provide a permanent solution-side anode current collector. The cassettes of the test cell (Figure 7) weigh 1.1 g/cm² and the cell typically delivers a peak power of 5 kW/m². Figure 8 shows vertical displacement is continuous and constant, while the junction losses amount to 7 mV—about 0.2% of cell voltage.

We have optimized the current collection in these cells by determining the current distribution as a function of collector design. Figures 9 and 10 describe respectively the modeled cell resistance network and the corresponding current distribution.
Figure 5(a). Surface power density based on medial cell area. RX808 and Diamond Shamrock standard air-electrode; 4M NaOH + 1M Al(OH)₃ + 0.06M Na₂Sn(OH)₆; 60°C. 5(b) Cell and electrode polarization (uncorrected for IR drop) for systems of 5(a).
Figure 6. Polarization characteristics of 25-cm² aluminum-air cell, using Reynolds alloy RX808-F and Diamond-Shamrock Standard Air Electrode. Electrolyte as in Figure 5. Operating conditions: 60 °C; 4M NaOH + 1M Al(OH)₃ + 0.06M Na₂Sn(OH)₆; flowing electrolyte, Re = 1000. Interelectrode gap: (a) 1.5 mm, (b) 3.2 mm.
Figure 7. Wedge-shaped cell M3-1 consists of two replaceable air-electrode cassettes held in a slotted plexiglass tank.
Figure 8. Displacement of the anode into the cell under gravity feed is continuous and constant at a rate of 1.24 micrometers/s. The theoretical rate of fall (1.4 micrometers/s) is calculated on the basis of idealized cell geometry and Faraday's law. Anode/SSCC voltage losses of 7 mV are small compared to the cell voltage (1.5 V) under these operating conditions.

Figure 9. Network analysis of the wedge-shaped cell, M3, leads to the dimensionless current distribution equation discussed in the text.
Figure 10. Relative current density increases with the relative distance from the leading edge of the anode. Parameter $r$ is a dimensionless ratio of cell resistivities and geometric ratios given in Table 1.

$$j = \frac{\cosh(x\sqrt{r})}{\cosh(\sqrt{r})}$$
Table 1 gives the magnitudes of the resistance elements in the M3 cassette. The relative current distribution obtained by the solution of the network problem is given by:

\[ j = \frac{\cosh(x \cdot r^{1/2})}{\cosh(r^{1/2})}, \]

where \( r \) is a dimensionless ratio of resistance elements defined in Table 1, \( j \) is the current density relative to that at the point where metal enters the cell, and \( x \) is the dimensionless distance from the leading edge (apex) of the wedge. \( A_a \) is anode length (parallel to ribs), \( g \) = interelectrode gap; and \( W \) is rib separation. For the M3 cell, \( r = 0.13 \), and current density is uniform to within +/- 3%. This nonuniformity imparts a steady-state curvature to the anode which differs from a plane by less than 5 micrometers over the entire surface.

Table 1. Cell Resistance Elements in the M3-Cassette for \( w = 28 \text{ mm} \), \( g = 2 \text{ mm} \), and \( A_a = 0.123 \text{ m} \).

<table>
<thead>
<tr>
<th>Element</th>
<th>Resistivity</th>
<th>Units</th>
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<tr>
<td>Cathode screen</td>
<td>( 1.0 \times 10^{-3} )</td>
<td>ohm</td>
<td>( k )</td>
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<tr>
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<td>ohm-cm(^2)</td>
<td>( m_o )</td>
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<tr>
<td>Interelectrode gap</td>
<td>1.770</td>
<td>ohm-cm</td>
<td>( R_e )</td>
</tr>
<tr>
<td>Anode/SSCC rib junction</td>
<td>0.042</td>
<td>ohm-cm</td>
<td>( R_a )</td>
</tr>
<tr>
<td>SSCC rib</td>
<td>( 7.5 \times 10^{-5} )</td>
<td>ohm/cm</td>
<td>( R_r )</td>
</tr>
<tr>
<td>Characteristic resistance</td>
<td>0.13</td>
<td>--</td>
<td>( r )</td>
</tr>
</tbody>
</table>
We have developed an advanced Al/air cell based on this geometry (Figure 11) which will provide the program with a reproducible basis, or "reference" for aluminum-air full-cell testing. The cells are machined by computer control, which allows low-cost modifications of dimensions and design according to the intended use of the cells -- e.g., research cell, massive reserve battery, low-weight vehicle module. In this cell, electrolyte and air flows are internally manifolded. The module stack at LLNL is plumbed for series electrolyte flow. Smaller cells (25 cm² anodes) are also available for program-wide uses.

Wedge cells were originally developed by this program because of full-utilization and partial recharge capability, and simple refueling by addition to plates to a dry chamber above the (undisturbed) cell. The feed slab thickness is independent of cell capacity and can be manufactured by continuous casting operations at an optimum thickness. There are no moving mechanical parts in this design, other than the gravity-fed anode.

4.2 Integration of Prototype Cell, Hydrocyclone and Crystallizer

The hydraulic power consumption of a hydrocyclone can be minimized with the use of an involute entrance chamber. A hydrocyclone of this design (supplied by Krebs Engineers, Menlo Park, CA), was tested with a wedge cell and crystallizer. We confirmed manufacturer's specifications by means of the operation of this cyclone with a single cell. As this unit was large enough for a crystallizer sized for 30-50 of the 600-cm² cells, 97% of the overflow was returned to the crystallizer. Measured hydraulic power consumption (product of flow rate and pressure drop) was 35 W. Three would consume about 1% of the 18 kW gross power output of 100 cells (assuming 50% motor/pump power efficiency).
Figure 11. Reference Al/Air cells (advanced generation wedge cells) consist of trapezoidal cassettes with internal manifolding of air and electrolyte flows. Anode area is 600 cm$^2$, and SSCC design is identical to that of earlier cells.
The rate equation derived by Alcoa describes the kinetics of hydragillite particle growth:

$$-dC_{Al}/dt = k_0 \exp(-E/RT) \left( C_{Al} - C_{Al}^{(sat)} \right)^2 / \left( C_{Na} - C_{Al} \right)^2$$

where $C_{Al}^{(sat)}$ is the solubility of Al(OH)$_3$, a function of temperature.

Independent particle growth is the predominate mode of precipitation under anticipated battery operating conditions: 40-80°C; well-stirred bed; seed-area/electrolyte-volume ratio, $A_r = 10-70$ m$^2$/liter; and $C_{Al}$ less than 2.8 M. Under these conditions, particle nucleation is suppressed. Some particle breakage (attrition) or agglomeration is expected. Precipitation rate in the bed is proportional to the total surface area of the crystals, the square of supersaturation, and the inverse square of a term reflecting caustic activity. The term in the denominator explains the sharp increase in the rate above $C_{Al} = 2.3$ M (Figure 12).

Figure 13 shows time dependence of electrolyte composition when a crystallizer/hydrocyclone system was used to control aluminate concentration. The crystallizer was initially charged with 0.18 kg of seed (specific area, 120 m$^2$/kg), and Al(OH)$_3$ solids were retained in the crystallizer for the duration of the 6 hour run. The peaking of aluminate concentration in cell and crystallizer after 3 h reflects equal rates of dissolution and precipitation. The current density, 2.3 kA/m$^2$, is the highest long-duration dissolution rate anticipated for vehicle operation. In this experiment we used unalloyed aluminum; coulombic efficiency exceeded 97% for the duration of the experiment.

Evaluating Alcoa's rate equation at points during the experiment, we determined the rate of precipitation (Figure 14). This rate was then integrated to predict the accumulation of solid Al(OH)$_3$. As shown, this
Figure 12. Rate of hydrargillite precipitation increases with temperature and oversaturation, and depends on the nature and concentration of impurities. Rate relations were independently determined by LLNL\textsuperscript{11} and Alcoa\textsuperscript{10}.

![Figure 12](image12.png)

Figure 13. Time dependences of the electrolyte volume and composition, and of dissolution current ($I_d$) during joint operation of wedge cell and crystallizer/hydrocyclone. Concentration of aluminate is given for the crystallizer as well as the cell circuit.

![Figure 13](image13.png)
Figure 14. Rate of precipitation, integrated rate of precipitation, and mass of seed (determined from mass-balance calculations) are plotted against dissolution time for the joint operation of wedge cell and crystallizer.

Figure 15. Increases in air-electrode cycle life reflect advances in catalysis as well as electrode carbons, wet-proofing, and sintering processes.
agrees well with the separate experimental mass balance based on Faraday's law, changes in aluminate concentration, and anode weight loss. The salient conclusions are (1) Alcoa rate equation applies to the simultaneous operation of prototype cell and hydrocyclone/crystallizer and (2) this verification was done within the range of critical vehicular operating conditions shown in Table 2. This is the first time that the basic processes of dissolution and crystallization have been integrated using either full-scale prototype components (cell and hydrocyclone).

Table 2. Anticipated operating conditions of a vehicle battery and actual operating conditions of the M3-wedge/hydrocyclone/crystallizer. $T = 60^\circ C$.

<table>
<thead>
<tr>
<th>Experimental System</th>
<th>Seed Mass</th>
<th>Seed area/volume</th>
<th>Seed mass/amperage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-Cell System (60°C)</td>
<td>0.18-0.83</td>
<td>8-55</td>
<td>1.3-6</td>
</tr>
<tr>
<td>100-cell system</td>
<td>25</td>
<td>20-30</td>
<td>2</td>
</tr>
<tr>
<td>100-cell vehicle system</td>
<td>18</td>
<td>20-30</td>
<td>1.5</td>
</tr>
</tbody>
</table>

$C_{Al} = 2.7 \text{ M}$

Current efforts will integrate a five-celled prototype module with an appropriately scaled hydrocyclone separator. The larger scale is convenient for investigation of long term behavior of anode shape, particle size distribution, mass balance of minor components (stannate, or gallium in case of KX808), and behavior of crystallizer during standby when all electrolyte is drained into the crystallizer. This same system will be integrated with auxiliaries for withdrawal and post treatment of mature seed by the prime subcontractor in the first year of the program.
4.3 Progress in Electrode Research and Development

There has been considerable progress in the development of durable and cost-effective air electrodes. Air electrodes are tested on a standard driving cycle consisting of constant current plateaus of 1-, 6, and 2 kA/m² and lasting a total of 14 min/cycle; this is followed by a period on standby in cold, supersaturated electrolyte lasting between 1 and 24 h, and typically 3 h. This sequence is representative of a typical automobile trip of 11 km length. By correlating life under such drive cycles with changes in the duration of a specific phase of the cycle, Eltech determined that cycle life depends strongly on the number of cold startups. The original program goal of 1500 cold startups, or two year road life, has now been met (Figure 15). The current generation of air electrodes are projected to survive beyond 2000 cycles. The goal has been reset to 3000 drive cycles, which corresponds to a four-year road life. Table 3 provides air-electrode polarization data for current air electrodes (catalyzed with CoTMPP), program goal, and earlier LLNL specifications in FY 1979 RFP.

Table 3. Current performance, technical goal, and LLNL Specifications for air electrode polarization (initial performance) T = 60°C; 4M NaOH + 1M Al(OH)₃.

<table>
<thead>
<tr>
<th>Current density (kA/m²)</th>
<th>Best Obtained CoTMPP V vs. RHE</th>
<th>Technical goal V vs. RHE</th>
<th>LLNL specs V vs. RHE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>807</td>
<td>841</td>
<td>836</td>
</tr>
<tr>
<td>2</td>
<td>766</td>
<td>830</td>
<td>796</td>
</tr>
<tr>
<td>3</td>
<td>741</td>
<td>823</td>
<td>756</td>
</tr>
<tr>
<td>4</td>
<td>706</td>
<td>816</td>
<td>716</td>
</tr>
<tr>
<td>5</td>
<td>667</td>
<td>810</td>
<td>676</td>
</tr>
<tr>
<td>6</td>
<td>583</td>
<td>805</td>
<td>636</td>
</tr>
</tbody>
</table>
These drive cycles lives were attained with the use of a non-noble metal catalyst (CoTMPP) as necessary to meet programmatic goals of $100/m²
cathode.

Progress in anode development has been slow because of the greater emphasis on the development of refuelable cells and crystallization processes. Economic feasibility will ultimately depend on energy yield/cost ratio of the alloy. Common scrap aluminum containing iron generally shows low coulombic efficiency associated with the low overpotential for hydrogen evolution on iron inclusions. Under subcontract, Reynolds Aluminum took the approach of segregating iron as Mn-Fe(Al)₃ intermetallic clusters with greatly reduced activity from the standpoint of hydrogen evolution.¹³ The effect of the introduction of 0.04% Mn to commercial purity aluminum containing 0.04-0.06% Fe is shown in Figure 16. Coulombic efficiency is greatly increased, approaching that of an analogous alloy, RX808, based on 4-9's purity metal. This Al-Ga-Mn-Fe class of alloys was never optimized by the Reynolds subcontract. This and other approaches will be again be pursued in 1984 by Eltech and Ohio State University under subcontract. Although compositions are proprietary, Alcan has produced a number of alloys using the Ca 0.05% commercial purity base with net performance at least as good as this.¹⁴ In all, the program has yet to pursue the scope of research necessary to develop cost-effective anodes; the major effort here will be lead by the prime industrial subcontractor because of the potential value of basic patents in this area.

4.4 Battery Weight Determinations

The battery weight determination given in Table 4 reflects the actual weights of dry laboratory cells, the weights of reactants and hydrargillite seed, and the weights of electrolyte required for battery operation. We have
Figure 16. Improvement of coulombic efficiency of RX808 analogues based on commercial purity aluminum is achieved by additions of Mn. The additions form intermetallic clusters which segregate and reduce the activity of Fe from the standpoint of hydrogen evolution. Operating conditions: 60°C; 4M NaOH + 1M Al(OH)₃ + 0.06M Na₂Sn(OH)₆. (a) RX808 (Al -0.04Ga -0.8Mg). (b) Al -0.04Ga -0.06Sn -0.8Mg. (c) Al -0.04Ga -0.04Fe -0.8Mg. (d) Al -0.04Ca -0.06Fe -0.8Mg.
assumed a hydrocyclone of cast PVC construction, and surface power density
\((W \, m^2)\) and aluminum energy yields which span those of current model
electrodes. The optimum weight of the battery and efficiency is achieved if
crystallizer and cell operating temperatures are allowed to increase with
aluminate concentration such that power density and coulombic efficiency
roughly constant. The battery weight resulting from this optimization
indicates specific energy of 320 Wh/kg and specific power of about 140 W/kg.
Improvements in surface power density anticipated with further alloy
development would increase specific power proportionately. These figures
reflect the characteristics of reserve batteries as well as large traction
systems, were they to be built consistent with today's understanding. The
aluminum-air battery is a fuel cell; hence specific power and energy have no
unique meaning. These parameters can be changed by changing the ratio of mass
of the limiting reactant (either water or aluminum) to the total area of the
cells.
## Table 4. Battery Weight Determination: 70 kWh, 31 kW (peak) Scale.

<table>
<thead>
<tr>
<th>Component</th>
<th>Basis for Determination</th>
<th>Weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cells</td>
<td>M3 wedge cassettes: 1.1 g/cm²; 5-7 kW/m²</td>
<td>69-49</td>
</tr>
<tr>
<td>Cyclones</td>
<td>Krebs PC-1; PVC construction</td>
<td>2</td>
</tr>
<tr>
<td>Electrolyte</td>
<td>Contained in cells, crystallizer, cyclones and manifolding</td>
<td>35&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Seed</td>
<td>Alcoa rate equation; $C_{Sn} = 0.06$ M</td>
<td>18&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Fuel requirement, 4-5 kWh/kg</td>
<td>17.5-14</td>
</tr>
<tr>
<td>Wedge</td>
<td>3° angle geometry</td>
<td>26</td>
</tr>
<tr>
<td>Water</td>
<td>Reaction and evaporation loses</td>
<td>32</td>
</tr>
<tr>
<td>Storage</td>
<td>Water, electrolyte, hydrargillite storage tanks</td>
<td>3</td>
</tr>
<tr>
<td>Misc.</td>
<td>Cell case, impellers, air-pretreatment, drive motor, startup battery etc. (estimate)</td>
<td>30</td>
</tr>
</tbody>
</table>

Total: 209-233

<sup>a</sup> Temperature = 70° at maximum $C_{Al} = 2.7$ M; seed area/mass ratio = 66.1 m²/kg; seed area/electrolyte volume ratio = 30 m²/liter.

### 5.0 Major Problem Areas and Technical Approach

Vehicle operating cost depends predominately on the energy yield and production cost of the fuel alloys. An increase in energy/cost ratio of 30% over that of the Reynolds Al-Mn-Ga is required before our goal of 8.5-10¢/mile is to be realized. The approaches to be taken include (1) reduction of dissolution overpotential through alloying with such materials as Ga at 0.02-0.04% levels; (2) selective poisoning of the hydrogen evolution reaction by use of alloyed or dissolved corrosion inhibitors (e.g. Sn, P) or intermetallic formation to segregate Fe or other undesirable impurities;
(3) use of a porous surface barrier formed by the reaction of an alloyed component (e.g., Mg) to form a high-concentration layer with higher coulombic efficiency; (4) use of trace metals to expand or contract the metal sublattice of the surface film which effects the balance of electronic and ionic conduction, and hence relative rates of water reduction and aluminum dissolution. Fundamental anode research will be emphasized as battery development approaches full-scale verification. No definitive projection of fuel cost can be made until this area is understood.

A potentially important area is the chemical balance of the battery, i.e., problems in battery efficiency and operating stability that could conceivably arise from the inadvertent buildup of trace impurities in the electrolyte and on the electrodes, or from the depletion of corrosion inhibitors. The control of impurities will be investigated by Alcan, Ltd.

It is important to determine or predict purity constraints of current and projected aluminum production techniques. In addition to alloys based on the limiting commercial purity of conventional Hall smelter operation (0.04-0.06% Fe), higher purity bases may be obtained through partial recrystallization from the combined outputs of large arrays of undedicated cells. Advanced processes such as the Alcoa Smelting Process, subhalide processes, sulfide or nitride electrolysis, or dimensionally-stable anode processes do not have the purity limits of the conventional Hall Process. The Mitsui Carbothermic Reduction Process involves the sublimation of Al from an Al/Pb intermediate product; the purity of the aluminum exceeds that of the common Hall Smelters yet the process consumes no net electricity. Thus research in alloy development must take into consideration parallel advances likely to occur within the appropriate time frame for vehicle fleet introduction and growth.
Another barrier is cathode reliability (as distinct from drive cycle life). Insufficient experiments have been conducted to allow a statistical understanding of the failure rate. This problem is less severe than with fuel cells because of the ability to sense incipient failure from electrode potential decay and to replace individual cathode cassettes.

None of these problems, if given appropriate attention, is expected to deter the different but straightforward development and testing of a vehicular prototype battery—a major and necessary step toward the realization of this concept. Required development separating the current level of technology from that of the prototype vehicle battery is difficult but reasonably straightforward. The prospects for developing cost-effective alloys are still unknown, but the range of variables known to effect electrode efficiency is cause for optimism.

6.0 Cost and Energy Consumption

The alloys (RX808 and analogues) used as a model anode for cell testing and process development are not economically suitable for a consumer vehicle, as they are based on metal purities (99.99+% Al) greater than those achievable with conventional Hall smelter practice. McMinn and Brandscomb of Reynolds determined the cost of the Al-0.04Mn-0.04Fe-0.04Ga alloy mentioned above, as part of an effort to bracket the production cost of fuel plates. The composition of a cost-effective alloy will no doubt differ; the unit costs of fabrication and alloying will probably not differ appreciably from those shown in Table 5. To estimate fuel cost, the cost of alloying agents is added to the U.S. Industry published price (which includes delivery charges to any point in Continental U.S.). This in turn is increased by the costs of continuous casting and shearing operations; and retail markups to equalize profitability of aluminum and ICE refueling. Credit for recycled Al(OH)$_3$ is derived from producers' price less 15% profit, collection and handling.
freight and calcining costs. The fuel cost requires assumptions concerning energy yield. Time-averaged energy yields of 4.3–5.9 kWh/kg-Al correspond to roughly 36–42 tonne-km/kg vehicular efficiencies, which in turn indicate fuel costs of 8–10 $/mile. (See Ref. 4 for details of these relations.)

Table 5. Estimates of the Cost of Fuel Plates with Reference to Al-0.04Ga-0.04Fe-0.04Mn.1,4

<table>
<thead>
<tr>
<th>Cost Factor</th>
<th>Basis for Estimate</th>
<th>Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base price</td>
<td>U.S. Industry published price (ingot delivered to point in continental U.S. (1981 $) (^a))</td>
<td>1.670</td>
</tr>
<tr>
<td>Fabrication</td>
<td>Continuous casting and shearing to rectangular slabs</td>
<td>0.154</td>
</tr>
<tr>
<td>Alloying agents</td>
<td>Ga and Mn</td>
<td>0.053</td>
</tr>
<tr>
<td>Premium purity</td>
<td>5A base containing 0.04% Fe</td>
<td>0.077</td>
</tr>
<tr>
<td>Retail markup</td>
<td>Profit equivalent to that of gasoline used in comparable vehicle</td>
<td>0.070</td>
</tr>
<tr>
<td>Recycle credit</td>
<td>Producer's price less 15% profit, collection, transport, and calcining charges</td>
<td>-0.306</td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td>1.7249</td>
</tr>
</tbody>
</table>

\(^a\)This is also the current price as of January, 1984.

Electrical energy uses for current and advanced process for aluminum production are shown in Table 6. Since our earliest studies of energy cost of aluminum production, several process advancements or new processes have emerged and been demonstrated in pilot plant operation. A new plant built in
the 1990's time frame will likely reflect these or comparable advances.

The significance of energy use calculations is rather questionable. Ideally, we make such calculations in an effort to estimate the impact of the introduction of a fleet of vehicles on national energy consumption. The introduction of one million aluminum-air vehicles in the 1990's may cause an increase in the nation's consumption of energy or a decrease; or no measurable change at all. The change of energy use depends on how the production market responds to small perturbation on demand—i.e., whether the demand is met by new (efficient) plant construction increase of production at existing (less efficient) plants. Electrical energy use would go down if aluminum (as fuel) merely displaces other uses of aluminum where cheaper alternatives are available (for example, containers and packaging). The net change in primary energy use will reflect the net changes in electrical energy use and petroleum (or synfuel) savings. The fact of the matter is simply: there is no way to predict the short-term effect on energy use caused by a small fleet of aluminum-air vehicles.

In the very long run (year 2000 and beyond) new production plants will have to be built to accommodate a growing fleet of aluminum-air vehicles, and the energy use of new processes will enter the determination. We are in no position today to speculate which process (or processes) or how much electricity (if any) is used by the new plants constructed in so remote a time frame. The evolution of the aluminum industry is a currently ongoing process and is driven by the same basic energy considerations that mandate the development of alternative fuels for transportation. Thus the process of Table 6, which represents current industrial (Pechiney) or pilot processes are conservative estimates for the year 2000 and beyond.
Table 6. Electrical Energy Use of Current and Advanced Processes for Aluminum Production. (For comparison, unalloyed aluminum yields a maximum of 4.5 kWh/kg in test cells).

<table>
<thead>
<tr>
<th>Process</th>
<th>Basis</th>
<th>DC Electrical Energy Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pechiney, St. Lucienne</td>
<td>Advanced Hall process</td>
<td>11.3 kWh/kg</td>
</tr>
<tr>
<td>Alcos Smelting Process</td>
<td>Electrolysis of AlCl₃</td>
<td>8.3 kWh/kg</td>
</tr>
</tbody>
</table>
REFERENCES


REFERENCES (cont.)


APPENDIX J

METHOD OF ANALYSIS
METHOD OF ANALYSIS

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METHOD OF ANALYSIS

This appendix describes the method of analysis used to assess Battery Developer Estimates for the projected selling price of advanced batteries. The method yields a revised subjective estimate which is identified as an Investigator Estimate. The method has been developed in a series of battery cost analysis projects performed by the author beginning in 1978 (Ref. Resource List).

From this experience, the following general observations can be made. The margin of uncertainty or potential error in any early new product cost estimates is strongly related to the level of knowledge, and the related experience the developer has for both product design and manufacture at the time the estimate is generated. The higher the level of knowledge and related experience the lower is the likely margin of uncertainty or potential error in the estimate.

In my judgement, early product cost estimates are more likely to underestimate rather than to overestimate the realized product cost.

The analysis procedures provide a framework for systematically examining the available information. The major thrust of the analysis is to identify qualitative and quantitative factors which permit an assessment of the developer's level of knowledge and related experience at the time the estimate was generated.

On the basis of this assessment subjective quantitative adjustments are made to the three key parameters--material and component costs, direct labor hours, and installed equipment costs--to obtain the Investigator Estimate.

The major segments of the method of analysis are outlined in Table J-1. A brief elaboration is given for each segment with illustrations of some for the factors examined in each segment.
**BATTERY TECHNOLOGY**

The primary interest is to identify materials or components not fully developed or commercially available which if current goals are not achieved could significantly impact on the cost estimate. Examples of these factors are porous graphite cost projections for the zinc-chloride battery and electrolyte tube material purity and cost projections for the sodium-sulfur battery.

**MANUFACTURING TECHNOLOGY**

The primary interest is to examine the process flow sheet definition and the extent of process development and equipment development needs. Examples of these factors are the need to demonstrate that large scale graphite production costs will meet projected costs used in the estimates for zinc-chloride battery. Another example is the ability to achieve projected yields of electrolyte tubes for the sodium-sulfur battery.

**KEY PARAMETERS**

The primary interest is to establish on a quantitative basis the reasonableness of the values generated by the developer for material and component costs, direct labor hours, and installed equipment costs.

**Material and Component Costs**

The factors of interest in this category are the development status of dominant cost items, consistency in estimates made at different times, recent progress in performance and design improvements, the level at which these improvements have been demonstrated i.e. single cell versus full scale hardware at current level of demonstration, and finally the basis for and documentation of process yields and unit costs assumed.
Direct Labor Hours and Equipment Costs

The direct labor hours and equipment costs must be examined together since for a given product design and manufacturing process they are interrelated. The exact relationship depends on the type of processes and equipment employed; and the trade-offs made between decreasing labor content and the increased costs of automation or scaling of equipment as a function of production rate.

The principal considerations in the analysis for this segment are:

- The development status and definition of the manufacturing process and equipment needs.
- The basis and documentation of the direct labor and equipment estimates.
- The consistency of the estimates referenced to a lead-acid battery manufacturing parameter correlation.

The choice of the lead-acid battery as reference for measuring the consistency of the developer estimates is based on several factors. Lead-acid battery manufacture is based on a mature technology, and reflects the benefits of optimized and automated process and plants. The data base for the lead-acid battery system is more accurate than the data base generated for batteries still under development.

The consistency of the developer estimates for direct labor hours and manufacturing equipment costs is based on examining how these values correlate with corresponding lead-acid values. The correlating parameter utilized is the ratio of the total number of manufacturing operations required for the battery under consideration to the total number of manufacturing operations for the lead-acid battery. Interpretation of this correlation requires a comparison of three other parameters for the battery under consideration and the lead-acid battery. These parameters are the scaling
factors for the operations, the number of components processed per unit of product, and the capacity of the manufacturing plant. From this analysis it is possible to obtain a subjective quantitative estimate of the consistency of the developer's estimates. A more detailed description and derivation of this analysis is given in the Appendix K.

DEVELOPER DISCUSSIONS

Issues and questions raised in the above segments are discussed with the developer for clarification. It is my experience that these discussions do not yield uniform clarification. The major barrier is the developer's position or perception that the issues impinge upon information that is considered company proprietary. It should be noted that the extent to which this method of analysis can be implemented depends significantly on the amount of information the developer wishes to share. The greater the cooperation between the developer and investigator, the less important is the subjective element in the Investigator Estimate.

DEVELOPER CAPABILITY ASSESSMENT

From the analysis results of the first four segments described above, an assessment is made of the developer's overall capability at the time the developer generated the estimates under evaluation. This assessment considers three factors:

- Level of knowledge with respect to product design and product manufacture.
- Extent of related experience with respect to product design and product experience.
- Depth, detail and the extent of documentation presented in the design and cost estimate study supporting the estimates made by the developer.
An additional subjective estimate is made as to whether the overall approach of the estimate is conservative or optimistic.

This assessment is one factor utilized in making the determination of the Investigator Estimate.

**INVESTIGATOR ESTIMATE**

On the basis of the results of the Key Parameter Analysis, Developer Discussions, and Developer Overall Capability Assessment subjective adjustments are made to the Key Parameters to determine the Investigator Estimate.
Table J-1. Outline for Determining Investigator Estimate

(1) Status of Battery Technology, especially in relation to battery design, materials and components and performance specification assumed in the design for the cost estimate.

(2) Status of Manufacturing Technology, especially with regard to the definition or demonstration of process flowsheet, process and equipment development needs for manufacturing the battery design assumed for cost estimate.

(3) Analysis of developer's estimates for the three key parameters--materials and component costs, direct labor hours, and installed equipment costs for the production rate specified.

(4) Discussion with developer to clarify issues raised in the above analyses.

(5) Evaluation of developer's "overall capability" at the time of generating his developer selling price estimate.

(6) Determine Investigator's Estimate by making subjective adjustments to item (3) parameters in conjunction with evaluations made in items (3), (4) and (5).
RESOURCE LIST

Method of Analysis

(1) Cost Analyses - Nickel-Iron and Nickel-Zinc Batteries; and Lead-Acid Batteries (1978)
J.A. Consiglio, Solva-Tek Associates
Argonne National Laboratory Purch. Order No. 955230

(2) Advanced Batteries Cost Analyses For Electric Vehicle Applications (1980)
J.A. Consiglio, Solva-Tek Associates
Dept. of Energy Contract No. DE-AC02-ET25418

(3) An Assessment of Westinghouse Ni-Fe Battery Cost Parameters (1981)
J.A. Consiglio, Solva-Tek Associates
Westinghouse Electric Corp. Purch. Order No. 54-7WAE 318866

(4) Evaluation of Developmental Battery Cost Estimates (1983-84)
P.C. Symons, Electrochemical Engineering Consultants, Inc.
J.A. Consiglio, Solva-Tek Associates
Electric Power Research Institute
Agreement RP-1136-24,25
APPENDIX K

DIRECT LABOR AND EQUIPMENT COST CORRELATIONS
DIRECT LABOR AND EQUIPMENT COST CORRELATIONS

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This appendix describes the method utilized to assess the magnitude of the direct labor and installed equipment cost estimates prepared by the developers. This assessment is then utilized to make subjective adjustments to these two parameters to generate the Investigator Estimate. (Reference Method of Analysis Text.)

The assessment is based on the use of corresponding information (direct labor and equipment cost estimates) for the lead-acid battery as a reference point. The following discussion includes three topics:

- Relation of direct labor and equipment costs to parameters
- Correlation of direct labor and equipment costs
- Correlation results

DIRECT LABOR AND EQUIPMENT COST PARAMETERS

A manufacturing process for the production of a battery can be represented by a number of process operations by which materials and components are fabricated and assembled into the battery. A given material or component may require a number of different operations prior to being assembled into the battery. Thus, for a specific battery design with a known number of components, a total manufacturing process can be specified with process operations of the appropriate type and capacity to produce the battery at a specified rate.

These concepts are illustrated for a single manufacturing operation and a single component in Figure K-1. Note that the illustration is for Direct Labor, but the arguments and relationships to the parameters also apply to Equipment Costs.
For this process operation, there is associated a direct labor content per component expressed as $DL_c$ in hours per component. $DL_c$ can be expressed as a function of three parameters: the capacity of the process operation (components per unit time); and a scaling factor and a complexity factor which characterize the type of operation. This relation is expressed symbolically in the first equation. The term $F_C(SF*CF)$ signifies a function $F_C$ of the two parameters scaling factor (SF) and complexity factor (CF).

The scaling factor (SF) is expressed as an exponent. For example, in the case of a punch press having a specified capacity, if there is a need to double the production rate, then two punch presses would be required. The corresponding amount of labor and/or equipment requirement is doubled. For this type of operation the scaling factor exponent has a value of 1.0.

Another type of operation is illustrated by a chemical reactor in which the volume of the reactor is the critical parameter. The capacity of the reactor can be doubled by doubling the volume of the reactor. The scaling factor exponent for this type of operation, based on experience, is generally less than 1.0—varying from 0.6 to 0.8. In this case, labor and/or equipment costs would range from 1.52 - 1.74 instead of doubling as in the first case.

The complexity factor (CF) reflects the fact that a more complex process operation will have associated with it a higher intrinsic labor requirement and/or equipment cost. Examples of this situation are a machining operation on a lathe operating to a variable slope pattern and high tolerances versus the stamping out of metal pieces in a punch press. The former will have higher intrinsic labor content and higher equipment cost than the latter.
The second equation in Figure K-1 expresses the labor requirement on a per unit product basis. This is obtained by multiplying the DLc value of the first equation by the number of components required per unit product. The last equation represents symbolically the total labor required to produce a product by summing up all component and associated operations in the manufacturing process to produce the product.

The estimates from the developer in most cases were not presented with the detailed information for the parameters just described. The most common set of information included a process flowsheet indicating the number and types of operations. From this information a subjective judgement could be made as to the scaling factor being 1.0 or less than 1.0. The production capacity of the battery manufacturing facility was also specified. From the battery design specification the total number of components per product unit could usually be determined.

Thus, the common set of available information permits an assessment based on:

- The number of total manufacturing operations
- The fraction of total operations having scaling factors of 1.0 or conversely less than 1.0
- The total number of components per product unit
- The capacity of the manufacturing facility

The method whereby this information is correlated to the corresponding lead-acid battery data is presented in the next sub-section.
DIRECT LABOR AND EQUIPMENT COST CORRELATION

The following discussion is facilitated by defining a number of terms which will be used in abbreviated form as follows:

- **DL**: direct labor estimate in hours per KWH of battery rated capacity
- **EQ**: equipment cost estimate (installed basis) in $/KWH of annual manufacturing capacity
- **EXP**: the exponent of a straight line on a log-log plot, which is the value for the slope of the line.

**Manufacturing Operation Ratio**
The ratio of the number of manufacturing process operations for the production of a given battery to the number of manufacturing process operations for the production of the reference lead-acid battery. These are obtained from an analysis of a manufacturing process flow sheet.

The primary comparison is made by examining the relationship of DL and EQ for a given battery versus the Manufacturing Operations Ratio. The values of DL and EQ for the lead-acid battery are used as reference point origins for drawing tie lines between the origin and the given battery data points. One plot is made for DL comparisons and one for EQ comparisons.

The data are plotted as log-log type plots. This type of plot is illustrated in Figure K-2 for the Ni-Fe and Na-S batteries with selected non-proprietary data generated in earlier studies.

The dotted line extension from the origin point with an exponent of 1.0 represents an Imaginary lead-acid plant with additional number of operations. The mix 'n types of
the additional operations in terms of scaling factor exponents, and DL to EQ ratio are the same as the original reference lead-acid battery plant. The plant capacity for the Imaginary plant adds no additional capacity. The capacity of the original lead-acid plant combined with the Imaginary plant equals the original lead-acid battery capacity.

The question addressed in the comparison - are the positions, or slopes, or exponents for the DL and EQ lines, in each plot, consistent with reference to the Imaginary lead-acid plant line of slope 1.0?

Three parameters in Table K-1 impact on the value of the exponents of the tie lines to differing degrees and in different directions. The parameters are:

- Plant capacity or production rate
- Number of components per KWH of battery rating (in this illustration limited to components through the cell level or equivalent thereof).
- Percentage of manufacturing operations judged to have a scaling factor exponent of approximately 1.0 with respect to production rate.

The procedure used is to make a comparison of the parameter values for the given battery versus the lead-acid battery values for the same parameter - Table K-1. From this comparison a judgement is made as to the expected impact of the parameter on the position of DL or EQ tie line with respect to the Imaginary lead acid plant tie line with an exponent of 1.0.

The complexity factor (CF) also impacts on the value of the exponents of the tie line. This information was not quantifiable in this analysis. A qualitative subjective assessment of this factor was utilized as a guide in making the judgement of the expected impact of the three parameters listed above.
The process is illustrated for one parameter - Plant Capacity for Ni-Fe. Nickel-Iron plant capacity is much less than the capacity of reference plant (21 MWH versus 2500 MWH per year). At lower production rates DL and EQ increase markedly, therefore the expectation is that for this parameter, Ni-Fe DL and EQ tie lines will be much greater than 1.0.

This process is repeated for each parameter for each battery. The results are summarized in Table K-2. All entries are expectations against the reference exponent value of 1.0.

In summary the expectation is that the exponents for Ni-Fe DL and EQ lines are much greater than 1.0 and for Na-S the exponents are about equal to 1.0. A comparison with Figure K-2 indicates that the results for Ni-Fe and Na-S meet the expectations.

For cases in which the developer DL or EQ values do not meet the expected values as obtained by comparisons drawn in Table K-2 a qualitative assessment is made to determine if there are significant differences between the complexity factor for the developer's process operations and the reference lead-acid process operations. A subjective adjustment is made to the developer's DL and EQ values taking into consideration the above assessment.
DIRECT LABOR (DL_C) - HOURS/COMPONENT

PARAMETERS

CAPACITY (CAP) - COMPONENTS/TIME
SCALING FACTOR - SF
COMPLEXITY FACTOR - CF
NUMBER OF COMPONENTS - NO. COMP.

A M'F'G PROCESS
OPERATION

Basis per component

\[ DL_C = \frac{F_C (SF \times CF)}{CAP} \]

Basis per product

\[ DL = NO.\ COMP. \times DL_C \]

Basis per Total M'f'g Process

\[ DL = \text{SUM OF TOTAL NO. OF OPERATIONS} \]

Figure K-1. Direct Labor Correlation Parameters
Figure K-2. Direct Labor and Equipment Costs vs Manufacturing Operations Ratio
Table K-1. Selected Parameters for Direct Labor and Equipment Comparisons

<table>
<thead>
<tr>
<th></th>
<th>Pb/Acid Ref.</th>
<th>Ni/FE EPI</th>
<th>Na/S FORD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components-No. KWH</td>
<td>218</td>
<td>230</td>
<td>70</td>
</tr>
<tr>
<td>M'f'g Operations-No.</td>
<td>29</td>
<td>34</td>
<td>139</td>
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<tr>
<td>M'f'g Operations Ratio</td>
<td>1</td>
<td>1.2</td>
<td>4.7</td>
</tr>
<tr>
<td>Percentage of Operations with Scaling Factor Exponent = 1.0</td>
<td>66</td>
<td>38</td>
<td>74</td>
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<tr>
<td>M'f'g Production Capacity--MWH/y</td>
<td>2500</td>
<td>21</td>
<td>3000</td>
</tr>
<tr>
<td>Direct Labor--hr/KWH</td>
<td>.25</td>
<td>.99</td>
<td>.9</td>
</tr>
<tr>
<td>Equipment Inv.--$/KWH of annual m'f'g capacity</td>
<td>6.0</td>
<td>58</td>
<td>31</td>
</tr>
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</table>

aValues for Cell Level.
bSee text for definition.
Table K-2. Expected Impact of Parameters on Direct Labor and Equipment Cost Tie Lines in Figure K-2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expectation Referenced to Exponent Line Value of 1.0</th>
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<tbody>
<tr>
<td></td>
<td>Ni/Fe Eagle</td>
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<td>Na/S FORD</td>
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<tr>
<td>Production Rate</td>
<td>Much</td>
</tr>
<tr>
<td></td>
<td>Greater</td>
</tr>
<tr>
<td></td>
<td>Equal</td>
</tr>
<tr>
<td>No. Components Per KWH</td>
<td>Equal</td>
</tr>
<tr>
<td></td>
<td>Less</td>
</tr>
<tr>
<td>% of M'f'g Operations with Scaling Factor</td>
<td>Some-what</td>
</tr>
<tr>
<td>Exponent of 1.0</td>
<td>Less</td>
</tr>
<tr>
<td></td>
<td>Greater</td>
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<tr>
<td>Summary Expectation</td>
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<td></td>
<td>Greater</td>
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<tr>
<td></td>
<td>About</td>
</tr>
<tr>
<td></td>
<td>Equal</td>
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</tbody>
</table>
APPENDIX L

WEIGHT AND COST COMPARISON OF ALUMINUM AND STEEL VEHICLE BODIES
Weight and Cost Comparison of Aluminum and Steel Vehicle Bodies

A. Marshall Zann
Consulting Engineer
Santa Barbara, CA
I. INTRODUCTION

Efforts by transportation system designers and manufacturers to produce more efficient and higher performance vehicles have led to weight reduction through downsizing and material substitution. The most efficient approach to weight reduction is accomplished by a combination of vehicle redesign in conjunction with material substitution. This allows for the most efficient use of the selected materials.

The purpose of this study is to analyze the impact on the different aspects of manufacturing and to determine a weight and cost comparison of an aluminum body to that of a steel body. For this study it was assumed that the vehicle was redesigned to obtain the optimal use of aluminum while incorporating the necessary changes to effect proper aluminum processing in fabrication and assembly. It was also assumed that the production methods utilized would produce 300,000 units per year.

Supportive materials published over the past six years were reviewed along with discussions with automotive manufacturers and manufacturing development personnel to determine the present status and development of aluminum in automobiles.
along with any advantages or disadvantages encountered. The writer also relied on his experience with substitution of aluminum in the fabrication and assembly processes at the GM Lordstown facility. During this time the Vega 15 style substituted aluminum for steel on the load floor cover and a production tryout of aluminum deck lids was conducted on the 11 style.

The published materials were well documented in the material costs and forming of component panels. In most studies when no weight savings was accomplished the component item was then left as steel. This would not be practical in a unitized body due to galvanic reaction, therefore, components would require to be made of aluminum even though a weight reduction were not realized and a resultant cost penalty would be encountered.

The technology exists to design and manufacture vehicles with an all aluminum construction. Existing aluminum alloys have the capability to be formed and welded with existing mass production techniques. In reviewing the materials it was noted that cost penalties were found in all facets of manufacturing that would increase the purchase price of the vehicle. The
trade off of economy and performance to the increased purchase price must be analyzed to determine if the material substitution is economically desirable.

This report is divided into four sections as follows:

II Summary

III Material Weight and Cost Comparison

IV Impact on Fabrication Operations

V Impact on Assembly Operations

An area not covered would be the impact on after market and repair procedures. Increased skills and improved equipment will be required in welding and repair of the aluminum primary and secondary structural components. This would result in higher repair costs and possibly insurance premium increases.
II CONCLUSIONS

Construction of an all aluminum body can be accomplished with existing mass production methods and obtain a weight savings of approximately 41% in the body structure. This, when related to the total automobile, including the propagated weight savings would be approximately 21% of a base 820 kg vehicle.

The cost impacts were found in all areas of manufacturing. This included higher base material cost increased tooling, facilities, and manpower. All areas considered, it is estimated that the body would cost 240% more than the steel body.
III. MATERIAL WEIGHT AND COST COMPARISON

As a basis for this comparison the vehicle used in SAE papers 810228(1) and 810229(2) was used. This was a 1981 front wheel drive, four passenger compact vehicle. The components evaluated for alternate material were the body-in-white primary structural and secondary structural components. These components made up the major portion of the body structure with a total mass of 315 Kg. This breakdown is shown pictorially in figure 1.

The major consideration in determining material substitution is to insure that the resultant component has adequate stiffness and strength. The material thickness must also be sufficient to withstand the manufacturing processes such as forming, surface finishing and handling. Exposed components must have sufficient resistance to denting.

The costs for steel and aluminum used were the same as the GM reports. Aluminum costing $1.79/Kg and steel at $0.40/Kg. Only one cost for aluminum at a median price was used rather than the different prices for exposed and unexposed finish materials. Also no price difference was established for blank size and offal. Such an analysis would be time consuming and require full design and processing information. A penalty of 15% was assumed in the price impact to compensate for the larger blank requirement and increased material cost.
Figure 1- Pictoral Breakdown of Automotive Body
The primary structural members function as the main load carrying structures. These consist of upper and lower front frames, all pillars, rockers, roof rails, headers, floor tunnel, etc. The secondary structural members do not contribute significantly to the structural stiffness requirements. The design criteria of the secondary structural members are generally governed by localized requirements. These consist of the roof panel, doors, floor pan, hood, deck lid, etc.

The total mass of the vehicle as developed in the GM reports are shown in Table 1. The primary structure was developed in aluminum and optimized utilizing the computerized program ODYSSEY, developed by GM. This program, through material substitution and optimization of component design, established an all aluminum primary structure mass of 71Kg or a savings of 34Kg. The secondary structural components were developed as shown in Table 2. A secondary structural mass of 122.5Kg was established or a savings of 52.25Kg.

Approximately 54Kg of the body weight is in brackets, braces, reinforcements and attaching parts that would not benefit from the primary reduction of material substitution. However, some weight reduction would be obtained by the propagated weight savings. This is the weight savings that can be obtained in the chassis, engine, brakes, etc. as a result of the base weight
reductions. Each manufacturer and the different research firms have developed different methods of calculating the propagated weight savings. For this report a factor of 1:1 was used. This means that for every 1Kg of weight saved by material substitution a secondary savings of 1Kg would be obtained. As this is a unitized body it was assumed that half of this amount was to be realized in the auto body and the other half in the drive and suspension. This relates to an additional 43Kg savings in the body or a total of 86Kg for the total vehicle.

As shown in Table 1 this would be an increased material cost of $237.15 or a 289% increase. This related to the finished component and assembly purchase price would be a 30% increase of the final product.
# Material Weight and Cost Comparison

<table>
<thead>
<tr>
<th>Vehicle Area</th>
<th>Steel</th>
<th>Aluminum</th>
<th>Weight Savings</th>
<th>Cost Penalty</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Weight</td>
<td>Cost</td>
<td>Weight</td>
<td>Kg</td>
</tr>
<tr>
<td>Primary Structure</td>
<td>105 Kg</td>
<td>$42.00</td>
<td>71 Kg</td>
<td>34 Kg</td>
</tr>
<tr>
<td>Secondary Structure</td>
<td>175 Kg</td>
<td>$70.00</td>
<td>122.75 Kg</td>
<td>52.25 Kg</td>
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<tr>
<td>Miscellaneous</td>
<td>35 Kg</td>
<td>$14.00</td>
<td>35 Kg</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>315 Kg</td>
<td>$126.00</td>
<td>228.75 Kg</td>
<td>86.25 Kg</td>
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<tr>
<td>Secondary Savings</td>
<td>43 Kg</td>
<td>-73.10</td>
<td>43 Kg</td>
<td>-73.10</td>
</tr>
<tr>
<td></td>
<td>185.75 Kg</td>
<td>$315.78</td>
<td>129.25 Kg</td>
<td>$ 47.37</td>
</tr>
</tbody>
</table>

| Offal penalty 15% | $ 363.15 | $47.37 |

Table 1
### MATERIAL WEIGHT/COST COMPARISON FOR MAJOR SECONDARY STRUCTURAL COMPONENTS

**CRS vs ALUMINUM**

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>QTY</th>
<th>STEEL Mass</th>
<th>STEEL Cost</th>
<th>ALUMINUM Mass</th>
<th>ALUMINUM Cost</th>
<th>Weight Savings Per Vehicle</th>
<th>Cost Penalty Per Vehicle</th>
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<tr>
<td>Compt Pan Frt</td>
<td>1</td>
<td>6.75kg</td>
<td>$2.70</td>
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<td>$6.09</td>
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<td>6.44</td>
<td>3.37</td>
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<td>1.48</td>
<td>2.52</td>
<td>1.55</td>
<td>1.31</td>
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<td>1.98</td>
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<td>0.97</td>
<td>1.65</td>
<td>1.01</td>
<td>0.86</td>
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<tr>
<td>Dash Flt</td>
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<td>5.30</td>
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<td>2.60</td>
<td>4.42</td>
<td>2.70</td>
<td>2.30</td>
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<td>Roof Flt</td>
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<td>5.10</td>
<td>7.51</td>
<td>12.77</td>
<td>5.24</td>
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<td>2.26</td>
<td>0.90</td>
<td>1.33</td>
<td>2.26</td>
<td>0.93</td>
<td>1.36</td>
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<tr>
<td>Qtr Innr Rr Flt</td>
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<td>1.02</td>
<td>0.41</td>
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<td>0.85</td>
<td>0.52</td>
<td>0.44</td>
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<td>15.28</td>
<td>25.98</td>
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<td>19.67</td>
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<td>1.59</td>
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<td>4.74</td>
<td></td>
<td>19.67</td>
<td>19.67</td>
</tr>
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</table>

1. Steel 7.83 g/cm³ $0.40/Kg
2. Aluminum 2.71g/cm³ $1.70/Kg

Table 2
IV IMPACT OF FABRICATION OPERATIONS

The substitution from CRS to aluminum would impact the fabrication plant's tooling, facilities and manpower costs as follows:

1. Increased Manpower
   a. The use of aluminum creates problems in removal of protective materials in the form of edge protectors and separators from the sheets and coils prior to any cutting or forming operations.
   b. Increased line maintenance on material handling equipment, increased line cleaning and die maintenance to eliminate surface damage.
   c. Offal separation from steel. This may be accomplished automatically, however, the system would require maintenance.
   d. The increased possibility of process damage would increase the inspection required throughout the fabrication processes.
   Estimated cost impact 23%

2. Increased Tooling Cost
   Aluminum can be formed using the same equipment as steel, however, experience has shown greater care is required in making the dies and in some cases additional dies are required to obtain the required quality. Increased die maintenance, numbers of dies and associated equipment would affect the facility usage, set up
time, and secondary equipment usages.
Estimated cost impact 35%

3. Increased Material Handling Equipment

The ease with which aluminum surfaces can be damaged in the processing of the component requires special care and increased expenditures in the handling equipment. This can range from air stackers, increased and padded rollers, increased and larger vacuum lifters, redesigned die clearing tools, etc. The entire processing of some components may require revision to eliminate surface damage. Exposed surfaces that normally are processed with the exposed surfaces against conveyors would have to be processed with the exposed surface free of contact.
Estimated cost impact 20%

4. New Material Shipping Systems

Aluminum components shipped from fabrication to assembly plants will require newly designed shipping racks and containers. Where steel deck lids or hoods may be shipped on edge, aluminum components would be severely damaged. This item would vary greatly dependent on the banks required, shipping distance, the number of plants involved and line speed differences between fabrication and assembly.
Estimated cost impact 30%
5. Increased Scrap and Repair

With all the precautions that are taken it would be expected that a higher incidence of scrap and repair would be generated in the fabrication processes. The creation of special containers or shipping racks would require increased maintenance and if special separators are used automated systems or manpower to install the items would be required.

Estimated cost impact 10%
Little information was available on the impact of aluminum on assembly plan operations and costs. The majority of information related to tip wear and recommended procedures in welding. These are of major importance, but don't address the many areas and costs that would be affected. All of the problems seen in the fabrication plant would be present in the assembly operations, plus a major impact in the body shop welding equipment, facilities, maintenance and repair areas.

1. Resistance Welding

Aluminum requires a higher current for welding than required for steel. Approximately three times when welding the same material thickness. The material is seldom substituted on a one to one material thickness basis, therefore, the welding current increase would be in excess of three times.

In welding aluminum a preliminary forging force is recommended to prepare for the weld. This force application is higher than the welding force and requires added controls and larger weld gun cylinders. The requirement for alternate gun application to the weld surface to prevent shunting also increases the control
systems and weld cycle time.

Structural adhesive bonding may alleviate some areas of difficulty, however, the technology is not adequate at this time to be considered reliable for structural components and high production rates. It is being used on secondary structural components such as doors, deck lids and hoods.

The increased power, pressure and control requirements would affect the following:

a. Facility power requirements and installations
b. Facility welder water installations
c. Welder control systems
d. Increased transformer sizes
e. Weld gun cable size increase and increased use of water cooled jumpers.
f. Weld gun arm size increases
g. Increased tip wear
h. Increased cylinder sizes including use of sav-air or hydraulic systems.
i. Increased support equipment. The increased sizes of weld guns, cables, transformers, and gun arms would increase the number of welders to hold the multiple gun stations. Also the larger robotic systems would be required to manipulate the increased weight.
Estimated cost impact 40%

2. Material Handling.
The same problems faced in fabrication would be present in the assembly plant. Subassembly and assembly operation would require gaging, clamping, conveyors, and handling devices that would not damage exposed surfaces or mutilate weld flanges. Once designed and built greater maintenance costs will be incurred. Estimated cost impact 2%

3. Repair and Surface Finish
An area not covered in available materials is the effect of any repairs or joint finishing that will require a filler material. With steel bodies solder is used that requires minimal line space for application and set up. For aluminum, epoxy fillers are required that require a large line space plus heaters to cure for finish. At 60 units/hour and 20 foot line spacing a 600 foot line area would be consumed for curing when a half hour is required. Also, like solder, the epoxies require special booths for grinding with operator hoods and make-up air to prevent respiratory diseases.

Standard tools are required for the surface finishing of aluminum, however, with its susceptibility to damage increased finish operations would be expected. Secondary problems occur with paint cycles as the filler and body expand at different rates and the repair or finished joint develops a crack around the perimeter.
The joint problems can be reduced in the vehicle design.

Estimated cost impact 20%.

4. Scrap Increase.

The susceptibility of aluminum to be damaged in sub assembly and line operations will increase the scrap that will be generated. Where steel panels may be repaired and used aluminum may have to be scrapped as the most economical method.

Estimated cost impact 5%
REFERENCES


10. C. Difiglio, D. Kulash, "Marketing and Mobility", March 1976


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17. N. W. Smith and J. E. Grant, "Reducing the Cost of Aluminum Body Panels.", SAE 800931


APPENDIX M

AVSIZING COMPUTER PROGRAM
ADVANCED VEHICLE ENERGY PROGRAM (AVEnergy)
ADVANCED VEHICLE COST PROGRAM (AVCost)
AVSIZING COMPUTER PROGRAM

M.A. Gyamfi
S.A. Herman
1.0 INTRODUCTION

AVISIZING is a computer program written for the IBM Personal Computer on the IBM version of Microsoft BASIC. The purpose of AVISIZING is to size a preliminary vehicle and (at the user's request) write to disk input files to the ELVEC computer program and also input files with partial sets of inputs to the programs AVENERGY and AVCOST. (AVENERGY and AVCOST are written in BASIC for the IBM Personal Computer).

In running AVISIZING the user has the following options:

1. Size a new vehicle targeted to a desired range. This logic allows for multiple passes and when a satisfactory vehicle is sized the user may generate an ELVEC input file using one of the 3 cycles:
   a. Federal
   b. Highway
   c. Van

2. Generate a 24-hour cycle input file for ELVEC using a previously-sized vehicle. (This vehicle may have been sized using option 1 or option 3.)

3. Redesign a vehicle previously sized by option 1 by changing the battery mass fraction (BMF).

2.0 PROGRAM STRUCTURE

For any run, whether it is a run to size a new vehicle or a redesign of a previous vehicle, the following basic set of variables must be defined.

a. Is the vehicle electric or hybrid?

b. Battery type chosen from the following list:

1. AL-AIR
2. FE-AIR
3. LI-FE-S
4. LI-FE-S2
5. NA-S
6. NI-FE
7. NI-ZN
8. PB-AC/ADV
9. PB-AC/BIPL
10. ZN-BR
11. ZN-CL2

* LI-FE-S2 is not currently operational

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c. Power to energy ratio from the following list:

1. P/E = 1.0
2. P/E = 2.1
3. P/E = 2.4
4. P/E = 3.3

From the values of b and c, a valid battery name for the ELVEC program is constructed, e.g., FE-AIR 2.4.

Some of the batteries have a single name independent of the power to energy ratio. These names are:

1. AL-AIR
2. NI-ZN 2.0
3. PB-AC/BIPL

Some of the batteries names are the same for the power to energy ratios of 2.1 and 2.4 and are given the 2.1 designation. These names are:

1. LI-FE-S 2.1 (also 2.4)
2. NI-FE 2.1 (also 2.4)
3. PB-AC/AD 2.1 (also 2.4)

The fusion of names occurs because in ELVEC these batteries have the same specific power X cutoff DOD tables. This implies that the user must provide CH-coefficients and other battery data whenever the battery with the omitted power to energy ratio is used. AVSIZING supplies its own battery data (including CH-coefficients) for each power to energy ratio.

2.1 THE RANGE EQUATIONS

For each battery and power to energy ratio there is a set of coefficients A, B which define the BMF as a function of ELVEC range. (A and B are part of the battery data set). The equations are given by:

\[
BMF = \frac{(A \times R + B)}{100}
\]

where R is the ELVEC range.

These equations are used only when running a new vehicle targeted to a desired range. Because of recent changes made to ELVEC after A and B were determined, they probably should be rederived.

2.2 NUMBER OF CYCLES FOR 5-PASSENGER VEHICLES

When running a 24-hour cycle, the number of cycles used is dependent upon the desired ranges for the 5-passenger vehicle.
The choices are:

1. 100 mi. (uses 10 cycles)
2. 150 mi. (uses 11 cycles)
3. 250 mi. (uses 12 cycles)

2.3 MOTOR TYPE

Only the AC option is currently operational although some coding for a DC option is in place.

2.4 BATTERY DATA SETS

AVSIZING Supplies the following information for each battery:

a. battery name
b. the variables ---
   1. EFFCK
   2. SLFD
   3. ACC
c. The coefficients of the range equations i.e., \( A, B \)
d. constants in the volume equations \( Q_1, Q_2 \) and the battery power equation \( PBC \).
e. The CH-coefficients.

2.4 VEHICLE PARAMETERS

The values for grade power (GRADE) cycle power (CYCLE) and acceleration power (ACCN) are given in the following table.

<table>
<thead>
<tr>
<th>CAPACITY</th>
<th>GRADE</th>
<th>CYCLE</th>
<th>ACCN*</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>17.5</td>
<td>25.9</td>
<td>21.5</td>
</tr>
<tr>
<td>4 or 5</td>
<td>28.0</td>
<td>26.0</td>
<td>24.0</td>
</tr>
<tr>
<td>6</td>
<td>20.3</td>
<td>20.3</td>
<td>20.3</td>
</tr>
</tbody>
</table>

* unit is w/kg for GRADE, CYCLE and ACCN

The following parameters are used in the equation for test weight (see next section).

\[
\begin{align*}
WMOT1 & = 0.9* \text{GRADE}/\text{MOTSW} \\
WCON1 & = X1/\text{CONSW} \\
WTF1 & = X1/\text{TRFSW} \\
WHE1 & = \text{GRADE}/\text{HESW} \text{ (for hybrid)} \\
WTCVT1 & = \text{GRADE}/\text{TCVTSW} \text{ (for hybrid)} \\
WTR1 & = \text{WTF1} \text{ (for electric)} \\
& \quad \text{WTF1 + WTCVT1} \text{ (for hybrid)}
\end{align*}
\]
where for capacity 2 or 6 we have

\[ X_1 = \text{cycle} \]

and \[ X_1 = \text{GRADE} \] otherwise.

The various constants in the above equations are given below:

\[
\begin{align*}
\text{MOTSW} & = 490 \\
\text{CONSW} & = 2500 \\
\text{TRFSW} & = 1418 \\
\text{TRGVTSW} & = 1096 \\
\text{HESW} & = 450
\end{align*}
\]

2.5 THE WEIGHT EQUATIONS

The unit of weight is kilograms, volume is liter and power is kilowatt unless otherwise noted.

The basic equation is:

\[ WT = WSH + \text{PANDPL} + 1.3 \times (\text{SUM}) \]

where

\[ WSH \text{ is the shell weight} \]

\[ \text{PANDPL is passenger and payload weight} \]

and \( \text{SUM} \) is given by

\[ \text{SUM} = WB + \text{WMOT1} \times WT + \text{WCON1} \times WT + \text{WTR1} \times WT + \text{WH1} \times WT \]

where

\[ WT \text{ is the test weight} \]

\[ WB \text{ is the battery weight} \]

The remaining terms were defined in the previous sub-section.

Using the definition \( WB = \text{BMF} \times WT \) and solving for \( WT \) we obtain:

\[ WT = \text{WTERM1}/(1-1.3(WTERM2)) \]

where

\[ \text{WTERM1} = WSH + \text{PANDPL} \]

and

\[ \text{WTERM2} = \text{BMF} + \text{WMOT1} + \text{WCON1} + \text{WTR1} + \text{WH1} \]
The curb weight (WC) is the given by
\[ WC = W + PANDPL \]

The motor weight (WMOT) is given by
\[ WMOT = (0.9 \cdot \text{GRADE/MOTSW}) \cdot WT \]

The weights of the controller (WCON) fixed transmission (WTF), EV transmission power and controller power (CKW) are summarized by the equations:

\[
\begin{align*}
    CKW &= X1/1000 \\
    WCON &= X1/CONSW \\
    STF &= X1/TRFSW \\
    ETKW &= X1/1000
\end{align*}
\]

Where for capacity 2 or 6 we have

\[
\begin{align*}
    X1 &= CYCLE \cdot WT \\
    \text{and } X1 &= \text{GRADE} \cdot WT \text{ otherwise}
\end{align*}
\]

Further, if the vehicle is a hybrid we have:

\[
\begin{align*}
    WTCVT &= (\text{GRADE/TCVTSW}) \cdot WT \\
    EPOW &= (\text{GRADE} \cdot WT)/1000 \\
    ENGHP &= EPOW / 0.746 \text{ (horsepower units)} \\
    ENGKW &= EPOW \text{ (kilowatt units)} \\
    WHE &= (\text{GRADE/HESW}) \cdot WT \\
    PEPPWR &= 0.9 \cdot \text{GRADE} \cdot WT/1000
\end{align*}
\]

where

\[
\begin{align*}
    WTCVT \text{ is the weight of the CVT} \\
    EPOW \text{ is the ICE transmission power} \\
    ENGHP \text{ the engine power in horsepower} \\
    ENGKW \text{ is the engine power in kw.} \\
    WHE \text{ is the weight of the heat engine} \\
    PEPPWR \text{ is the motor power}
\end{align*}
\]

The volumes are computed by the following equations:

\[
\begin{align*}
    VMOT &= PEPPWR/1.54 \\
    VCT &= CKW/2.15 \\
    VTTIF &= ETKW/2.8
\end{align*}
\]

For hybrids only

\[
\begin{align*}
    ENGVOL &= EPOW/.5 \\
    GTRANVOL &= ETKW/2.8
\end{align*}
\]
where

\[ \text{VMOT} \text{ is the motor volume} \]
\[ \text{VCT} \text{ is the controller volume} \]
\[ \text{VTTIF} \text{ is the EV transmission volume} \]
\[ \text{ENGVOL} \text{ is the engine volume} \]
\[ \text{GTRANVOL} \text{ is the ICE transmission volume} \]

The volume of the batteries (BVOL) is given by:

\[ \text{BVOL} = (Q1*WB)/Q2 \]

Where Q1 and Q2 are part of the battery data sets.

The battery power (PB) is given by:

\[ \text{PB} = (PBC*WB)/1000 \]

Where PBC is part of the battery data sets.

All of the above weight-dependent variables are computed in subroutine WEIGHT.

2.6 ITERATION PROCEDURE FOR ACTUAL RANGE.

From the desired range (DRAM) which is input by the user, an estimate of the ELVEC range (R) is made:

\[ R = 1.2 \times \text{DRAM} \]

The iteration procedure begins by using the range equation to compute BMF.

\[ \text{BMF} = (A \times R + B)/100 \]

The specific power (WKG) is now computed

\[ \text{WKG} = \text{ACCN}/\text{BMF} \]

Call subroutine ACTUAL RANGE where a cutoff DOD is determined and an actual range (ACTRAN) is computed by the equation

\[ \text{ACTRAN} = \text{DOD}\times R/100 \]

If the actual range is within 5% of the desired range then the iteration procedure is terminated. If not, then the ELVEC range (R) is updated by the factor DRAN/ACTRAN and the BMF is computed beginning another iteration. The upper limit to the number of iterations is now set to 30.
2.7 DOMINANT BMF

The power density is given by

\[ PD = \exp(\text{LPD}) \]

where

\[ \text{LPD} = \text{CH}(1) + \text{CH}(2) \log(\text{TAU}) + \text{CH}(3) \times (\log(\text{TAU}))^2 \]

and \( \text{TAU} = \frac{6.6}{60} \)

If \( \text{GRADE/PD BMF} \) and the BMF is not input by the user, then the dominant BMF is "GRADE". Otherwise, the dominant BMF is "RANGE". For the case where the user enters the BMF (the redesign option) then the dominant BMF is "INPUT".

2.8 THE AVSIZING OUTPUT REPORT

The AVSIZING output report contains the following information:

a. Vehicle capacity
b. Vehicle type
c. Desired Rage
d. Dominant BMF
e. Battery name
f. BMF
g. Test weight
h. Actual range (est)

In addition, the weight (kg) and power (kw) are given for:

a. Motor
b. Controller
c. EV transmission
d. Battery
e. ICE transmission
f. Engine
A sample output report follows:

## AMBIZING OUTPUT REPORT

Range converged in 2 iterations.

**TEST CASE - 3 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC**

<table>
<thead>
<tr>
<th>Component</th>
<th>WT(Kg)</th>
<th>VOL(LTR)</th>
<th>PWR(KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTOR</td>
<td>90.35</td>
<td>28.75</td>
<td>44.27</td>
</tr>
<tr>
<td>CONTR</td>
<td>19.68</td>
<td>22.68</td>
<td>49.19</td>
</tr>
<tr>
<td>EV TRANS</td>
<td>34.69</td>
<td>17.57</td>
<td>49.19</td>
</tr>
<tr>
<td>BATTR</td>
<td>489.02</td>
<td>248.40</td>
<td>99.48</td>
</tr>
<tr>
<td>ICE TRANS</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ENGINE</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The BHF IS 0.278
The Test Weight is 1756.84 Kg
The Curb Weight IS 1630.86 Kg
The Actual Range Is 101.56 Mi

**END OF PROGRAM OPERATIONS**
2.9 PURPOSE OF SUBROUTINES

**SUBROUTINE**

<table>
<thead>
<tr>
<th>SUBROUTINE</th>
<th>PURPOSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRONT-END</td>
<td>Writes statement to disk that when sent to the VAX will create (open) the appropriate file. Writes the initial portion of the various cycles to disk. This subroutine is used by all cycles (Federal Highway, Van, and 24-hr. cycles).</td>
</tr>
<tr>
<td>PARAMVAR</td>
<td>Writes further statements for the various cycles to disk.</td>
</tr>
<tr>
<td>CYCLE - I</td>
<td>Writes the individual cycles (1-12) to disk for the 24-hr. cycle.</td>
</tr>
<tr>
<td>(I=1 to 12)</td>
<td></td>
</tr>
<tr>
<td>CYCLE-VAN</td>
<td>Writes portion of VAN cycle to disk.</td>
</tr>
<tr>
<td>VEHICLE-DATA</td>
<td>If not running a 24-hr. cycle, writes vehicle data to disk. It is called after a non-24-hr. cycle is written to disk. The file written by this subroutine is read only if a new vehicle is not being run.</td>
</tr>
<tr>
<td>CH-READ</td>
<td>Reads the CH-coefficient from data statements.</td>
</tr>
<tr>
<td>BATN$-READ</td>
<td>Reads battery names from data statements.</td>
</tr>
<tr>
<td>ACTUAL-RANGE</td>
<td>Contains the cutoff DOD vs. specific power tables. Computes actual range.</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>Computes weight-dependent quantities.</td>
</tr>
<tr>
<td>HYBRID</td>
<td>Writes hybrid inputs to ELVEC program to disk.</td>
</tr>
<tr>
<td>DATA</td>
<td>Writes data for ELVEC program to disk.</td>
</tr>
</tbody>
</table>
1.0 PRELIMINARIES

It is assumed that the SMARTCOMII communication package disk (Hayes Microcomputer Products Corp.) with a macro set for automatic log on is inserted in drive A. Drive B is reserved for a disk containing the programs: AVSIZING, BAS, AVENERGY, BAS and AVCOST, BAS. Normally the disk in drive A is used to boot the system.

![Design Procedure Flow Diagram](image)

Figure M-1. Design Procedure Flow Diagram
WRITE RNGE.DAT TO DISK

RUN AVENERGY AND AVCOST

FINISH
3.0 OUTLINE OF DESIGN PROCEDURE TERMINAL SESSION

This section steps through the design of a preliminary vehicle, 24-hour cycle and running of the energy and costing programs. Each step is numbered and represents an action taken by the user. The actions indicated are entered at the keyboard. Non-specific actions are bracketed and are not numbered. Comments are also bracketed or enclosed in parenthesis or explicitly labeled.

3.1 PHASE 1 (design preliminary vehicle)

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(prompt = A&gt;)</td>
<td></td>
<td>IBMPC</td>
</tr>
<tr>
<td>1.</td>
<td>B:</td>
<td>Change to B drive.</td>
</tr>
<tr>
<td>2.</td>
<td>BASIC AVSIZING</td>
<td>Request version of basic, load and run AVSIZING.</td>
</tr>
<tr>
<td></td>
<td>[Respond to prompts] in AVSIZING</td>
<td>Comment: In this case AVSIZING is used to size a preliminary vehicle.</td>
</tr>
<tr>
<td>3.</td>
<td>SYSTEM</td>
<td>Return to system.</td>
</tr>
<tr>
<td>4.</td>
<td>A:</td>
<td>Change to A drive</td>
</tr>
<tr>
<td>5.</td>
<td>SCOM</td>
<td>Activate SMARTCOM II</td>
</tr>
<tr>
<td>7.</td>
<td></td>
<td>Begin communications</td>
</tr>
<tr>
<td>8.</td>
<td></td>
<td>originate transmission</td>
</tr>
<tr>
<td>9.</td>
<td></td>
<td>dial</td>
</tr>
<tr>
<td></td>
<td>[Macro is activated for automatic log on.]</td>
<td>VAX environment)</td>
</tr>
<tr>
<td></td>
<td>(prompt = $)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[Ready to send file LOCAL.DAT to VAX]</td>
<td>Display SMARTCOM menu</td>
</tr>
<tr>
<td>10.</td>
<td>F1</td>
<td></td>
</tr>
<tr>
<td>STEP</td>
<td>ACTION</td>
<td>RESULT</td>
</tr>
<tr>
<td>------</td>
<td>--------</td>
<td>--------</td>
</tr>
<tr>
<td>11.</td>
<td>7 (optional)</td>
<td>printer on</td>
</tr>
<tr>
<td>12.</td>
<td>5</td>
<td>send file</td>
</tr>
<tr>
<td>13.</td>
<td>2</td>
<td>start/stop protocol</td>
</tr>
<tr>
<td>14.</td>
<td>LOCAL.DAT</td>
<td>Enter file name</td>
</tr>
<tr>
<td></td>
<td>[Wait until transmission]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[of file is complete.]</td>
<td></td>
</tr>
<tr>
<td>15.</td>
<td>control Z</td>
<td>Completes the creation of the file STAREL.COM</td>
</tr>
<tr>
<td>16.</td>
<td>@MAX* run</td>
<td>Execute MAX.COM to run ELVEC in demand mode.</td>
</tr>
<tr>
<td>17.</td>
<td>NG (normally) or YES</td>
<td>Response to question: do you wish to see 1 July message?</td>
</tr>
</tbody>
</table>
| 18.  | (normally) | Response to: BULK DATA FILE TO BE USED (NULL RETURN FOR DEFAULT):

The command file STAREL.COM will supply automatic inputs to the ELVEC program until run is completed.

(prompt = $) (VAX environment)

| 19.  | LOG | log off |
| 20.  | Fl | Display SMARTCOM menu |

* It is assumed that ELVEC is to be run in demand. If you wish to run ELVEC in batch (the correct response to question in AVSIZING must have been given) replace @MAX with SUBMIT STAREL.COM/NO PRINT/QUE= FIFO.
### 3.2 PHASE 2 (generate 24-hour cycle)

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>21. 0</td>
<td>end communications/program</td>
<td></td>
</tr>
<tr>
<td>22. Y</td>
<td>Response to question: Exit program?</td>
<td></td>
</tr>
</tbody>
</table>

**Comment:** In this case AVSIZING is used to generate a 24-hr. cycle.

- **Macro is activated for automatic log on**
  - (prompt = $)
- **Ready to send file**
  - XXX.DAT (batch) or STAREL.DAT (demand)

**Repeat above sequence (steps 1-22) until range constraint is satisfied.**

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>23.</td>
<td>XXX.DAT (for batch) or STAREL.DAT (for demand)</td>
<td>Enter file name</td>
</tr>
<tr>
<td>24.</td>
<td>Control Z</td>
<td>Completes creation of appropriate file.</td>
</tr>
<tr>
<td>25.</td>
<td>@MAX (for demand) or run ELVEC (in demand or batch)</td>
<td></td>
</tr>
</tbody>
</table>
## After running ELVEC with a set of inputs for a 24-hour cycle a VAX file named RNGE.DAT is created. This file contains a partial set of inputs for the IBMPC program AVENERGY.BAS. Therefore, this file (or at least a portion of it) must be written to disk. This is done as follows:

<table>
<thead>
<tr>
<th>STEP</th>
<th>ACTION</th>
<th>RESULT</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.</td>
<td>TYPE RNGE.DAT ** but do not enter.</td>
<td>(VAX environment) prepare to type RNGE.DAT</td>
</tr>
<tr>
<td>27.</td>
<td>F4</td>
<td>Receive file</td>
</tr>
<tr>
<td>28.</td>
<td>F1</td>
<td>complete typing of RNGE.DAT</td>
</tr>
<tr>
<td>29.</td>
<td></td>
<td>Completes file reception</td>
</tr>
</tbody>
</table>

Enter file name to be used on disk in B drive (This is optional since default = TEMP) SMARTCOM must be set for B directory. (This file is called the ELVEC OUTPUT FILE in AVENERGY.BAS)

For simplicity it is assumed that RNGE.DAT contains only the inputs for the current run. The case where this is not true will be discussed in section 4.
If ELVEC is run in batch, a file XXX.LOG is created which contains the result of the run. (XXX is the file name of the 24-hour input file.)

The user is now ready to run the programs AVENERGY and AVCOST. Nearly all of the input procedure has been made automatic, however, each of these programs prompts the user for some information. Part of the inputs are the names of files on disk which contain data for these programs. These files are:

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXX.ENG</td>
<td>(input to AVENERGY)</td>
</tr>
<tr>
<td>ELVEC OUTPUT FILE</td>
<td>(input to AVENERGY)</td>
</tr>
<tr>
<td>XXX.COS</td>
<td>(input to AVCOST)</td>
</tr>
<tr>
<td>ENERGY.DAT</td>
<td>(input to AVCOST -- but not requested. This file is created by AVENERGY.)</td>
</tr>
</tbody>
</table>

IMPORTANT: AVENERGY and AVCOST must be run in tandem.

The following section will discuss these and other files on disk in more detail.

4. FILES ON DISK

This following is a list of all the files on disk (B drive) generated or used by the various programs.

1 ELVEC OUTPUT FILE (Actual name specified by user)

This file contains information required by AVENERGY that is created when ELVEC is run for a 24-hour cycle. It is a copy on disk of all or a part of the file RNGE.DAT created in the VAX environment. The user specifies its name when downloading RNGE.DAT (all or part) to disk. If a name is not specified, the default name is TEMP.

If RNGE.DAT is not erased before running a 24-hour cycle, then the data contained in RNGE.DAT may be stacked for several runs. The data in the ELVEC OUTPUT FILE must contain the data for a single run. This can be accomplished by creating another file, i.e. XXX.RAN, which contains only the required information. The procedure is as follows:

1. Copy RNGE.DAT to XXX.RAN  
   (the command is: COPY RNGE.DAT XXX.RAN).

2. Delete unwanted lines using the VAX editor.

3. Download XXX.RAN to disk.

The data in the ELVEC OUTPUT FILE are:

- ELVEC range (one for each cycle)
- Actual range (one for each cycle)
Maximum DOD  
Maximum PD  
Energy consumption (one for each cycle)  
gal. per mi (one for each cycle)  
date  
time (one for each cycle)  

AVEENERGY requests the name of the ELVEC OUTPUT FILE in order to obtain the above information. If the user responds to this request with a carriage return (null response) then this allows the user to input the information from the keyboard.

2. ENERGY.DAT

This file is created by AVEENERGY and transfers information to AVCOST.

The data are:

<table>
<thead>
<tr>
<th>In AVEENERGY</th>
<th>In AVCOST</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETKM</td>
<td>TKM</td>
</tr>
<tr>
<td>E</td>
<td>AELC</td>
</tr>
<tr>
<td>ENER</td>
<td>EOLY</td>
</tr>
<tr>
<td>FUEL</td>
<td>RICE</td>
</tr>
<tr>
<td>DCON</td>
<td>KMYR</td>
</tr>
<tr>
<td>LITM</td>
<td>AFUS</td>
</tr>
<tr>
<td>BCL</td>
<td>CYCB</td>
</tr>
<tr>
<td>X365</td>
<td>ADOD</td>
</tr>
<tr>
<td>WB</td>
<td>WB</td>
</tr>
<tr>
<td>TIT$</td>
<td>PHD$</td>
</tr>
<tr>
<td>VEH</td>
<td>IVTYP</td>
</tr>
</tbody>
</table>

3. LOCAL.DAT

This file is the local file (on disk) created by AVSIZING whenever a new vehicle is being designed. It is also created when the redesign option is used. It is sent to the VAX where it creates a file called STAREL.COM which contains the inputs for the ELVEC program. (STAREL.COM is called the remote file). STAREL.COM may be used to run ELVEC in demand or batch mode.

4. STAREL.DAT

This is the local file (on disk) for running a 24-hour cycle in demand. The remote file is STAREL.COM. This file is created by AVSIZING.

5. XXX.COS (XXX is file name of 24-hour input file)

This file is created by AVSIZING. It contains data required by AVCOST.
The data are:

### IN AVSIZING
- PEFPWR
- CKW
- ETKW
- EPOW
- NAM$
- WC

### IN AVCOST
- MKW
- CKW
- ETKW
- EPOW
- BA:TS
- CURBWT

6. **XXX.DAT** (XXX is file name of 24-hour input file)
   - This file is created by AVSIZING. It is the local file (on disk) for running a 24-hour cycle in batch. The remote file is XXX.COM.

7. **XXX.ENG** (XXX is file name of 24-hour input file)
   - This file is created by AVSIZING. It contains data required by AVENERGY. The data are:

### IN AVSIZING
- WB
- WT
- TLE$
- VEH$

### IN AVENERGY
- WB
- WT
- TIT$
- VEH

8. **VEHICLE.DAT**
   - This file is created by AVSIZING and is used to transfer information from a new vehicle design to a redesign, or 24-hour cycle option. AVSIZING is the only program which uses the data in this file.
1.0 SAMPLE CASE

The vehicle used in this sample has the following parameters:

1. 5-passenger
2. electric
3. battery is Ni-FE1.0
4. desired range is 100 miles

2.0 SIZING NEW VEHICLE USING AVSIZING

The federal cycle was used along with the inputs given above to size a preliminary vehicle.

The local file (on disk) LOCAL.DAT was created by AVSIZING using the demand mode option. Sending LOCAL.DAT to the VAX created the file in the VAX environment STAREL.COM. Executing the command file MAX.COM then ran ELVEC in the demand mode.

2.1 RUNNING 24-HOUR CYCLE

AVSIZING was used to generate a 24-hour cycle corresponding to the preliminary vehicle indicated above. The file name of the 24-hour input file was chosen to be ELTEST.

This created the following files on disk:

ELTEST.DAT
ELTEST.ENG
ELTEST.COS

ELTEST.DAT was sent to the VAX in order to create the file ELTEST.COM which was used to run ELVEC in the batch mode. This, in turn created the files (in the VAX environment):

ELTEST.LOG
RNGR.DAT

RNGE.DAT was downloaded to disk under the name ELTEST.RAN.

3.0 RUNNING AVENERGY

The inputs for this sample case are:

FILE OF THE FORM XXX.ENG      ELTEST.ENG
ELVEC OUTPUT FILE              ELTEST.RAN
VEHICLE NUMBER                 3
BATTERY CYCLE LIFE             750
4.0 RUNNING AVCOST

The inputs for this sample case are:

FILENAME OF THE FORM XXX.COS ELTEST.COS
COST OF ELECTRICITY IN C/KW-H 5
BATTERY SHELF LIFE IN YEARS 10
DEPTH OF DISCHARGE 0.8
MAINTENANCE FACTOR 1
LIFE OF VEHICLE IN YEARS 10
MOTOR TYPE 1
CONTROLLER TYPE 1
SALVAGE VALUE (%) 10
REAL INTEREST RATE (%) 10
REAL DISCOUNT RATE (%) 10
FINANCE TERM IN YEARS 4
EV TRANSMISSION TYPE 1

The computer output for this sample case starting with the AVSIZING output report for the preliminary vehicle and ending with the results of AVCOST follows.

AVSIZING OUTPUT REPORT
-------------

Range converged in 2 iterations.

TEST CASE - 5 PAS = NI-FEI.0 = 100MI. DESIRED RANGE = ELECTRIC

<table>
<thead>
<tr>
<th>THE VEHICLE CAPACITY IS</th>
<th>THE VEHICLE TYPE IS ELECTRIC</th>
<th>THE DESIRED RANGE IS 100.00 MI</th>
<th>THE DOMINANT BFF IS RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>MOTOR</td>
<td>CONTR</td>
<td>EV TRANS</td>
</tr>
<tr>
<td></td>
<td>90.33</td>
<td>19.68</td>
<td>34.69</td>
</tr>
<tr>
<td></td>
<td>23.75</td>
<td>22.68</td>
<td>17.57</td>
</tr>
<tr>
<td></td>
<td>44.27</td>
<td>49.19</td>
<td>49.19</td>
</tr>
<tr>
<td></td>
<td>THE BATTERY IS NI-FEI.0</td>
<td>THE BATTERY IS NI-FEI.0</td>
<td>THE BATTERY IS NI-FEI.0</td>
</tr>
<tr>
<td></td>
<td>BATIR</td>
<td>489.02</td>
<td>268.49</td>
</tr>
<tr>
<td></td>
<td>ICE TRANS</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td>ENGINE</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

THE BFF IS 0.370
THE TEST WEIGHT IS 1756.06 KG
THE CURB WEIGHT IS 1620.96 KG
THE ACTUAL RANGE IS 101.56 MI

**END OF PROGRAM OPERATIONS**
Do you want to see July message?

BULK DATA FILE TO BE USED (NULL RETURN FOR DEFAULT)

 Orc Electric Vehicle/Battery Simulation, Version 0.4 16Aпре4
 Specify desired output units - Metric or English...

INITIATING BULK READ...DO YOU WANT TO SEE INTRODUCTORY PRINTOUT (Y or N)?

BULK READ COMPLETE -
GETLVI ONE DATA NOT CURRENTLY IN CORE
SEARCHING BULK DATA FILE FOR IT.
DO YOU WANT CARD IMAGES OF SPECIAL DATA PRINTED (Y or N)?

EV2-13/A BATT DATA NOT CURRENTLY IN CORE
SEARCHING BULK DATA FILE FOR IT.
DO YOU WANT CARD IMAGES OF SPECIAL DATA PRINTED (Y or N)?

INPUT CHANGES FOR NEXT RUN-

NAME OF DATA PACKAGE...

WT 1060 WT 166 CDA 0.555 CNDIAL 0.95
NAMECYC FEDERAL M2C M2G 2 VMINKO 5MPH ACLFAC 0.5 ACLRCS 1.5MPH
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC
DATE 26-SEP-64
TIME 08:31:26

FEDERAL SEARCH DATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
FEDERAL CYCLE: 1372 VALUES READ.
**KEY PARAMETERS (METRIC UNITS)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB WT</td>
<td>489 1737</td>
</tr>
<tr>
<td>TIRES AC CLFAC ALCRC</td>
<td>2 409 1737</td>
</tr>
<tr>
<td>ENS EVN ECH EFFCFW</td>
<td>0.563 0.00 0.563</td>
</tr>
</tbody>
</table>

**MODELS**

<table>
<thead>
<tr>
<th>Schedule</th>
<th>Period</th>
<th>Range</th>
<th>Average</th>
<th>Road Energy</th>
<th>Max Road Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEDERAL</td>
<td>1371</td>
<td>7.450</td>
<td>19.6</td>
<td>202.4</td>
<td>97.6</td>
</tr>
</tbody>
</table>

**ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED**

<table>
<thead>
<tr>
<th>Component</th>
<th>WH/MI</th>
<th>Percent</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Batt Sys MTR/CNT</td>
<td>227.5</td>
<td>0.881</td>
<td>0.528</td>
</tr>
<tr>
<td>Drive Train</td>
<td>55.6</td>
<td>8.9</td>
<td>0.806</td>
</tr>
<tr>
<td>Power Train</td>
<td>100.0</td>
<td>7.1</td>
<td>0.783</td>
</tr>
<tr>
<td>Brakes Misc</td>
<td>33.2</td>
<td>0.4</td>
<td>0.786</td>
</tr>
</tbody>
</table>

**COMPONENT LOSS BY DRIVING PHASE (WH/MI AND PERCENT OF OVERALL)**

<table>
<thead>
<tr>
<th>Phase</th>
<th>WH/MI</th>
<th>Percent</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL</td>
<td>428.4</td>
<td>0.309</td>
<td>0.530</td>
</tr>
<tr>
<td>ACCEL</td>
<td>23.7</td>
<td>0.9</td>
<td>0.093</td>
</tr>
<tr>
<td>CRUISE</td>
<td>19.4</td>
<td>0.7</td>
<td>0.087</td>
</tr>
<tr>
<td>COAST</td>
<td>3.0</td>
<td>0.1</td>
<td>0.045</td>
</tr>
<tr>
<td>BRAKE</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>DWELL</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

**BATTERY AND CHARGER**

<table>
<thead>
<tr>
<th>Battery and Charger</th>
<th>Power Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUT IN LOSS EFF</td>
<td>43 10.00 0.900</td>
</tr>
<tr>
<td>MH/MI MH/MI I BATT</td>
<td>54 185 43.1</td>
</tr>
<tr>
<td>FINAL BATT W/LB</td>
<td>41.2 16.9 0.000</td>
</tr>
<tr>
<td>MH/MI I CHARGER</td>
<td>50 25 0.9</td>
</tr>
</tbody>
</table>

**EQUIVALENT FUEL CONSUMPTION AND ECONOMY (GASOLINE)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Consumption</th>
<th>Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary</td>
<td>Lit/KM</td>
<td>0.076768</td>
</tr>
<tr>
<td>Petroleum</td>
<td>13.0 30.6</td>
<td></td>
</tr>
<tr>
<td>Coal</td>
<td>0.04450</td>
<td>22.3 52.0</td>
</tr>
</tbody>
</table>

**DO YOU WANT THE CAFE VALUE COMPUTED?**

Yes

**INPUT CHANGES FOR NEXT RUN**

Quit
Range converged in 2 iterations.

**TEST CASE** - 5 PAS - **NI-Fe1.0** - 100MI. DESIRED RANGE - ELECTRIC

<table>
<thead>
<tr>
<th>MTK(KG)</th>
<th>VOL(LTR)</th>
<th>PWRT(KW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MUTUK</td>
<td>90.35</td>
<td>28.75</td>
</tr>
<tr>
<td>LUNIK</td>
<td>19.68</td>
<td>22.88</td>
</tr>
<tr>
<td>EV TRANS</td>
<td>34.69</td>
<td>17.57</td>
</tr>
<tr>
<td>BATIR</td>
<td>489.02</td>
<td>268.48</td>
</tr>
<tr>
<td>ICE TRANS</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>ENGINE</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**THE BRF IS** 0.2/8
**THE TEST WEIGHT IS** 1756.86 KG
**THE CURB WEIGHT IS** 1620.86 KG
**THE ACTUAL RANGE IS** 101.56 MI

**END OF PROGRAM OPERATIONS**
AN INPUT FILE HAS BEEN WRITTEN TO DISK USING THE 24 HOUR CYCLE AND DATA FROM THE
LAST RUN FOR WHICH A FEDERAL, HIGHWAY, OR VAN INPUT FILE WAS CREATED

YOU WISH TO RUN THE 24 HR. CYCLE IN BATCH THEREFORE:
THE LOCAL FILE IS ELTEST.DAT
THE REMOTE FILE IS ELTEST.COM
THE SUBMIT COMMAND IS SUBMIT ELTEST.COM/NOPRINT/QUE=FIFO

** END OF PROGRAM OPERATIONS **

TYPE RUN TO RE-START
CREATE/LUG ELTEST.COM
% SIAO1 [USER,STOR] RUNELVEC

USERDATA
ADVEV
MDLMDT ANALYT
MDLBAT ACTRN
NAMBAT Nl-FE1.0
PARAMVAR
NAMCYC
N
URBI 1 URB2 1
Park 1.9hr
URB3 1 URB4 1 URB5 1 URB6 1 URB7 1 URB8 1
Park 21.90hr
END
RUN
N
SLFDSC .016
ECHO ON
PACC 0
MT 1756.86
MB 489.0174
CDA .6
CRDIAL 1
PTIRE 38
PEFPWR KW 44.27287 44.27287
PMXANL 86.54573KM
PKEFF .95 .95
EFFCD .58
CH 3.85954 -7.73694 -9.85473E-03
END
TEST CASE - 5 PAS - NI-FE1.0 - 100ML. DESIRED RANGE - ELECTRIC - CYCLE 1
N
PARAMVAR
NAMCYC
N
URBI 1 URB2 1 URB3 1 URB4 1 URB5 1 URB6 1
Park 5.01hr
URB7 1 URB8 1 URB9 1 URB10 1 URB11 1 URB12 1 URB13 1 URB14 1 URB15 1 URB16 1
URB17 1
Park 18.60hr
END
RUN
TEST CASE - 5 PAS - NI-FE1.0 - 100ML. DESIRED RANGE - ELECTRIC - CYCLE 2
N
PARAMVAR
NAMCYC
N
URBI 1
Park 5.16hr
URB2 1 URB3 1 URB4 1 URB5 1 URB6 1
Park 0.75hr
URB7 1 URB8 1 URB9 1 URB10 1 URB11 1 URB12 1 URB13 1 URB14 1 URB15 1 URB16 1
URB17 1

(ELTEST.DAT)
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 3
N
PARAMVAR
NAMCYC
N
federal 1
park 2.77hr
URB1 1 URB2 1 URB3 1 URB4 1 URB5 1 URB6 1
URB7 1 URB8 1 URB9 1
park 14.73hr
END
RUN

TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 4
N
PARAMVAR
NAMCYC
N
federal 1
park 0.95hr
URB2 1
park 3.44hr
federal 1
park 18.79hr
END
RUN

TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 5
N
PARAMVAR
NAMCYC
N
federal 2
park 1.04hr
URB1 1 URB2 1 URB3 1 URB4 1 URB5 1 URB6 1
URB7 1 URB8 1 URB9 1
park 0.87hr
URB1 1 URB2 1
park 6.83hr
URB3 1 URB4 1 URB5 1 URB6 1 URB7 1 URB8 1 URB9 1 URB10 1 URB11 1
URB12 1 URB13 1 URB14 1 URB15 1 URB16 1 URB17 1
park 1.63hr
federal 1
park 11.89hr
END
RUN

TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 6
N
PARAMVAR
NAMCYC
N
federal 2
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 7
N
PARAMVAR
NAMCYC
N
federal 2
park 4.37hr
URB1 1
federal 2
park 0.60hr
federal 2
park 2.57hr
federal 1
park 1.38hr
federal 1
park 12.53hr
END
RUN
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 8
N
PARAMVAR
NAMCYC
N
hiway 4
park 7.04hr
federal 1
hiway 1
federal 1
park 0.66hr
federal 1
park 14.09hr
END
RUN
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 9
N
PARAMVAR
NAMCYC
N
hiway 4
park 6.53hr
federal 1
hiway 4
federal 1
park 15.04hr
END
RUN
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 10
N
QUIT
%CREATE-I-CREATED: SIA01[ORCUSER]ELTEST.COM:1 created

* SUBMIT EL:TEST.COM/HOPRINT/QUE=FIFO

Job 330 entered on queue FIFO

SUBMIT BATCH JOB
% log
type eltest.log

@ ON CONTROL-Y THEN @SET NOCONTROL-Y !Trap for escapes to the @
@ IF FMode() .eqs."BATCH" Then Goto Batch_Exit
@ Batch_Exit: ! These are only commands executed by everyone.
@ @ Exit
@ SET PROT=(S:REM,O:REM,O:REM,W:REM)/DEFAULT
@ IF "BATCH".eqs."BATCH" THEN GOTO BATCH
@ BATCH!
@©SIA01(©RCUSER,©STORE)RUNELVEC
@ set verify
@ ORC ELECTRIC VEHICLE/BATTERY SIMULATION. VERSION 8.4 16APR84
@ -
@ SPECIFY DESIRED OUTPUT UNITS - METRIC OR ENGLISH . . .
@ >
@ INITIATING BULK READ...DO YOU WANT TO SEE INTRODUCTORY PRINTOUT(Y OR N)?
@ >
@ BULK READ COMPLETE-
@ GEEV1 VDATA NOT CURRENTLY IN CORE
@ SEARCHING BULKDATA FILE FOR IT.
@ DO YOU WANT CARD IMAGES OF SPECIAL DATA PRINTED (Y OR N)?
@ >
@ EV2-13/A BATTDATA NOT CURRENTLY IN CORE
@ SEARCHING BULKDATA FILE FOR IT.
@ DO YOU WANT CARD IMAGES OF SPECIAL DATA PRINTED (Y OR N)?
@ >
@ INPUT CHANGES FOR NEXT RUN-
@ >
@ NAME OF DATA PACKAGE...
@ >
@ WT 1060 HB 166 CDA 0.553 CRDIAL 0.85
@ NACPYC FEDERAL NREGN 2 VMINR 5MPH ACLFAC 0.5 ACLRCS 1.5MPH
@ NAMHYD EV
@ MDLMT FCTUT NMBMT AL-AIR
@ MDLMOT ANALYT PKEFF 0.9 0.9 EXPTRQ 0.15 0.15 PEFOMO RPM 10000 10000
@ PEPTMR KW 20 20
@ NAMCLC DRCOP RATIO .282 16 GEAR 1 1 1 1
@ VELSDM 300 300 300 SHFDMN 300 300 300 EFFCT 0.9 0.9 0.9 0.9
@ DELT 1 TSTOP 20000
@ END DATA
@ >
@ >
@ INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS--
@ >
@ FEDERAL SCHEDATA NOT CURRENTLY IN CORE
@ SEARCHING BULKDATA FILE FOR IT.
@ FEDERAL CYCLE. 1372 VALUES READ.
@ DO YOU WANT A SUMMARY OF THE URBAN SUBSEOMENTS (Y OR N)?
@ >
@ INPUT NAME AND NUMBER OF CYCLES, INPUT END WHEN DONE.
@ FOR 'PARK' AND 'IDLE' CYCLES. INPUT NAME AND PERIOD
@ >
@ >
@ >
@ INPUT COMPLETE FOR THIS CASE
@ >

M-40
NI-FE1.0 BATT DATA NOT CURRENTLY IN CORE
SEARCHING BULK DATA FILE FOR IT.
DO YOU WANT CARD IMAGES OF SPECIAL DATA PRINTED (Y OR N)?

> VALUE DEFINED FOR UNIT NAME SCFL.
NEW DATA HEAD IN TABLES...OVERWRITE IF NECESSARY

> PACC 0
> WT 1754.86
> WB 489.0176
> CDA .6
> CRDIAL 1
> PIER 38
> PEFFM 44.22767 44.22767
> PMXIAL 0.545376
> PKEFF .95 .95
> EFFCD .56
> CH 3.85654 -.723649 -9.855735-03
> END
INPUT COMPLETE FOR THIS CASE
INPUT A 1-76 CHARACTER TITLE FOR THIS CASE

TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 1
DATE 4-OCT-84
TIME 09:56:19

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE

KEY PARAMETERS (METRIC UNITS)

-----------VEHICLE------------ STRATEGY----------
WB WT CDA PIER PIER ACLFAC ACLRCS FRKHS NHEGEN EFFCM EFFCFW
489 1757 0.600 RADIAL 38.0 0.50 -0.67 0.30 2 0.000 0.585

-----------MODELS------------
DRGROUP ANALYT NI-FE1.0 EV

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE
PARKING FOR 1,900 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 3 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE

PARKING FOR 21.900 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD
SEC MI MI/H WH/MI HP
URB1 06373 4.224 0.2 215.5 110.5 50.6

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED-

<table>
<thead>
<tr>
<th>MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES-</th>
<th>BATT SYS HTR/CNT DRVTRN PMTRN BRAKES MISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH/MI</td>
<td>280.0 36.1 31.7 67.8 34.3 44.4</td>
</tr>
<tr>
<td>PERCENT</td>
<td>41.3 12.7 50.5 93.6</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>52.1 6.7 5.9 12.6 6.4 8.3</td>
</tr>
</tbody>
</table>

COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL)-

<table>
<thead>
<tr>
<th>TOTAL</th>
<th>ACCEL</th>
<th>CRUISE</th>
<th>COAST</th>
<th>BRAKE</th>
<th>DWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFICIENCY</td>
<td>0.270</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>337.1</td>
<td></td>
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<tr>
<td>EFFICIENCY</td>
<td>0.270</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

-----------------------BATTERY AND CHARGER----------------------

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>POWER</th>
<th>FINAL</th>
<th>BATT</th>
<th>CHARGER</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUT IN</td>
<td>LOSS</td>
<td>OUT IN</td>
<td>STATE</td>
<td>EFF</td>
</tr>
<tr>
<td>WH/MI</td>
<td>WH/MI</td>
<td>WM/MI</td>
<td>WM/MI</td>
<td>WM/MI</td>
</tr>
<tr>
<td>313</td>
<td>55</td>
<td>226</td>
<td>42.1</td>
<td>16.9</td>
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</table>

TOTAL ELECT CONSUME ELECT COST
RANGE AT WALL (AT 10.0C/KWH)
MI WM/MI WM/MI+TUN C/MI
101.8 537.2 277.4 5.37
80.9 *

* - BASED ON LOWEST DEPTH OF DISCHARGE (0.794) WHICH COULD
SUSTAIN THE MAXIMUM POWER DENSITY (90.9 W/KO).

EQUIVALENT FUEL CONSUMPTION AND ECONOMY (GASOLINE)-

<table>
<thead>
<tr>
<th>SOURCE OF PRIMARY ENERGY</th>
<th>CONSUMPTION LIT/KM</th>
<th>ECONOMY KM/LIT</th>
<th>ECONOMY MI/GEAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETROLEUM</td>
<td>0.09947</td>
<td>10.2</td>
<td>23.9</td>
</tr>
<tr>
<td>COAL</td>
<td>0.05693</td>
<td>17.6</td>
<td>41.3</td>
</tr>
</tbody>
</table>

DO YOU WANT THE CAFE VALUE COMPUTED?

N

INPUT CHANGES FOR NEXT RUN-

PARAMVAR
INPUT NAME OF PARAMETER; INITIAL VALUE; FINAL VALUE; AND NUM STEPS-

NANCY
DO YOU WANT A SUMMARY OF THE URBAN SUBSEMENTS (Y OR N)?

N

INPUT NAME AND NUMBER OF CYCLES. INPUT END WHEN DONE.
FOR 'PARK' AND 'IDLE' CYCLES; INPUT NAME AND PERIOD

URB1 1  URB2 1  URB3 1  URB4 1  URB5 1  URB6 1

PARK 5.01HR

URB7 1  URB8 1  URB9 1  URB10 1  URB11 1  URB12 1  URB13 1  URB14 1  URB15 1  URB16 1

URB17 1

PARK 18.60HR

END

RUN

INPUT COMPLETE FOR THIS CASE

INPUT A 1-76 CHARACTER TITLE FOR THIS CASE-

TEST CASE - 5 PAG - Nl-Fe1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 2
DATE 4-OCT-84
TIME 09:57:07

ITERATION NUMBER 1 CONSISTING OF SUBSEMENT 1 OF THE URBAN SCHEDULE

KEY PARAMETERS (METRIC UNITS)

----------VEHICLE----------  STRATEGY---------
WB  WT  CD  TIIR  TIITI  ACFAC  ACFACS  FBRKS  NHEGEN  EFFCM  EFFCFW
459 1757 0.600 RADIAL 38.0 0.50 -0.67 0.30 2 0.000 0.505

----------MODELS----------

M-43
DNCOUP ANALYT NI-FE1.0 EV

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 3 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE

PARKING FOR 5.010 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 9 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 10 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 11 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 12 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 13 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 14 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 15 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 16 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 17 OF THE URBAN SCHEDULE

PARKING FOR 18.600 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD
SEC MI MI/H MPH
URBI 86367 7.455 0.3 202.3 97.6 50.6

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED-

<table>
<thead>
<tr>
<th>MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES-</th>
<th>BATT SYS</th>
<th>MTR/CNT</th>
<th>DRVTRN</th>
<th>PHTRN</th>
<th>BRAKES</th>
<th>MISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>WM/MI</td>
<td>250.1</td>
<td>37.9</td>
<td>30.3</td>
<td>68.2</td>
<td>34.6</td>
<td>25.2</td>
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<tr>
<td>PHCNTRPHTRN</td>
<td>346.5</td>
<td>55.6</td>
<td>44.4</td>
<td>100.0</td>
<td>50.7</td>
<td>36.9</td>
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<tr>
<td>PHCNTOVERALL</td>
<td>32.6</td>
<td>8.0</td>
<td>6.4</td>
<td>14.3</td>
<td>7.3</td>
<td>5.3</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.528</td>
<td>0.981</td>
<td>0.899</td>
<td>0.793</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>COMPONENT LOSS BY DRIVING PHASE(WMH/MI AND PERCENT OF OVERALL)</th>
<th>TOTAL</th>
<th>ACCEL</th>
<th>CRUISE</th>
<th>COAST</th>
<th>BRAKE</th>
<th>DWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERALL WM/MI</td>
<td>475.7</td>
<td></td>
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<tr>
<td>EFFICIENCY</td>
<td>0.278</td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>MOTOR</td>
<td>37.9</td>
<td>22.7</td>
<td>5.0</td>
<td>0.0</td>
<td>11.9</td>
<td>0.0</td>
</tr>
<tr>
<td>PERCENT</td>
<td>8.0</td>
<td>3.0</td>
<td>0.5</td>
<td>0.0</td>
<td>2.5</td>
<td>0.0</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.891</td>
<td>0.893</td>
<td>0.871</td>
<td>0.000</td>
<td>0.850</td>
<td>0.000</td>
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</tbody>
</table>
TRANSMISSION  30.3  19.8  1.7  0.0  8.8  0.0
PERCENT    6.4    4.2  0.4  0.0  1.9  0.0
EFFICIENCY  0.898  0.899  0.895  0.000  0.895  0.000
AERIAL      36.0  14.7  5.6  0.0  15.7  0.0
PERCENT    7.6    3.1  1.2  0.0  3.3  0.0
TIRES       61.6  27.6  7.6  0.0  26.4  0.0
PERCENT    12.9    5.8  1.6  0.0  5.6  0.0
MISCELLAN   25.2  0.2  0.0  0.0  0.1  24.9
PERCENT    5.3    0.0  0.0  0.0  0.0  5.2

---------------------BATTERY AND CHARGER---------------------
EMERGENCY----- POWER/MX FINAL BATT -----CHARGER------
OUT IN LOSS OUT IN STATE EFF LOSS EFF
WH/MI WH/MI PRCNT W/LB WH/MI PRCNT
200 54 203 42.6 41.2 16.9 0.000 0.39 49 10.00 0.900

TOTAL ELECT CONSM ELECT COST
 RANGE AT MALL (AT 10.0C/KWH)
MI WH/MI WH/MI TON C/MI
119.9 475.6 245.7 4.76
95.2

- BASED ON LOWEST DEPTH OF DISCHARGE (0.794) WHICH COULD
SUSTAIN THE MAXIMUM POWER DENSITY (90.9 W/KG).

EQUIVALENT FUEL CONSUMPTION AND ECONOMY (OASOLINE)-

SOURCE OF CONSUMPTION ECONOMY
PETROLEUM 0.00442 11.6 27.2
COAL      0.04996 20.0 47.1

DO YOU WANT THE CAPE VALUE COMPUTED?

N

INPUT CHANGES FOR NEXT RUN-

PARAMAV
INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS-

DO YOU WANT A SUMMARY OF THE URBAN SUBSEGMENTS (Y OR N)?

N

INPUT NAME AND NUMBER OF CYCLES. INPUT END WHEN DONE,
FOR "PARK" AND "IDLE" CYCLES: INPUT NAME AND PERIOD

URB 1

PARK 5.16HR

URB 1 URB 3 1 URB 4 1 URB 5 1 URB 6 1
INPUT COMPLETE FOR THIS CASE
INPUT A 1-78 CHARACTER TITLE FOR THIS CASE

TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 3
DATE 4-OCT-84
TIME 09:50:02

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE

KEY PARAMETERS (METRIC UNITS)

--- --------------- --------------- --------------- --------------- --------------- --------------- --------------- --------------- --------------- --------------- 
WE WT CDAS MT APLA APLAC FOAKS MREDE EFFCM EFFCFW
69 1770 0.600 RADIAL 36.0 0.50 -0.67 0.30 2 0.000 0.585

--- MODELS ---

DRCOU 1 ANALYT 1 NI-FE1.0 EV

PARKING FOR 5.160 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE

PARKING FOR 0.750 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 9 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 10 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 11 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 12 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 13 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 14 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 15 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 16 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 17 OF THE URBAN SCHEDULE

PARKING FOR 2.770 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 3 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 9 OF THE URBAN SCHEDULE

PARKING FOR 14.730 HOURS

<table>
<thead>
<tr>
<th>SCHEDULE PERIOD RANGE</th>
<th>AVERAGE ROAD ENERGY MAX ROAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SPEED W/O RON W RON POWER</td>
</tr>
<tr>
<td>SEC MI MI/H WH/MI HP</td>
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</tr>
<tr>
<td>URB1 96143 12.002 0.5 208.4 101.6 50.6</td>
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</tbody>
</table>

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED-

| COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL)- |
|---------------------|--------|--------|--------|--------|--------|
| TOTAL MN/MI         | ACCEL  | CRUISE | COAST  | BRAKE  | Dwell  |
| OVERALL MN/MI       | 0.242  | 2.4    | 0.5    | 0.0    | 11.6   |
| EFFICIENCY          | 37.9   | 5.0    | 0.0    | 0.0    |
| PERCENT EFFICIENCY  | 0.867  | 0.000  | 0.000  |
| TRANSMISSION        | 31.1   | 0.0    | 0.0    |

- M-47
<table>
<thead>
<tr>
<th></th>
<th>PERCENT</th>
<th>EFFICIENCY</th>
<th>AERO</th>
<th>PERCENT</th>
<th>TIRES</th>
<th>PERCENT</th>
<th>MISCELLAN</th>
<th>PERCENT</th>
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<tbody>
<tr>
<td></td>
<td>6.6</td>
<td>0.898</td>
<td>39.9</td>
<td>0.5</td>
<td>61.7</td>
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<td>15.6</td>
<td>3.3</td>
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<td>0.899</td>
<td>16.4</td>
<td>3.3</td>
<td>27.8</td>
<td>5.9</td>
<td>0.2</td>
<td>0.0</td>
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<td>0.896</td>
<td>6.2</td>
<td>1.3</td>
<td>7.5</td>
<td>1.6</td>
<td>0.0</td>
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<td>3.7</td>
<td>26.3</td>
<td>5.6</td>
<td>0.1</td>
<td>15.3</td>
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<td>0.0</td>
<td>0.0</td>
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<td>0.0</td>
<td>3.3</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>BATTERY AND CHARGER</th>
<th>ENERGY</th>
<th>POWER</th>
<th>MX</th>
<th>FINAL</th>
<th>BATT</th>
<th>-----</th>
<th>CHARGER</th>
<th>-----</th>
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</thead>
<tbody>
<tr>
<td>OUT</td>
<td>LOSS</td>
<td>IN</td>
<td>STATE</td>
<td>EFF</td>
<td>LOSS</td>
<td>EFF</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WH/MI</td>
<td>WH/MI PRCNT</td>
<td>W/LB</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>277</td>
<td>56</td>
<td>201</td>
<td>42.8</td>
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<td>16.9</td>
<td>0.000</td>
<td>0.38</td>
<td>47</td>
<td>10.00</td>
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</table>

**TOTAL** | **ELECT CONSUMPTION** | **ELECTRIC COST** |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE</td>
<td>AT WALL</td>
<td>(AT 10.0c/KWH)</td>
</tr>
<tr>
<td>MI</td>
<td>WH/MI</td>
<td>WH/MI PRCNT</td>
</tr>
<tr>
<td></td>
<td>C/MI</td>
<td></td>
</tr>
<tr>
<td>118.7</td>
<td>469.0</td>
<td>242.2</td>
</tr>
<tr>
<td>94.3</td>
<td>E</td>
<td></td>
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</table>

- Based on lowest depth of discharge (0.794) which could sustain the maximum power density (90.9 W/KD).

**Equivalent fuel consumption and economy (gasoline)** -

<table>
<thead>
<tr>
<th>SOURCE OF PRIMARY ENERGY</th>
<th>CONSUMPTION</th>
<th>ECONOMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETROLEUM</td>
<td>0.08483</td>
<td>11.0</td>
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<td></td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td>COAL</td>
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<td>20.4</td>
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<tr>
<td></td>
<td>48.0</td>
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</tr>
</tbody>
</table>

Do you want the CAPE value computed?

> N

**INPUT CHANGES FOR NEXT RUN** -

PARAMVAR

INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS -

NAMECYC

Do you want a summary of the urban subsegments (Y or N)?

> N

INPUT NAME AND NUMBER OF CYCLES, INPUT END WHEN DONE. FOR 'PARK' AND 'IDLE' CYCLES, INPUT NAME AND PERIOD

> FEDERAL 1
> PARK 0.95HR
> URBAN 1
>
PARK 3.44HR
>
FEDERAL 1
>
PARK 18.79HR
>
END
>
RUN
INPUT COMPLETE FOR THIS CASE
INPUT A 1-78 CHARACTER TITLE FOR THIS CASE-
>
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 4
DATE 4-OCT-84
TIME 10:04:102

ITERATION NUMBER 1 NAMCYC = FEDERAL

KEY PARAMETERS (METRIC UNITS)

<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>STRATEGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>WB</td>
<td>MT</td>
</tr>
<tr>
<td>469</td>
<td>1737</td>
</tr>
<tr>
<td>CDA</td>
<td>TIRE</td>
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<td>0.600</td>
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<tr>
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<td>ACLFAC</td>
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<td>ACLRCS</td>
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<tr>
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<td>PBKS</td>
</tr>
<tr>
<td>-0.67</td>
<td>NREOEN</td>
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<tr>
<td>0.30</td>
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<td>2</td>
<td>EFFCFW</td>
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<td>0.000</td>
<td>0.385</td>
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</tbody>
</table>

MODELS

DRCOUP ANALYT NI-FE1.0 EV

PARKING FOR 0.930 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE

PARKING FOR 3.440 HOURS

ITERATION NUMBER 1 NAMCYC = FEDERAL

PARKING FOR 18.790 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD

<table>
<thead>
<tr>
<th>SEc</th>
<th>MI</th>
<th>MI/H</th>
<th>WH/MI</th>
<th>HP</th>
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</thead>
<tbody>
<tr>
<td>FEDERAL</td>
<td>86373</td>
<td>16.862</td>
<td>0.7</td>
<td>202.5</td>
</tr>
</tbody>
</table>

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED

| MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES-
| BATT SYS | MTR/CNT | DRVTRAN | PWTRAN | BRAKES | MISC |
| WH/MI | 237.1 | 36.7 | 30.0 | 66.7 | 33.0 | 11.1 |
| PRCNT(PWTRAN) | 395.3 | 75.0 | 45.0 | 100.0 | 49.4 | 16.7 |
| PRCNT(OVERALL) | 52.6 | 8.1 | 6.7 | 14.8 | 7.3 | 2.5 |
| EFFICIENCY | 0.520 | 0.884 | 0.890 | 0.796 | |

| COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL)-
| TOTAL | ACCEL | CRUISE | COAST | BRAKE | DMELL |
| OVERALL, WH/MI | 450.4 | 0.0 | 11.5 | 0.0 |
| EFFICIENCY | 0.301 | 36.7 | 22.7 | 2.4 |
| MOTOR | 0.0 | 0.0 | 0.0 | 0.0 |

M-49
PERCENT 8.1 5.1 0.5 0.0 2.6 0.0
EFFICIENCY 0.884 0.896 0.875 0.000 0.852 0.000
TRANSMISSION 6.7 4.4 0.4 0.0 1.9 0.0
PERCENT 0.898 0.899 0.896 0.000 0.895 0.000
AER TRANS 30.0 19.3 1.8 0.0 9.6 0.0
PERCENT 607 4.4 0.4 0.0 1.9 0.0
EFFICIENCY 0.899 0.899 0.896 0.000 0.895 0.000
VS 40.7 16.5 6.4 0.0 17.8 0.0
PERCENT 13.7 6.1 1.7 0.0 5.9 0.0
TIES 258 11.1 0.1 0.0 0.1 10.0
PERCENT 2.5 0.0 0.0 0.0 0.0 2.4

-----------------------BATTERY AND CHARGER----------------------
-------ENERGY------ POWER.MX FINAL BATT ------CHARGER-----
OUT IN LOSS OUT IN STATE EFF LOSS EFF
WH/MI WH/MI PRENT W/LB WH/MI PRENT
265 52 192 42.6 41.2 16.9 0.000 0.38 45 10.00 0.900

TOTAL ELECT CONSM ELECT COST
RANGE AT WALL (AT 10.0C/KWH)
MI WH/MI WH/MI*TON C/MI
123.1 450.5 232.6 4.50
97.7 *

* - BASED ON LOWEST DEPTH OF DISCHARGE (0.794) WHICH COULD
SUSTAIN THE MAXIMUM POWER DENSITY (90.9 W/KO).

EQUIVALENT FUEL CONSUMPTION AND ECONOMY (GASOLINE)-

SOURCE OF CONSUMPTION ECONOMY
PRIMARY ENERGY LIT/KM KM/LIT MI/GAL
PETROLEUM 0.00171 12.2 28.8
COAL 0.04724 21.2 49.8

DO YOU WANT THE CAFE VALUE COMPUTED?
>
N

====================================================================

INPUT CHANGES FOR NEXT RUN-
>
PARAMVAR
INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS-
>
NAMCYC
DO YOU WANT A SUMMARY OF THE URBAN SUBSEOMENTS (Y OR N)?
>
N
INPUT NAME AND NUMBER OF CYCLES. INPUT END WHEN DONE.
FOR 'PARK' AND 'IDLE' CYCLES, INPUT NAME AND PERIOD
>
URB1 1 URB2 1 URB3 1 URB4 1 URB5 1 URB6 1
>
PARK 7.13HR
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE

KEY PARAMETERS (METRIC UNITS)

----------------------------------------VEHICLE--------------------- STRATEGY---------------------
WB  WT  CDA  TIIRE  TPtIRE  ACLFAC  ACLRCS  FRKS  NREGEN  EFFCM  EFFCFM
489  1757  0.600  RADIAL 38.0    0.50  -0.67  0.30  2    0.000  0.585

-------------------------MODEL S--------------------------
DRCOUP ANALYT NI-FE1.0  EV

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 3 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE

PARKING FOR 7.130 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 9 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 10 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 11 OF THE URBAN SCHEDULE

M-51
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 12 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 13 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 14 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 15 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 16 OF THE URBAN SCHEDULE

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 17 OF THE URBAN SCHEDULE

PARKING FOR 1.560 HOURS

ITERATION NUMBER 1 NUANCYC = FEDERAL

PARKING FOR 6.870 HOURS

ITERATION NUMBER 1 NUANCYC = FEDERAL

PARKING FOR 7.280 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD

<table>
<thead>
<tr>
<th>TIME</th>
<th>MI</th>
<th>MI/H</th>
<th>WH/MI</th>
<th>HP</th>
</tr>
</thead>
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<tr>
<td>URB1</td>
<td>8640</td>
<td>22.35</td>
<td>97.6</td>
<td>50.6</td>
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ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRaveled-

MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES-

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>MTR/CNT</th>
<th>DRVTRN</th>
<th>PWTRN</th>
<th>BRAKES</th>
<th>MISC</th>
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</thead>
<tbody>
<tr>
<td>WH/MI</td>
<td>234.8</td>
<td>37.9</td>
<td>0.3</td>
<td>34.6</td>
<td>6.4</td>
</tr>
<tr>
<td>PRCT(PWTRN)</td>
<td>344.0</td>
<td>55.6</td>
<td>44.4</td>
<td>100.0</td>
<td>12.3</td>
</tr>
<tr>
<td>PRCT(overall)</td>
<td>52.9</td>
<td>8.6</td>
<td>6.8</td>
<td>7.8</td>
<td>1.9</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.528</td>
<td>0.891</td>
<td>0.899</td>
<td>0.793</td>
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COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL)-

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>TOTAL</th>
<th>ACCEL</th>
<th>CRUISE</th>
<th>COAST</th>
<th>BRAKE</th>
<th>DWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOTOR</td>
<td>37.9</td>
<td>23.7</td>
<td>2.3</td>
<td>0.0</td>
<td>11.9</td>
<td>0.0</td>
</tr>
<tr>
<td>PERCENT</td>
<td>8.6</td>
<td>5.3</td>
<td>0.5</td>
<td>0.0</td>
<td>2.7</td>
<td>0.0</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.0298</td>
<td>0.0181</td>
<td>0.871</td>
<td>0.000</td>
<td>0.850</td>
<td>0.000</td>
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<tr>
<td>TRANSMISSION</td>
<td>30.3</td>
<td>19.9</td>
<td>1.7</td>
<td>0.0</td>
<td>8.8</td>
<td>0.0</td>
</tr>
<tr>
<td>PERCENT</td>
<td>6.8</td>
<td>4.5</td>
<td>0.4</td>
<td>0.0</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.896</td>
<td>0.899</td>
<td>0.895</td>
<td>0.000</td>
<td>0.895</td>
<td>0.000</td>
</tr>
<tr>
<td>AERD</td>
<td>36.0</td>
<td>14.8</td>
<td>5.6</td>
<td>0.0</td>
<td>15.7</td>
<td>0.0</td>
</tr>
<tr>
<td>PERCENT</td>
<td>8.1</td>
<td>3.3</td>
<td>1.3</td>
<td>0.0</td>
<td>3.5</td>
<td>0.0</td>
</tr>
<tr>
<td>TIMES</td>
<td>41.6</td>
<td>27.6</td>
<td>7.6</td>
<td>0.0</td>
<td>26.4</td>
<td>0.0</td>
</tr>
<tr>
<td>PERCENT</td>
<td>13.9</td>
<td>6.2</td>
<td>1.7</td>
<td>0.0</td>
<td>6.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MISCELLAN</td>
<td>8.4</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>PERCENT</td>
<td>1.9</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

BATTERY AND CHARGER-

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>POWER/MI</th>
<th>FINAL BATT</th>
<th>CHARGER</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUT</td>
<td>IN</td>
<td>LOSS</td>
<td>EFFECT</td>
</tr>
<tr>
<td>WH/MI</td>
<td>WH/MI</td>
<td>PRCT</td>
<td>W/LB</td>
</tr>
<tr>
<td>263</td>
<td>54</td>
<td>190</td>
<td>42.9</td>
</tr>
</tbody>
</table>

H-52
TOTAL ELECT CONSM ELECT COST
RANGE AT WALL (AT 10.0C/KWH)
MI WH/MI WH/MI*TON C/MI
127.1 443.8 229.2 4.44
100.9 *

- BASED ON LOWEST DEPTH OF DISCHARGE (0.794) WHICH COULD SUSTAIN THE MAXIMUM POWER DENSITY (90.9 W/KU).

EQUIVALENT FUEL CONSUMPTION AND ECONOMY (GASOLINE)-

SOURCE OF CONSUMPTION ECONOMY
PRIMARY ENERGY LIT/KM KM/LIT MI/GAL
PETROLEUM 0.08002 12.3 29.4
COAL 0.04627 21.6 50.8

DO YOU WANT THE CAFE VALUE COMPUTED?
>
N

INPUT CHANGES FOR NEXT RUN-
>
PARAMVAR
INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS-
>
NAMCYC
DO YOU WANT A SUMMARY OF THE URBAN SUBSEOMENTS (Y OR N)?
>
N
INPUT NAME AND NUMBER OF CYCLES, INPUT END WHEN DONE,
FOR ‘PARK’ AND ‘IDLE’ CYCLES, INPUT NAME AND PERIOD
>
FEDRAL 2
>
PARK 1.04HR
>
URB1 1 URB2 1 URB3 1 URB4 1 URB5 1 URB6 1
>
URB7 1 URB8 1 URB9 1
>
PARK 0.87HR
>
URB1 1 URB2 1
>
PARK 6.83HR
>
URB3 1 URB4 1 URB5 1 URB6 1 URB7 1 URB8 1 URB9 1 URB10 1 URB11 1
>
URB12 1 URB13 1 URB14 1 URB15 1 URB16 1 URB17 1
>
PARK 1.63HR
>
FEDERAL 1
>
PARK 11.89HR
>
END
>
RUN
INPUT COMPLETE FOR THIS CASE
INPUT A 1-78 CHARACTER TITLE FOR THIS CASE
>
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 6
DATE 4-OCT-84
TIME 10118137

ITERATION NUMBER 1 NAMCYC = FEDERAL
KEY PARAMETERS (METRIC UNITS)

--VEHICLE------- STRATEGY-------
MB WT CDA TTIRE PTIRE ACLFAC ACLRGS FORKS NREGEN EFFCM EFFCFW
489 1737 0.600 RADIAL 38.0 0.30 -0.67 0.30 2 0.000 0.383

--MODELS---------

DRCOUP ANALYT NI-FE1.0 EV

ITERATION NUMBER 2 NAMCYC = FEDERAL

PARKING FOR 1.040 HOURS
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 3 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 9 OF THE URBAN SCHEDULE

PARKING FOR 0.870 HOURS
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 2 OF THE URBAN SCHEDULE

PARKING FOR 6.830 HOURS
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 3 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 4 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 5 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 6 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 7 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 8 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 9 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 10 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 11 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 12 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 13 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 14 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 15 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 16 OF THE URBAN SCHEDULE
ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 17 OF THE URBAN SCHEDULE

PARKING FOR 1.630 HOURS
ITERATION NUMBER 1 NAMCYC = FEDERAL
PARKING FOR 11.890 HOURS

<table>
<thead>
<tr>
<th>SCHEDULE</th>
<th>PERIOD RANGE</th>
<th>AVERAGE ROAD SPEED</th>
<th>ENERGY</th>
<th>MAX ROAD MAX ROAD</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>SEC</td>
<td>MI</td>
<td>MI/H</td>
</tr>
<tr>
<td>FEDERAL</td>
<td>6535</td>
<td>34.353</td>
<td>1.4</td>
<td>204.3</td>
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</table>

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED:

MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES:

<table>
<thead>
<tr>
<th></th>
<th>BATT SYS</th>
<th>MTR/CNT</th>
<th>DREVTRN</th>
<th>PWTRN</th>
<th>BRAKES</th>
<th>MISC</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH/MI</td>
<td>234.3</td>
<td>37.9</td>
<td>30.6</td>
<td>68.5</td>
<td>34.8</td>
<td>5.5</td>
</tr>
<tr>
<td>PRCNT(PWTRN)</td>
<td>341.1</td>
<td>55.3</td>
<td>44.7</td>
<td>100.0</td>
<td>50.8</td>
<td>8.0</td>
</tr>
<tr>
<td>PRCNT(OVERALL)</td>
<td>53.0</td>
<td>8.6</td>
<td>6.9</td>
<td>15.5</td>
<td>7.9</td>
<td>1.2</td>
</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.528</td>
<td>0.882</td>
<td>0.898</td>
<td>0.794</td>
<td></td>
<td></td>
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</tbody>
</table>

COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL):

<table>
<thead>
<tr>
<th>TOTAL PHASE</th>
<th>ACCEL</th>
<th>CRUISE</th>
<th>COAST</th>
<th>BRAKE</th>
<th>DWELL</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVERALL(WH/MI)</td>
<td>442.1</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>EFFICIENCY</td>
<td>0.903</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>MOTOR</td>
<td>37.9</td>
<td>23.7</td>
<td>2.4</td>
<td>0.0</td>
<td>11.9</td>
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<tr>
<td>EFFICIENCY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PERCENT</td>
<td>8.6</td>
<td>5.4</td>
<td>0.3</td>
<td>0.0</td>
<td>2.7</td>
</tr>
<tr>
<td>TRANSMISSION</td>
<td>30.6</td>
<td>0.894</td>
<td>0.873</td>
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<td>0.851</td>
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<tr>
<td>EFFICIENCY</td>
<td>0.882</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PERCENT</td>
<td>6.9</td>
<td>4.5</td>
<td>0.4</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>AERO</td>
<td>37.4</td>
<td>15.3</td>
<td>5.8</td>
<td>0.0</td>
<td>16.2</td>
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</tbody>
</table>

M-55
### Battery and Charger

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<th>PERCENT</th>
<th>8.5</th>
<th>3.5</th>
<th>1.3</th>
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<th>3.7</th>
<th>0.0</th>
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<td>TIRES</td>
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<td>26.4</td>
<td>0.0</td>
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<tr>
<td>PERCENT</td>
<td>13.9</td>
<td>6.3</td>
<td>1.7</td>
<td>0.0</td>
<td>6.0</td>
<td>0.0</td>
</tr>
<tr>
<td>MISCELLAN</td>
<td>5.5</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>5.1</td>
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<td>PERCENT</td>
<td>1.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.2</td>
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### Energy

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<tr>
<th>OUT</th>
<th>IN</th>
<th>LOSS</th>
<th>OUT</th>
<th>IN</th>
<th>STATE</th>
<th>EFF</th>
<th>LOSS</th>
<th>EFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH/MI</td>
<td>WH/MI</td>
<td>PERCENT</td>
<td>WH/MI</td>
<td>WH/MI</td>
<td>PERCENT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>262</td>
<td>55</td>
<td>190</td>
<td>43.0</td>
<td>41.2</td>
<td>16.9</td>
<td>0.000</td>
<td>0.38</td>
<td>44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOTAL</th>
<th>ELECT CONSUME</th>
<th>ELECT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE</td>
<td>AT MALL</td>
<td>(AT 10.0C/KWH)</td>
</tr>
<tr>
<td>MI</td>
<td>WH/MI</td>
<td>WH/MI*TON</td>
</tr>
<tr>
<td>126.3</td>
<td>442.2</td>
<td>228.3</td>
</tr>
</tbody>
</table>

* - Based on lowest depth of discharge (0.794) which could sustain the maximum power density (90.9 W/KO).

### Equivalent Fuel Consumption and Economy (Gasoline)

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<thead>
<tr>
<th>SOURCE OF CONSUMPTION</th>
<th>ECONOMY</th>
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</thead>
<tbody>
<tr>
<td>PRIMARY ENERGY</td>
<td>LIT/KM</td>
</tr>
<tr>
<td>PETROLEUM</td>
<td>0.07962</td>
</tr>
<tr>
<td>COAL</td>
<td>0.04603</td>
</tr>
</tbody>
</table>

Do you want the CAFE value computed? 

N

### Input Changes for Next Run

Parameter

Input name of parameter, initial value, final value, and num steps.

NAMCYC

Do you want a summary of the urban subsegments (Y or N)?

N

Input name and number of cycles, input end when done, for 'park' and 'idle' cycles, input name and period.

FEDERAL 2

PARK 4.57HR

URB1

PARK 0.60HR

FEDERAL 2

M-56
INPUT COMPLETE FOR THIS CASE
INPUT A 1-76 CHARACTER TITLE FOR THIS CASE-

TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 7
DATE 4-OCT-04
TIME 11144140

ITERATION NUMBER 1 NAMCYC = FEDRAL

KEY PARAMETERS (METRIC UNITS)

<table>
<thead>
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<th>VEHICLE</th>
<th>STRATEGY</th>
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<td>MT</td>
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<tr>
<td>469</td>
<td>1757</td>
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INPUT AS MODEL N1-FE1.0 EV

ITERATION NUMBER 2 NAMCYC = FEDRAL

PARKING FOR 4.570 HOURS

ITERATION NUMBER 1 CONSISTING OF SUBSEGMENT 1 OF THE URBAN SCHEDULE

PARKING FOR 0.600 HOURS

ITERATION NUMBER 1 NAMCYC = FEDRAL

ITERATION NUMBER 2 NAMCYC = FEDRAL

PARKING FOR 2.570 HOURS

ITERATION NUMBER 1 NAMCYC = FEDRAL

PARKING FOR 1.380 HOURS

ITERATION NUMBER 1 NAMCYC = FEDRAL

PARKING FOR 12.550 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD

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<th>SPEED</th>
<th>W/O RON</th>
<th>W RON</th>
<th>POWER</th>
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<tbody>
<tr>
<td>SEC</td>
<td>MI</td>
<td>MI/H</td>
<td>WH/MI</td>
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M-57
ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED:

<table>
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<tr>
<th>MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES</th>
<th>BATT SYS</th>
<th>MTR/CNT</th>
<th>DRVTRN</th>
<th>PWTRN</th>
<th>BRAKES</th>
<th>MISC</th>
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<tbody>
<tr>
<td>WH/MI</td>
<td>230.8</td>
<td>37.9</td>
<td>30.3</td>
<td>68.2</td>
<td>34.6</td>
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<td>PRCNT(PWTRN)</td>
<td>336.2</td>
<td>89.5</td>
<td>44.4</td>
<td>100.0</td>
<td>50.7</td>
<td>6.1</td>
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<td>PRCNT(OVERALL)</td>
<td>53.0</td>
<td>8.7</td>
<td>7.0</td>
<td>15.7</td>
<td>8.0</td>
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<td>EFFICIENCY</td>
<td>0.526</td>
<td>0.881</td>
<td>0.899</td>
<td>0.793</td>
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COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL):

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<tr>
<th>OVERALL WH/MI</th>
<th>TOTAL</th>
<th>ACCEL</th>
<th>CRUISE</th>
<th>COAST</th>
<th>BRAKE</th>
<th>DWELL</th>
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<tbody>
<tr>
<td>425.2</td>
<td>0.303</td>
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</table>

MOTOR:

| EFFICIENCY | 0.881 |
| PERCENT | 8.7 |
| EFFICIENCY | 0.693 |

TRANSMISSION:

| EFFICIENCY | 0.899 |
| PERCENT | 7.0 |
| EFFICIENCY | 0.899 |

AERO:

| EFFICIENCY | 0.899 |
| PERCENT | 8.2 |
| EFFICIENCY | 0.899 |

TIRES:

| EFFICIENCY | 0.899 |
| PERCENT | 14.2 |
| EFFICIENCY | 0.899 |

MISCELLANEOUS:

| EFFICIENCY | 0.899 |
| PERCENT | 1.0 |
| EFFICIENCY | 0.899 |

BATTERY AND CHARGER:

--- ENERGY --- POWER MX FINAL BATT --- CHARGER ---

<p>| OUT IN LOSS | OUT IN STATE EFF | LOSS EFF |</p>
<table>
<thead>
<tr>
<th>WH/MI</th>
<th>WH/MI</th>
<th>PRCNT</th>
<th>W/LB</th>
<th>WH/MI</th>
<th>PRCNT</th>
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<tr>
<td>259</td>
<td>54</td>
<td>187</td>
<td>43.0</td>
<td>41.2</td>
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TOTAL ELECT CONSUMPTION:

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<tr>
<th>RANGE (AT WALL)</th>
<th>ELECT CONSUMPTION</th>
<th>ELECT COST</th>
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<tr>
<td>MI</td>
<td>WH/MI</td>
<td>WH/MI#TON</td>
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<tr>
<td>127.4</td>
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EQUIVALENT FUEL CONSUMPTION AND ECONOMY (GASOLINE):

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<th>SOURCE OF CONSUMPTION</th>
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<tr>
<td>PRIMARY ENERGY</td>
<td>LIT/KM</td>
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<td>PETROLEUM</td>
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<td>22.1</td>
<td>51.9</td>
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</table>

DO YOU WANT THE CAFE VALUE COMPUTED?

> N

M-58
INPUT CHANGES FOR NEXT RUN—

PARAMVAR
INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS—

NAMCYC
DO YOU WANT A SUMMARY OF THE URBAN SUBSECTIONS (Y OR N)?

N
INPUT NAME AND NUMBER OF CYCLES. INPUT END WHEN DONE.
FOR 'PARK' AND 'IDLE' CYCLES, INPUT NAME AND PERIOD

FEDERAL 2
PARK 0.62HR

FEDERAL 2
PARK 0.15HR

FEDERAL 2
PARK 3.73HR

URB1 1 URB2 1
PARK 0.216HR

URB3 1 URB4 1 URB5 1 URB6 1 URB7 1 URB8 1 URB9 1 URB10 1 URB11 1
URB12 1 URB13 1 URB14 1 URB15 1 URB16 1 URB17 1
PARK 16.42HR
END
RUN
INPUT COMPLETE FOR THIS CASE
INPUT A 1-70 CHARACTER TITLE FOR THIS CASE—

TEST CASE - 5 PAS - HI-FEI.0 - 100KMI. DESIRED RANGE - ELECTRIC - CYCLE 0
DATE 4-OCT-04
TIME 11456712

ITERATION NUMBER 1 NAMCYC = FEDERAL

KEY PARAMETERS (METRIC UNITS)
---------VEHICLE-------- STRATEGY---------
WB WT CDV TIME PTIME ACIFAC ACIFAC MKKS NREGEN EFFCH EFFCFW
489 1757 0.600 RADIAL 34.0 0.50 -0.67 0.30 2 0.000 0.595
---------MODELS---------
DRCOUP ANALYT HI-FEI.0 EV
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| Schedule Period Range Average Road Energy Max Road Speed W/O Ron W Ron Power SEC Mi Mi/H Mi/Mi HP | Federal 04406 32.157 2.2 202.3 97.6 50.6 |

Energy and efficiency summary for range traveled.
### Major Subsystem Losses and Efficiencies

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<thead>
<tr>
<th>Component</th>
<th>Total BH/Mi</th>
<th>Motor</th>
<th>Percent</th>
<th>Efficiency</th>
<th>Transmision</th>
<th>Percent</th>
<th>Efficiency</th>
<th>Aerial</th>
<th>Percent</th>
<th>Efficiency</th>
<th>Tires</th>
<th>Percent</th>
<th>Efficiency</th>
<th>Misc</th>
<th>Percent</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brakes</td>
<td>34.6</td>
<td>3.6</td>
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<td>0.8</td>
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<tr>
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### Component Loss by Driving Phase (BH/MI and Percent of Overall)

<table>
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<tr>
<th>Overall</th>
<th>BH/MI</th>
<th>ACCEL</th>
<th>CRUISE</th>
<th>COAST</th>
<th>BRAKE</th>
<th>DWELL</th>
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<tbody>
<tr>
<td>Motor</td>
<td>37.9</td>
<td>23.7</td>
<td>2.3</td>
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<td>11.9</td>
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<tr>
<td>Percent</td>
<td>8.7</td>
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<td>2.7</td>
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<tr>
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<td>0.881</td>
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<td>0.871</td>
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<td>Transmision</td>
<td>30.3</td>
<td>19.8</td>
<td>1.7</td>
<td>0.0</td>
<td>8.8</td>
<td>0.0</td>
</tr>
<tr>
<td>Percent</td>
<td>7.0</td>
<td>4.6</td>
<td>0.4</td>
<td>0.0</td>
<td>2.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.890</td>
<td>0.899</td>
<td>0.895</td>
<td>0.000</td>
<td>0.895</td>
<td>0.000</td>
</tr>
<tr>
<td>Aerial</td>
<td>36.0</td>
<td>14.8</td>
<td>5.6</td>
<td>0.0</td>
<td>15.7</td>
<td>0.0</td>
</tr>
<tr>
<td>Percent</td>
<td>8.3</td>
<td>3.4</td>
<td>1.3</td>
<td>0.0</td>
<td>3.6</td>
<td>0.0</td>
</tr>
<tr>
<td>Tires</td>
<td>61.6</td>
<td>27.6</td>
<td>7.6</td>
<td>0.0</td>
<td>26.5</td>
<td>0.0</td>
</tr>
<tr>
<td>Percent</td>
<td>14.2</td>
<td>6.3</td>
<td>1.7</td>
<td>0.0</td>
<td>6.1</td>
<td>0.0</td>
</tr>
<tr>
<td>Misc</td>
<td>3.6</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
<td>3.3</td>
</tr>
<tr>
<td>Percent</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

### Battery and Charger

<table>
<thead>
<tr>
<th>Battery</th>
<th>Final BH/MI</th>
<th>Charger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Out</td>
<td>WH/MI</td>
<td>Out</td>
</tr>
<tr>
<td>Battery</td>
<td>54 187 43.0</td>
<td>16.9 0.000 43.1000 0.900</td>
</tr>
<tr>
<td>Range</td>
<td>129.4 434.7</td>
<td>224.5 4.35</td>
</tr>
<tr>
<td>Mi</td>
<td>102.7 6.21</td>
<td></td>
</tr>
</tbody>
</table>

### Equivalent Fuel Consumption and Economy (Gasoline)

<table>
<thead>
<tr>
<th>Source of Primary Energy</th>
<th>Consumption Economy</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETROLEUM</td>
<td>0.07819 12.8 30.1</td>
</tr>
<tr>
<td>COAL</td>
<td>0.04521 22.1 52.0</td>
</tr>
</tbody>
</table>

**Do you want the CAPE value computed?**

**Input Changes for Next Run**
PARAMVAR
INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUN STEPS-
>
NAMCYC
DO YOU WANT A SUMMARY OF THE URBAN SUBSEGMENTS (Y OR N)?
>
N
INPUT NAME AND NUMBER OF CYCLES. INPUT END WHEN DONE.
FOR 'PARK' AND 'IDLE' CYCLES, INPUT NAME AND PERIOD
>
HIWAY 4
>
PARK 7.04HR
>
FEDRAL 1
>
HIWAY 1
>
FEDRAL 1
>
PARK 0.66HR
>
FEDRAL 1
>
PARK 14.09HR
>
END
>
RUN
INPUT COMPLETE FOR THIS CASE
>
INPUT A 1-78 CHARACTER TITLE FOR THIS CASE-
>
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 9
DATE 4-OCT-84
TIME 12:02:45

ITERATION NUMBER 1 NAMCYC = HIWAY
HIWAY SCHEDDATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
HIWAY CYCLE. 766 VALUES READ.

KEY PARAMETERS (METRIC UNITS)
--------------VEHICLE---------------------STRATEGY---------
WB WT CDA TIURE PTIRE ACLFAC ACLHCS FBRKS NREOEN EFFCM EFFCFW
499 1757 0.600 RADIAL 36.0 0.50 -0.67 0.30 2 0.000 0.595

--------------MODELS--------------
DRCOUPT ANALYT NI-FE1.0 EV

ITERATION NUMBER 2 NAMCYC = HIWAY
ITERATION NUMBER 3 NAMCYC = HIWAY
ITERATION NUMBER 4 NAMCYC = HIWAY
PARKING FOR 7.040 HOURS

ITERATION NUMBER 1 NAMCYC = FEDERAL
FEDERAL SCHUDATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
FEDERAL CYCLE. 1372 VALUES READ.

ITERATION NUMBER 1 NAMCYC = HIWAY
HIWAY SCHUDATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
HIWAY CYCLE. 766 VALUES READ.

ITERATION NUMBER 1 NAMCYC = FEDERAL
FEDERAL SCHUDATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
FEDERAL CYCLE. 1372 VALUES READ.

PARKING FOR 0.660 HOURS

ITERATION NUMBER 1 NAMCYC = FEDERAL
PARKING FOR 14.090 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD
SECONDS MI/H MI/H POWER POWER
HIWAY 06382 73.635 3.1 101.2 132.6 50.6

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED-

<table>
<thead>
<tr>
<th>MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES</th>
<th>WH/MI</th>
<th>BATT SYS</th>
<th>MTR/CNT</th>
<th>DRVTRN</th>
<th>PWTRN</th>
<th>BRAKES</th>
<th>MISCELLANEOUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>EFFICIENCY</td>
<td>0.525</td>
<td>0.894</td>
<td>0.899</td>
<td>0.808</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

COMPONENT LOSS BY DRIVING PHASE(WH/MI AND PERCENT OF OVERALL) -

| OVERALL WH/MI | 407.2 |
| TOTAL EFFICIENCY | 0.364 |
| MOTOR | 27.0 |
| EFFICIENCY | 0.894 |
| TRANSMISSION | 23.8 |
| EFFICIENCY | 0.899 |
| AERO | 70.1 |
| EFFICIENCY | 0.899 |
| TIRES | 62.5 |
| EFFICIENCY | 0.899 |
| PERCENT | 15.3 |
| EFFICIENCY | 0.899 |
| MISCELLANEOUS | 2.5 |
| EFFICIENCY | 0.899 |

-----------------------BATTERY AND CHARGER----------------------

M-63
TOTAL ELECT CONSM ELECT COST
RANGE AT WALL (AT 10.0 C/KWH)
Ml WH/Ml WH/Ml*TON C/MI
134.4 407.2 210.3 4.07
106.7

*BASED ON LOWEST DEPTH OF DISCHARGE (0.794) WHICH COULD SUSTAIN THE MAXIMUM POWER DENSITY (90.9 W/KG).

EQUIVALENT FUEL CONSUMPTION AND ECONOMY (GASOLINE)-

<table>
<thead>
<tr>
<th>PRIMARY ENERGY</th>
<th>CONSUMPTION</th>
<th>ECONOMY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PETROLEUM</td>
<td>0.07724</td>
<td>12.9</td>
</tr>
<tr>
<td>COAL</td>
<td>0.04466</td>
<td>22.4</td>
</tr>
</tbody>
</table>

DO YOU WANT THE SAFETY VALUE COMPUTED?
N

************** INPUT CHANGES FOR NEXT RUN- 

PARAMVAR
INPUT NAME OF PARAMETER, INITIAL VALUE, FINAL VALUE, AND NUM STEPS-

NANCYC
DO YOU WANT A SUMMARY OF THE URBAN SUBSEQUENT (Y OR N)?
N

INPUT NAME AND NUMBER OF CYCLES, INPUT END WHEN DONE.
FOR 'PARK' AND 'IDLE' CYCLES, INPUT NAME AND PERIOD

HIWAY 4
PARK 6.5HR
FEDERAL 1
HIWAY 4
FEDERAL 1
PARK 15.04HR
END
RUN

INPUT COMPLETE FOR THIS CASE
INPUT A 1-78 CHARACTER TITLE FOR THIS CASE-
TEST CASE - 5 PAS - NI-FE1.0 - 100MI. DESIRED RANGE - ELECTRIC - CYCLE 10
DATE  4-OCT-84
TIME  12:00:07

ITERATION NUMBER 1 NAMCYC = HIWAY
HIWAY SCHODATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
HIWAY CYCLE.  766 VALUES READ.

KEY PARAMETERS (METRIC UNITS)
---------------------------
<table>
<thead>
<tr>
<th>VEHICLE</th>
<th>STRATEGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB</td>
<td>MT</td>
</tr>
<tr>
<td>46V</td>
<td>1737</td>
</tr>
<tr>
<td>0.60</td>
<td>38.0</td>
</tr>
<tr>
<td>-0.67</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>0.000</td>
</tr>
<tr>
<td>0.383</td>
<td>0.585</td>
</tr>
</tbody>
</table>

-----------MODELS-----------
OR000P ANALYT NI-FE1.0 EV

ITERATION NUMBER 2 NAMCYC = HIWAY
ITERATION NUMBER 3 NAMCYC = HIWAY
ITERATION NUMBER 4 NAMCYC = HIWAY

PARKING FOR 6.500 HOURS

ITERATION NUMBER 1 NAMCYC = FEDERAL
FEDERAL SCHODATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
FEDERAL CYCLE. 1372 VALUES READ.

ITERATION NUMBER 1 NAMCYC = HIWAY
HIWAY SCHODATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
HIWAY CYCLE. 766 VALUES READ.

ITERATION NUMBER 2 NAMCYC = HIWAY
ITERATION NUMBER 3 NAMCYC = HIWAY
ITERATION NUMBER 4 NAMCYC = HIWAY

ITERATION NUMBER 1 NAMCYC = FEDERAL
FEDERAL SCHODATA NOT CURRENTLY IN CORE
SEARCHING BULKDATA FILE FOR IT.
FEDERAL CYCLE. 1372 VALUES READ.

PARKING FOR 15.040 HOURS

SCHEDULE PERIOD RANGE AVERAGE ROAD ENERGY MAX ROAD
<table>
<thead>
<tr>
<th>SECONDS</th>
<th>MI</th>
<th>MI/H</th>
<th>W/O RON</th>
<th>W RON</th>
<th>MAX POWER</th>
</tr>
</thead>
<tbody>
<tr>
<td>HIWAY</td>
<td>86,400</td>
<td>96.954</td>
<td>4.0</td>
<td>176.7</td>
<td>140.1</td>
</tr>
</tbody>
</table>

ENERGY AND EFFICIENCY SUMMARY FOR RANGE TRAVELED:

<table>
<thead>
<tr>
<th>MAJOR SUBSYSTEM LOSSES AND EFFICIENCIES-</th>
</tr>
</thead>
<tbody>
<tr>
<td>BATT SYS</td>
</tr>
<tr>
<td>WH/MI</td>
</tr>
<tr>
<td>COMPONENT LOSS BY DRIVING PHASE (WH/MI AND PERCENT OF OVERALL)</td>
</tr>
<tr>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>OVERALL, WH/MI</td>
</tr>
<tr>
<td>EFFICIENCY</td>
</tr>
<tr>
<td>MOTOR</td>
</tr>
<tr>
<td>PERCENT</td>
</tr>
<tr>
<td>EFFICIENCY</td>
</tr>
<tr>
<td>TRANSMISSION</td>
</tr>
<tr>
<td>PERCENT</td>
</tr>
<tr>
<td>EFFICIENCY</td>
</tr>
<tr>
<td>AERU</td>
</tr>
<tr>
<td>PERCENT</td>
</tr>
<tr>
<td>TIRES</td>
</tr>
<tr>
<td>PERCENT</td>
</tr>
<tr>
<td>MISCELLAN</td>
</tr>
<tr>
<td>PERCENT</td>
</tr>
</tbody>
</table>

**---BATTERY AND CHARGER---**

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>POWER</th>
<th>FINAL</th>
<th>BATT</th>
<th>CHARGER</th>
</tr>
</thead>
<tbody>
<tr>
<td>OUT</td>
<td>IN</td>
<td>LOSS</td>
<td>EFF</td>
<td></td>
</tr>
<tr>
<td>WH/MI</td>
<td>WH/MI</td>
<td>PRCNT</td>
<td>W/LB</td>
<td>WH/MI</td>
</tr>
<tr>
<td>220</td>
<td>20</td>
<td>160</td>
<td>39.9</td>
<td>41.2</td>
</tr>
</tbody>
</table>

**TOTAL**

<table>
<thead>
<tr>
<th>ELECT CONSM</th>
<th>ELECT COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANGE MI</td>
<td>AT WALL</td>
</tr>
<tr>
<td>135.7</td>
<td>400.5</td>
</tr>
<tr>
<td>107.7</td>
<td></td>
</tr>
</tbody>
</table>

* - BASED ON LOWEST DEPTH OF DISCHARGE (0.794) WHICH COULD SUSTAIN THE MAXIMUM POWER DENSITY (90.9 W/KG).

**EQUIVALENT FUEL CONSUMPTION AND ECONOMY (OASOLINE)**

<table>
<thead>
<tr>
<th>SOURCE OF CONSUMPTION</th>
<th>ECONOMY</th>
<th>EconomY</th>
<th>EconomY</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIMARY ENERGY</td>
<td>LIT/KM</td>
<td>KM/LIT</td>
<td>MI/OAL</td>
</tr>
<tr>
<td>PETROLEUM</td>
<td>0.07689</td>
<td>13.0</td>
<td>30.6</td>
</tr>
<tr>
<td>COAL</td>
<td>0.04445</td>
<td>22.5</td>
<td>52.9</td>
</tr>
</tbody>
</table>

DO YOU WANT THE CAPE VALUE COMPUTED?

> N

**---INPUT CHANGES FOR NEXT RUN---**

<table>
<thead>
<tr>
<th>WUIUT</th>
<th>ORCUSER</th>
<th>Job terminated at 4-OCT-1984 12:14:56.78</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Accountings information:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buffered I/O count: 115</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak working set size: 529</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Direct I/O count: 1963</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Peak page file size: 493</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Page faults: 1290</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mounted volumes: 0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elapsed CPU time: 0 00:09:46.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Elapsed time: 0 02:13:56.90</td>
</tr>
</tbody>
</table>

M-66
< (ELTEST.RAN)

<table>
<thead>
<tr>
<th>cycle</th>
<th>wh/mile</th>
<th>miles/day</th>
<th>days</th>
<th>cum miles</th>
<th>kwh</th>
<th>DOD cycles</th>
<th>cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>537.2</td>
<td>4.2</td>
<td>57</td>
<td>239.4</td>
<td>128.6057</td>
<td>4.125736E-02</td>
<td>2.35167</td>
</tr>
<tr>
<td>2</td>
<td>475.8</td>
<td>7.45</td>
<td>50</td>
<td>372.5</td>
<td>177.2355</td>
<td>6.213511E-02</td>
<td>3.106756</td>
</tr>
<tr>
<td>3</td>
<td>469</td>
<td>8.2</td>
<td>43</td>
<td>352.6</td>
<td>165.3694</td>
<td>6.908171E-02</td>
<td>2.970514</td>
</tr>
<tr>
<td>4</td>
<td>430.5</td>
<td>16.86</td>
<td>32</td>
<td>539.52</td>
<td>243.0538</td>
<td>1.136918</td>
<td>4.382778</td>
</tr>
<tr>
<td>5</td>
<td>443.8</td>
<td>22.35</td>
<td>63</td>
<td>1409.05</td>
<td>624.8926</td>
<td>1.758459</td>
<td>11.07628</td>
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<tr>
<td>6</td>
<td>442.2</td>
<td>27</td>
<td>27</td>
<td>729</td>
<td>322.3638</td>
<td>2.134387</td>
<td>5.762846</td>
</tr>
<tr>
<td>7</td>
<td>469.3</td>
<td>45.4</td>
<td>29</td>
<td>1316.6</td>
<td>573.116</td>
<td>3.506501</td>
<td>10.17465</td>
</tr>
<tr>
<td>8</td>
<td>434.7</td>
<td>59.6</td>
<td>18</td>
<td>1072.8</td>
<td>466.3462</td>
<td>4.605874</td>
<td>8.290572</td>
</tr>
<tr>
<td>9</td>
<td>457.2</td>
<td>73.6</td>
<td>19</td>
<td>1398.4</td>
<td>569.4285</td>
<td>5.947691</td>
<td>10.40476</td>
</tr>
<tr>
<td>10</td>
<td>400.5</td>
<td>105.5</td>
<td>8</td>
<td>844</td>
<td>338.022</td>
<td>7.774503</td>
<td>6.219602</td>
</tr>
</tbody>
</table>

8272.87 miles 3608.433 Kw-hrs 64.74244 cycles 0 FUEL MILES 0

Electric... 0 Fuel... 0
Annual travel in Km= 13236.59
Battery Cycle Life= 750 Cycles
Depth of discharge Average Daily= .1773763

(AVENERGY OUTPUT REPORT)
## ELECTRIC AND HYBRID VEHICLE COST MODEL

**TEST CASE - 3 PRO - HI-PEL.0 - 100M. BEREAL RANGE - ELECTRIC**

**INPUTS**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-PASS.</td>
<td></td>
</tr>
<tr>
<td>REAL. INTEREST RATE</td>
<td>10%</td>
</tr>
<tr>
<td>VEHICLE HEIGHT</td>
<td>128.046</td>
</tr>
<tr>
<td>VEHICLE BALANCE VALUE</td>
<td>4.977</td>
</tr>
<tr>
<td>ACCESSORY COST</td>
<td>$0</td>
</tr>
<tr>
<td>BATTERY</td>
<td></td>
</tr>
<tr>
<td>BATTERY HEIGHT</td>
<td>480,617</td>
</tr>
<tr>
<td>BATTERY CYCLE LIFE</td>
<td>760</td>
</tr>
<tr>
<td>ELECTRICITY COST</td>
<td>$0.60/WH</td>
</tr>
<tr>
<td>REPAIR &amp; MAINTENANCE初</td>
<td>$0.50/WH</td>
</tr>
<tr>
<td>INSURANCE</td>
<td>$0.25/WH</td>
</tr>
<tr>
<td>OPERATING COST</td>
<td>$0.50/WH</td>
</tr>
<tr>
<td>VEHICLE BALANCE VALUE LOW</td>
<td>$357.14</td>
</tr>
<tr>
<td>BATTERY SALVAGE LOW</td>
<td>$179.68</td>
</tr>
</tbody>
</table>

**OUTPUTS**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>9-PASS.</td>
<td></td>
</tr>
<tr>
<td>REAL. INTEREST RATE</td>
<td>10%</td>
</tr>
<tr>
<td>VEHICLE HEIGHT</td>
<td>128.046</td>
</tr>
<tr>
<td>VEHICLE BALANCE VALUE</td>
<td>4.977</td>
</tr>
<tr>
<td>ACCESSORY COST</td>
<td>$0</td>
</tr>
<tr>
<td>BATTERY</td>
<td></td>
</tr>
<tr>
<td>BATTERY HEIGHT</td>
<td>480,617</td>
</tr>
<tr>
<td>BATTERY CYCLE LIFE</td>
<td>760</td>
</tr>
<tr>
<td>ELECTRICITY COST</td>
<td>$0.60/WH</td>
</tr>
<tr>
<td>REPAIR &amp; MAINTENANCE初</td>
<td>$0.50/WH</td>
</tr>
<tr>
<td>INSURANCE</td>
<td>$0.25/WH</td>
</tr>
<tr>
<td>OPERATING COST</td>
<td>$0.50/WH</td>
</tr>
<tr>
<td>VEHICLE BALANCE VALUE LOW</td>
<td>$357.14</td>
</tr>
<tr>
<td>BATTERY SALVAGE LOW</td>
<td>$179.68</td>
</tr>
</tbody>
</table>

**TOTAL LIFE CYCLE COST**

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEHICLE BALANCE VALUE LOW</td>
<td>$357.14</td>
</tr>
<tr>
<td>BATTERY SALVAGE LOW</td>
<td>$179.68</td>
</tr>
</tbody>
</table>

*(AVCOST OUTPUT REPORT)*
10 KEY OFFLY
20 '----------------------------------------------------------------------
30 ' ** AVSIZING **
40 ' SIZES A PRELIMINARY VEHICLE TARGETED TO A DESIRED RANGE.
50 '----------------------------------------------------------------------
60 ' 90 '----------------------------------------------------------------------
100 '----------------------------------------------------------------------
110 PRINT TAB(24)"WELCOME TO THE AVSIZING PROGRAM"
120 PRINT : PRINT
130 DIM CON(6),US(20),PE(12),C12(4),B14(4),DOM(50),RAN(50)
140 ERRUR%=0
150 ' 160 REM PROMPT FOR THE INPUT DATA
170 ' 180 PRINT "DO YOU WISH TO RUN 1"
190 PRINT " 1. NEW VEHICLE USING AN URBAN OR HIGHWAY CYCLE?" ; PRINT " 2. PRELIMINARY VEHICLE USING A 24 HR CYCLE?" ; PRINT " 3. REDESIGN OF VEHICLE BY CHAIN GUIDING THE BMF?"
200 INPUT "ENTER TYPE OF RUN (1.2.3) " , TURX
210 IF TURX<>1 AND TURX<>2 AND TURX<>3 THEN 200
220 ' 230 REM OPEN FILE VEHICLE.DAT
240 ' 250 IF TURX=1 THEN 370
260 OPEN "VEHICLE.DAT" FOR INPUT AS 02
270 INPUT#2, ILE$#, CAPX, VHX, ICHT, DRAN, NUMX, SNUMX, CDA, CNUMX, BMF1, BMF2, PIORX
280 CLOSE #2
290 IF TURX<>1 THEN 1000
300 ' 310 ' 320 PRINT : PRINT
330 PRINT "ENTER A VALUE BETWEEN"BMF1" AND 0.45"
340 PRINT : PRINT
350 INPUT "ENTER BMF 1 " , BMFIN
360 GOTO 1000
370 ' 380 REM SET RUN FLAW TO ZERO, (FIRST RUN)
390 ' 400 MF%=0
410 PRINT : PRINT
420 PRINT "ENTER TITLE OF RUN (67 CHARACTERS OR LESS - DO NOT USE COMMAS )"
430 INPUT "TITLE 1 ", TLE$#
440 Mnini
450 Mnini "VEHICLE CAPACITY"
460 Mnini SIRUN#$(14,196)
470 Mnini "2.4.5 OR 6 PASSENGERS"
480 Mnini "IF THE VEHICLE IS A VAN THEN SET CAPACITY EQUAL TO 6"
490 Mnini "ENTER VEHICLE CAPACITY(PASSENGERS) 1 " , CAPX
500 ' 510 REM IF INVALID NUMBER OF PASSENGERS THEN TRY AGAIN
520 ' 530 IF CAPX<>2 AND CAPX<>4 AND CAPX<>5 AND CAPX<>6 THEN 490
540 IF CAPX=2 OR CAPX=6 THEN VEHX=1
550 IF CAPX<>2 OR CAPX<>6 THEN GOTO 850
560 Mnini
570 Mnini "VEHICLE TYPE"
580 Mnini SIRUN#$(12,196)
PRINT "1. ELECTRIC VEHICLE" 1 PRINT "2. HYBRID VEHICLE"
120 INPUT "ENTER VEHICLE TYPE (1 OR 2) : ", VEH
140 CLS
160 INPUT "ENTER DESIRED RANGE (MI) : ", DRAM
180 INPUT "ENTER BATTERY TYPE NUMBER : ", NUM
200 CLS
220 PRINT "YOU WISH TO RUN ELVEC IN 1: DEMAND" 1 PRINT "2. BATCH"
240 INPUT "ENTER TYPE OF RUN (1 OR 2) : ", D06
260 IF DOBX<1 AND DOB<2 THEN 20
280 IF T0R<2 THEN CLS
300 IF T0R<2 THEN PRINT
320 IF T0R=2 THEN PRINT "ENTER FILENAME OF 24 HR. INPUT FILE : ", NN
340 IF T0R=2 AND CAPX<5 THEN PRINT "RUNS FOR 5 PAS VEHICLE" 1 PRINT "CAPACITY = 
360 ELSE NN=0=""STAREL"
380 CLS
400 REM INPUT RANGE FOR 5 PAS VEHICLE.
M1. VEHICLE
  PRINT "  3. 250 M1. VEHICLE"
1170 IF TOR%=2 AND CAPX=5 THEN INPUT "ENTER VEHICLE R\$wZE NO.41.2 OR 3)" • SC
1190 IF CAPX=2 THEN CYCLE%=9
1210 IF CAPX=8 AND SCAPX=1 THEN CYCLE%=10
1220 IF CAPX=5 AND SCAPX=3 THEN CYCLE%=12
1230 IF CAPX=4 THEN CYCLE%=12
1240 CLS
1250 REM SET MTX=1 FOR THE AC OPTION ONLY.
1260 MTX=1
1270 IF NUM%=1 THEN 1440 'BRANCH TO AL—AIR DATA SET
1290 IF NUM%=2 THEN 1530 'BRANCH TO FE—AIR DATA SET
1300 IF NUM%=3 THEN 1700 'BRANCH TO LI—FE—S DATA SET
1310 IF NUM%=4 THEN 2030 'BRANCH TO LI—FE—V2 DATA SET
1320 IF NUM%=5 THEN 2100 'BRANCH TO NA—S DATA SET
1330 IF NUM%=6 THEN 2350 'BRANCH TO NI—FE DATA SET
1340 IF NUM%=7 THEN 2500 'BRANCH TO NI—Z2 DATA SET
1350 IF NUM%=8 THEN 2700 'BRANCH TO PB—AC/ADV DATA SET
1360 IF NUM%=9 THEN 2950 'BRANCH TO PB—AC/BIP DATA SET
1370 IF NUM%=10 THEN 3170 'BRANCH TO IN—BR DATA SET
1380 IF NUM%=11 THEN 3420 'BRANCH TO IN—CL2 DATA SET
1390 '9
1400 REM BATTERY DATA SETS
1410 ' DATA SETS CONTAIN MASS DENSITY, SPECIFIC ENERGY AND SPECIFIC POWER —
1420 ' FOLLOWED BY THE CH COEFFICIENTS.
1430 '9
1440 NAME = "AL—AIR" : EFFCD=.18 I SLFD=0 I ACC=5!
1450 DATA 0.21..107.158.165.157
1460 DATA 4.9078.-.723035.-.096402
1470 RESTORE 1430
1480 READ A • B.111. 02• PBC
1490 RESTORE 1460
1500 DOSUB 9990
1510 UOTO 3660
1520 '9
1530 DATA "FE—AIR1.0", "FE—AIR2.1", "FE—AIR2.4", "FE—AIR3.3" I EFFCD=.5
1540 SLFD=114 I ACC=1.67
1550 RESTORE 1530
1560 DOSUB 10000
1570 NAME=BNUM(NUMX)
1580 DATA .12.3.671.109.148.110
1590 DATA .216.202.68.74.140
1600 DATA .229.329.68.54.157
1610 DATA .292.398.52.75.165
1620 DATA 4.48115.—.723075.—.0850794
1630 DATA 4.12545.—.832583.—.0698404
1640 DATA 4.13931.—.858481.—.0612641
1650 DATA 3.90664.—.886569.—.0563951
1660 IF NUMX=1 THEN RESTORE 1530
1670 IF NUMX=2 THEN RESTORE 1590
1680 IF NUMX=3 THEN RESTORE 1640
1690 IF NUMX=4 THEN RESTORE 1610
1700 READ A.B.01.02.PBC
1710 IF NUMX=1 THEN RESTORE 1620
1720 IF NUMX=2 THEN RESTORE 1630
1730 IF NUMX=3 THEN RESTORE 1640
1740 IF NUMX=4 THEN RESTORE 1650
1750 DOSUB 9990
1760 UOTO 3660
1770 '9

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2360 00910 10090
2370 NAM = BATH (SNUM)
2400 DATA -.195.3.836.54.102.120
2410 DATA -.205.3.526.94.121
2420 DATA -.205.3.521.52.141
2430 DATA .122.2.878.48.93.160
2440 DATA .205.2.1084.44.1267.92
2450 DATA .205.2.869.44.1267.92
2460 DATA .205.2.869.44.1267.92
2470 DATA .122.2.878.48.93.160
2480 DATA 2.430 W"ITA 3.90149-.902f949-.0924447
2490 DATA 3.912629-.9924799-.0504292
2500 IF SNUM11=1 THEN RESTORE 2400
2510 IF SNUM11=2 THEN RESTORE 2410
2520 IF SNUM11=3 THEN RESTORE 2420
2530 IF SNUM11=4 THEN RESTORE 2430
2540 IF SNUM11=5 THEN RESTORE 2440
2550 IF SNUM11=6 THEN RESTORE 2450
2560 IF SNUM11=7 THEN RESTORE 2460
2570 IF SNUM11=8 THEN RESTORE 2470
2580 GOSUB 9990
2590 GOTO 3660
2600 NAM = "NI-INV2.0" E FFCD=.7
2610 SFLOD=O I ACC=O
2620 DATA 1.71.6.784.60.100.54
2630 DATA 4.04499-.04499-.084799
2640 RESTORE 2620
2650 READ A.5.01.62.PBC
2660 RESTORE 2620
2670 GOSUB 9990
2680 GOTO 3660
2690
2700 DATA "PBAC/AD1.0", "PBAC/AD2.1", "PBAC/AD2.1", "PBAC/AD3.3" I EFFCD=.75
2710 SFLOD=O I ACC=O
2720 RESTORE 2700
2730 GOSUB 10080
2740 GOSUB 10080
2750 NAM = BATH (SNUM)
2760 DATA .224.8.226.45.99.120
2770 DATA .241.7.137.41.91.135
2780 DATA .241.7.137.41.91.135
2790 DATA .241.7.137.41.91.135
2800 DATA .241.7.137.41.91.135
2810 DATA .241.7.137.41.91.135
2820 DATA .241.7.137.41.91.135
2830 IF SNUM11=1 THEN RESTORE 2750
2840 IF SNUM11=2 THEN RESTORE 2760
2850 IF SNUM11=3 THEN RESTORE 2770
2860 IF SNUM11=4 THEN RESTORE 2780
2870 READ A.5.01.62.PBC
2880 IF SNUM11=1 THEN RESTORE 2790
2890 IF SNUM11=2 THEN RESTORE 2800
2900 IF SNUM11=3 THEN RESTORE 2810
2910 IF SNUM11=4 THEN RESTORE 2820
2920 GOSUB 9990
2930 GOTO 3660
2940
2950 NAM = "PB-AC/B1PL" I EFFCD=.85
2960 SFLOD=O I ACC=O
2970 DATA .26.3.6.50.99.400
2980 DATA .26.3.6.50.99.400
2990 DATA .26.3.6.50.99.400
3000 DATA .26.3.6.50.99.400
3010 DATA .26.3.6.50.99.400
3020 RESTORE 2970
3030 READ A.5.01.62.PBC
3040
3100 RESTORE 3010
3140 OOSUB 9990
3150 GOTO 3660
3190
3170 DATA "ZN-BR2/1.0","ZN-BR2/2.1","ZN-BR2/2.4","ZN-BR2/3.3" EFFCD=.36
3160 SLFD=.08 ACC=1.12
3190 RESTORE 3170
3200 OOSUB 10080
3210 OOSUB 9990
3220 DATA .145.9.3Y2.6.91.83
3230 DATA .244.4.402.49.62.115
3240 DATA .233.2.326.49.49.135
3250 DATA .32.2.678.40.53.150
3260 DATA .4.4.377.627864.151306
3270 DATA .3.4.39.819456.9931689
3280 DATA .3.8.12.837169.9851764
3290 DATA .3.65918.874489.0739032
3300 IF SNUM%1 THEN RESTORE 3220
3310 IF SNUM%=2 THEN RESTORE 3230
3320 IF SNUM%=3 THEN RESTORE 3240
3330 IF SNUM%=4 THEN RESTORE 3250
3340 READ A.BQ19029PBC
3350 IF SNUM%=1 THEN RESTORE 3260
3360 IF SNUM%=2 THEN RESTORE 3270
3370 IF SNUM%=3 THEN RESTORE 3280
3380 IF SNUM%=4 THEN RESTORE 3290
3390 OOSUB 9990
3400 GOTO 3660
3410
3420 DATA "ZN-CL2/1.0","ZN-CL2/2.1","ZN-CL2/2.4","ZN-CL2/3.3" EFFCD=.53
3430 SLFD=.02 ACC=.44
3440 RESTORE 3420
3450 OOSUB 10080
3460 OOSUB 9990
3470 DATA .127.2.882.89.111.86
3480 DATA .214.2.766.54.64.110
3490 DATA .215.2.242.54.40.127
3500 DATA .278.2.066.42.56.130
3510 DATA .4.2577.6.594575.117385
3520 DATA .3.90924.820198.90882068
3530 DATA .3.9250.848145.752426
3540 DATA .3.69599.878004.7930732
3550 IF SNUM%=1 THEN RESTORE 3470
3560 IF SNUM%=2 THEN RESTORE 3480
3570 IF SNUM%=3 THEN RESTORE 3490
3580 IF SNUM%=4 THEN RESTORE 3500
3590 READ A.BQ19029PBC
3600 IF SNUM%=1 THEN RESTORE 3510
3610 IF SNUM%=2 THEN RESTORE 3520
3620 IF SNUM%=3 THEN RESTORE 3530
3630 IF SNUM%=4 THEN RESTORE 3540
3640 OOSUB 9990
3650 GOTO 3660
3660 REM BASIC EQUATIONS (DEFINE VEHICLE PARAMETERS)
3670
3680 REM BASIC EQUATIONS (DEFINE VEHICLE PARAMETERS)
3690
3670 IF VEH%=1 THEN VEH="ELECTRIC"
3670 IF VEH%=2 THEN VEH="HYBRID"
3670 IF CAP%=2 THEN WSH=456
3670 IF CAP%=4 THEN WSH=596
3670 IF CAP%=5 THEN WSH=797
3670 IF CAP%=6 THEN WSH=989
3760 IF CAP%-2 THEN ORADE=17.3
3770 IF CAPX-2 THEN ACCN=21.3
3790 IF CAPX-2 THEN CYCLE=23.9
3800 IF CAP%-4 OR CAP%-3 THEN ORADE=28
3810 IF CAP%-4 OR CAP%-3 THEN ACCN=24
3820 IF CAP%-4 OR CAP%-3 THEN CYCLE=26
3830 IF CAP%-6 THEN ORADE=20.3
3840 IF CAPX-6 THEN ACCN=20.3
3850 IF CAPX-6 THEN CYCLE=20.3
3860 MOTS=490: CONSW=2500: TRFSW=1.418: TRCVTSW=1096: HESW=450
3870 IF CAP%-4 OR CAP%-5 THEN WCONI=GRADE/CONSW
3880 IF CAPX=3 THEN WTI=GRADE/TRFSW
3890 IF CAP%-2 OR CAPX-6 THEN WTI=CYCLE/CONSW
3900 IF CAP%-4 OR CAP%-6 THEN WTI=GRADE/TRFSW
3910 IF CAP%-4 OR VEH%-2 THEN WTCVTI=GRADE/TRCVTSW
3920 IF CAP%-5 AND VEH%-2 THEN WTCVTI=GRADE/TRCVTSW
3930 IF CAP%-3 AND VEH%-2 THEN WTCVTI=GRADE/TRCVTSW
3940 IF VEH%-1 THEN WTCVTI=0 ELSE WTCVTI=GRADE/TRCVTSW
3950 IF VEH%-2 THEN WHE1=GRADE/HESW ELSE WHE1=0
3960 IF VEH%-1 THEN WTR1=GRADE/HESW ELSE WTR1=WTCVTI
3970 IF VEH%-2 THEN WCON1=GRADE/CONSW
3980 IF PTOR%-3 AND TOR%-2 THEN WCON1=WCON1
3990 IF WCON1=GRADE/CONSW
4000 IF WTCVTI=GRADE/CONSW
4010 IF WTCVTI=GRADE/CONSW
4020 R=1.2*DRAM
4030 ICOUNT%=1
4040 IF NUM%-1 THEN OOTO 4120
4050 IF CMOSIX=101 THEN OOTO 4120
4060 IF COUNTX >-30 THEN OOTO 4120 ELSE ICOUNT%=ICOUNT%+1
4070 IF COUNTX >-30 THEN OOTO 4120 ELSE 4030
4080 IF COUNTX >-30 THEN OOTO 4120 ELSE 4030
4090 IF COUNTX >-30 THEN OOTO 4120 ELSE 4030
4100 LIMPRTX=1
4110 IF ACTRAN>=DRAM AND ACTRAN <=1.05+DRAM THEN 4100 ELSE 4100
4120 TAU=6.6601: LPD=CH(1)+CH(2)*LOG(TAU)+CH(3)*LOG(TAU)^2
4130 P=EXP(LPD)
4140 BMF=GRADE/PD
4150 IF BMF>=BMF THEN BMF=BMF
4160 IF BMF>BMF THEN BMF="GRADE" ELSE BMF="RANGE"
4170 IF BMF>BMF THEN BMF=BMF
4180 IF BMF>BMF THEN BMF=BMF
4190 IF BMF>BMF THEN BMF=BMF
4200 IF BMF>BMF THEN BMF=BMF
4210 IF BMF>BMF THEN BMF=BMF
4220 IF BMF>BMF THEN BMF=BMF
4230 WK0 = ACCN/BMF
4240 STAX%=1
4250 OSUB 10170
4260 IF RF%=1 THEN 7220 "END OF PROGRAM OPERATIONS"
4270 OSUB 13910 "COMPUTE WEIGHTS AND WEIGHT DEPENDENT VARIABLES."
4280 "REM PRINT AWSIZINO OUTPUT REPORT"
4290 "REM IF RF%=1 THEN SKIP OUTPUT REPORT HEADER."
4300 "REM PRINT AWSIZINO OUTPUT REPORT"
ORIGINAL PAGE IS
OF POOR QUALITY

4440 LPRINT TAB(29)"AVSIZINO OUTPUT REPORT"
4450 X = CSRLIN
4460 LOCATE X,29;PRINT STRINGS(22.196)
4470 X=STRINGS(22.95)
4480 LPRINT TAB(29)"x"
4490 PRINT : LPRINT
4495 IF NUMX=1 THEN GOTO 4565
4500 TORCHECK=TORX
4510 WHILE TORCHECK<3
4520 NOCONV="WARNING! Iteration limit exceeded. THE RESULTS BELOW MAY NOT BE ME"
4530 ANINGFUL." : CONV="Range converged in 
4530 " iterations."
4540 IF LPRINT=1 THEN LPRINT NOCONV ELSE PRINT CONV=COUNTX="iterations."
4550 TORCHECK=3
4560 WEND
4565 IF NUMX=1 THEN PRINT "Actual range not computed for AL-AIR."
4570 PRINT : LPRINT
4580 X=(180-LEN(TLE$))/2
4590 PRINT TAB(X)TLE$
4600 LPRINT TAB(X)TLE$
4610 PRINT : LPRINT
4620 F6-0
4630 PRINT USING "MT(KG)	 VOL(LTR)	 PWR(KW)"
4640 LPRINT USING "MT(KG)	 VOL(LTR)	 PWR(KW)"
4650 PRINT USING ":00.00" : "THE VEHICLE CAPACITY IS ", CAPX
4660 PRINT USING "00.00" : "THE VEHICLE TYPE IS ", VT11
4670 PRINT USING ":00.00" : "THE DESIRED RANGE IS ", IDRANI1
4680 PRINT USING ":00.00" : "THE DOMINANT BMF IS ", BMF
4690 PRINT USING ":00.00" : "THE BATTERY IS ", BATR
4700 PRINT USING "00.0000" : "THE CURB WEIGHT IS ", WC1
4710 PRINT USING "00.0000" : "THE ENGINE VOL.ENGK"
4720 PRINT USING "00.0000" : "THE ICE TRANS. VTXI"
4730 PRINT USING "00.0000" : "THE BATTERY IS ", BATR1
4740 PRINT USING "00.0000" : "THE TEST WEIGHT IS ", WT1
4750 PRINT USING "00.0000" : "THE ICE TRANS. VTXI"
4760 PRINT USING "00.0000" : "THE TEST WEIGHT IS ", WT1
4860 PRINT USING "N	 	NNN.NN"1 "THE ACTUAL RANGE IS 	" ; ACT
4870 LPRINT USING "\tN	NNN.NN"1 "THE ACTUAL RANGE IS 	" ; ACT
4880 IF TOR%-2 THEN 5100
4890 ' 4900 REM MULTIPLE RUN LOGIC
4910 ' 4920 PRINT
4930 LOCATE 22.411 PRINT "DO YOU WISH TO MAKE ANOTHER RUN?" 1
4940 ANS* = INKEY$ IF ANS*<="N" AND ANS*<="n" AND ANS*<="y" AND ANS*<="Y" THEN GOTO 4940
4950 IF ANS*="N" OR ANS*="n" THEN LOCATE 22.401 PRINT SPACE$(33)1 OOTO 4980
4960 IF ANS*="y" OR ANS*="Y" THEN RF% = 11 LPRINT LCS
4970 IF TOR%= 3 OOTO 320 ELSE GOTO 410
4980 PRINT "DO YOU WISH TO RUN ELVEC FOR THE VEHICLE SIZED IN THE LAST RUN(Y/N)?" 1
4990 ANS* = INKEY$ IF ANS*<="N" AND ANS*<="n" AND ANS*<="Y" AND ANS*<="Y" THEN
5000 GOTO 4990
5010 ' 5020 IF ANS*="N" OR ANS*="n" GOTO 7260
5030 ' 5040 REM INPUTS TO THE ELVEC PROGRAM.
5050 ' 5060 IF VEH%=1 AND CAP%=2 THEN CDA=.51
5070 IF VEH%=1 AND CAP%=3 THEN CDA=.555
5080 IF VEH%=1 AND CAP%=5 THEN CDA=.6
5090 IF VEH%=1 AND CAP%=6 THEN CDA=.59
5100 IF VEH%=2 AND CAP%=5 THEN CDA=.64
5110 PR%=38!
5120 PKEFF* =.95
5130 CR%=.9!1
5140 FK% = 1.98 !
5150 U8(2) = "URB8 1"1 U8(3) = "URB3 1"1 U8(4) = "URB4 1"
5160 U8(5) = "URB5 1"1 U8(6) = "URB6 1"1 U8(7) = "URB7 1"1 U8(8) = "URB8 1"
5170 U8(9) = "URB9 1"1 U8(10) = "URB10 1"1 U8(11) = "URB11 1"1 U8(12) = "URB12 1"
5180 U8(13) = "URB13 1"1 U8(14) = "URB14 1"1 U8(15) = "URB15 1"1 U8(16) = "URB16 1"
5190 CY(1) = " CYCLE 1"1 CY(2) = " CYCLE 2"1 CY(3) = " CYCLE 3"
5200 CY(4) = " CYCLE 4"1 CY(5) = " CYCLE 5"1 CY(6) = " CYCLE 6"
5210 CY(7) = " CYCLE 7"1 CY(8) = " CYCLE 8"1 CY(9) = " CYCLE 9"
5220 CY(10) = " CYCLE 10"1 CY(11) = " CYCLE 11"1 CY(12) = " CYCLE 12"
5230 ' 5240 REM UNCONSTRUCT SOME COMMON CYCLE SEQUENCES
5250 ' 5260 UC7.16*+U8(7)
5270 FOR I=8 TO 16
5280 UC7.16*+UC7.16*+U8(I)
5290 NEXT I
5300 UC3.11*+U8(3)
5310 FOR I=4 TO 11
5320 UC3.11*+UC3.11*+U8(I)
5330 NEXT I
5340 UC12.178+U8(12)
5350 FOR I=13 TO 17
5360 UC12.178+UC12.178+U8(I)
5370 NEXT I
5380 UC3.8*+U8(3)
5390 FOR I=4 TO 8
5400 UC3.8*+UC3.8*+U8(I)
5410 NEXT I

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5420 UC1.6=UC1.6U8(1)
5430 FOR I=2 TO 6
5440 UC1.6=UC1.66U8(1)
5450 NEXT I
5460 PRINT
5470 PRINT
5480 IF TORX=2 THEN 6260
5490 IF TORX=3 THEN 5450
5495 ' 5496 REM DETERMINE CYCLE (FEDERAL, HIGHWAY OR VAN)
5497 '
5500 CLS
5510 PRINT "CYCLE TYPE NUMBER LIST"
5520 PRINT "1. FEDERAL CYCLE";
5530 PRINT "2. HIGHWAY CYCLE";
5540 PRINT "3. VAN CYCLE"
5550 INPUT "ENTER CYCLE TYPE NUMBER(1, 2 OR 3) ", CNUMX
5560 IF CNUMX<1 AND CNUMX>2 AND CNUMX<>3 THEN 5550
5570 '
5580 REM WRITE APPROPRIATE CYCLE TO DISK.
5590 OPEN "LOCAL.DAT" FOR OUTPUT AS 01
5600 DGBUS 7660 CALL SUBROUTINE FRONT-EN
5610 IF CNUMX=1 THEN PRINT"NAMCYC FEDERAL"
5620 IF CNUMX=3 THEN DGBUS 7660 CALL SUBROUTINE PARAMVAR
5630 IF CNUMX=3 THEN DGBUS 9770 CALL SUBROUTINE CYCLE - VAN
5640 IF CNUMX=3 THEN PRINT"END"
5650 IF CNUMX=2 THEN PRINT"NAMCYC HIGHWAY"
5660 IF CNUMX=2 THEN PRINT"RUN"
5670 IF CNUMX=2 THEN PRINT"N"
5680 DGBUS 14250
5690 PRINT"END"
5700 PRINT"QUIT"
5710 CLOSE 01
5720 PRINT IF CNUMX=1 THEN "INPUT FILE HAS BEEN WRITTEN TO DISK USING THE FEDERAL CYCLE AND DATA FROM THE LAST RUN."
5730 IF CNUMX=2 THEN "THE REDESIGN OPTION HAS BEEN USED TO CREATE THIS FILE."
5740 IF CNUMX=3 THEN "YOU WISH TO RUN THE VAN CYCLE IN DEMAND THEREFORE I"
5750 PRINT "THE LOCAL FILE IS LOCAL.DAT";
5760 PRINT "THE REMOTE FILE IS STAREL.COM"
5770 PRINT "THE RUN COMMAND FILE IS FAX"
5780 PRINT "(RESPOND TO THE FIRST TWO PROMPTS FROM THE KEYBOARD)"
5790 DOB%=0: WEND
5800 DGBUS=2
5810 PRINT "YOU WISH TO RUN THE "FEDERAL CYCLE IN BATCH THEREFORE I"
5820 PRINT "THE LOCAL FILE IS LOCAL.DAT";
5830 PRINT "THE REMOTE FILE IS STAREL.COM"
5840 PRINT "THE SUBMIT COMMAND FILE IS 0130"
5850 DOB%=0: WEND
5860 IF CNUMX<>2 THEN DGBUS 9900 'WRITE TO THE VEHICLE.DAT FILE
5870 DQTO 7260
6230 ' 6240 RFM WRITE 24 HR. CYCLE TO DISK.
6250 ' 6255 OPEN "NAME&" DAT FOR INPUT AS 01
6270 IF CAP% = 6 THEN 6830
6280 GOSUB 7460 'CALL SUBROUTINE FRONT-END
6290 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6300 GOSUB 7950 'CALL SUBROUTINE CYCLE = 1
6310 PRINT#1, TLE$+CY$ (1)
6320 PRINT#1, "N"
6330 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6340 GOSUB 8000 'CALL SUBROUTINE CYCLE = 2
6350 PRINT#1, TLE$+CY$ (2)
6360 PRINT#1, "N"
6370 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6380 GOSUB 8130 'CALL SUBROUTINE CYCLE = 3
6390 PRINT#1, TLE$+CY$ (3)
6400 PRINT#1, "N"
6410 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6420 GOSUB 8310 'CALL SUBROUTINE CYCLE = 4
6430 PRINT#1, TLE$+BAT$+CY$ (4)
6440 PRINT#1, "N"
6450 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6460 GOSUB 8450 'CALL SUBROUTINE CYCLE = 5
6470 PRINT#1, TLE$+CY$ (5)
6480 PRINT#1, "N"
6490 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6500 GOSUB 8620 'CALL SUBROUTINE CYCLE = 6
6510 PRINT#1, TLE$+CY$ (6)
6520 PRINT#1, "N"
6530 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6540 GOSUB 8820 'CALL SUBROUTINE CYCLE = 7
6550 PRINT#1, TLE$+CY$ (7)
6560 PRINT#1, "N"
6570 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6580 GOSUB 9000 'CALL SUBROUTINE CYCLE = 8
6590 PRINT#1, TLE$+CY$ (8)
6600 PRINT#1, "N"
6605 IF VEH% = 2 THEN GOSUB 14110 'CALL HYBRID SUBROUTINE
6610 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6620 GOSUB 9190 'CALL SUBROUTINE CYCLE = 9
6630 PRINT#1, TLE$+CY$ (9)
6640 PRINT#1, "N"
6650 IF CYCLE% = 9 THEN 7040
6660 REM CYCLE 10
6670 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6680 GOSUB 9350 'CALL SUBROUTINE CYCLE = 10
6690 PRINT#1, TLE$+CY$ (10)
6700 PRINT#1, "N"
6710 IF CYCLE% = 10 THEN 7040
6720 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6730 GOSUB 9490 'CALL SUBROUTINE CYCLE = 11
6740 PRINT#1, TLE$+CY$ (11)
6750 PRINT#1, "N"
6760 IF CYCLE% = 11 THEN 7040
6770 REM CYCLE 12
6780 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6790 GOSUB 9630 'CALL SUBROUTINE CYCLE = 12
6800 PRINT#1, TLE$+CY$ (12)
6810 PRINT#1, "N"
6820 IF CYCLE% = 12 THEN 7040
6830 REM BRON VAN CYCLES
6840 IF CAP% > 6 THEN 7040
6845 GOSUB 7460 'CALL SUBROUTINE FRONT-END
6850 GOSUB 7760 'CALL SUBROUTINE PARAMVAR
6860 GOSUB 9770 'CALL SUBROUTINE CYCLE = VAN
AA97 PRINT#1, "MARK 10.5M"
REM END 24 HR. CYCLE STATEMENTS
7000 PRINT$"QUIT"
7010 CLOSE 01
7020 PRINT$"AN INPUT FILE HAS BEEN WRITTEN TO DISK USING THE 24 HOUR CYCLE AND DATA FROM THE LAST RUN FOR WHICH A FEDERAL, HIGHWAY, OR VAN INPUT FILE WAS CREATED"
7030 PRINT$"YOU WISH TO RUN THE 24 HR. CYCLE IN DEMAND THEREFORE THE LOCAL FILE IS STAREL.DAT"$"THE REMOTE FILE IS STAREL.COM"
7040 PRINT$"YOU WISH TO RUN THE 24 HR. CYCLE IN BATCH THEREFORE THE LOCAL FILE IS "NAM24S+.DAT" THE REMOTE FILE IS "NAM248+.COM"
7050 DOBX=0
7060 WEND
7070 PRINT$"OPEN FILES OF THE FORM XXX.COS AND XXX.ENO"
7080 OPEN NAM248+.COS FOR OUTPUT AS #3
7090 WRITE #3, NAM248+.COS"FOR OUTPUT AS #3
7100 CLOSE #3
7110 OPEN NAM248+.ENO FOR OUTPUT AS #3
7120 WRITE #3, NAM248+.ENO"FOR OUTPUT AS #3
7130 CLOSE #3
7140 REM DISPLAY WARNINGS OR ERROR MESSAGES (IF REQUIRED) BEFORE ENDING PROGRAM OPERATIONS.
7259 '  
7260 PRINT I PRINT I PRINT  
7270 PRINT I LPRINT  
7280 IF ERROR% = 1 THEN PRINT "SPECIFIC POWER IS OUT OF RANGE."
7290 IF ERROR% = 1 THEN LPRINT "SPECIFIC POWER IS OUT OF RANGE."
7300 IF ERROR% = 1 AND LPRINT% = 1 THEN PRINT "WARNING! The iteration limit in the Actual Range calculation was exceeded. Therefore the Actual Range may not have converged."
7310 IF ERROR% = 1 AND LPRINT% = 1 THEN LPRINT "WARNING! The iteration limit in the Actual Range calculation was exceeded. Therefore the Actual Range may not have converged."
7320 IF ERROR% = 1 AND LPRINT% = 1 THEN PRINT " The current value is" + LPRINT "ACTRAN"
7330 IF ERROR% = 1 AND LPRINT% = 1 THEN LPRINT " The current value is" + LPRINT "ACTRAN"
7340 '  
7350 REM END OF PROGRAM OPERATIONS  
7360 '  
7370 LOCATE 22.1 I PRINT SPACES(75)  
7380 LOCATE 23.25 I PRINT"*** END OF PROGRAM OPERATIONS***"  
7390 LPRINT TAB(15)"*** END OF PROGRAM OPERATIONS***"  
7400 LPRINT CHR$(12)  
7410 '  
7420 REM RESTART OPTION  
7430 '  
7440 LOCATE 25.30 I PRINT "TYPE RUN TO RE-START"  
7450 END  
7460 '+++++++++++++++++++++++++++++++
7470 '  
7480 REM SUBROUTINE FRONT-END.  
7490 '  
7500 '+++++++++++++++++++++++++++++++
7510 IF TOR%= 1 OR TOR%n3 THEN PRINT "CREATE/LOAD STAREL.COM"
7520 IF TOR%= 2 THEN PRINT "CREATE/LOAD " + LPRINT "NAM249+.COM"
7530 IF DOBX% = 1 THEN 7570
7540 PRINT; "SIAO1(ORCUSER,STORE)RUNELVEC"
7550 PRINT; "N"  
7560 PRINT; "N"  
7570 PRINT; "E"  
7580 PRINT; "N"  
7590 PRINT; "N"  
7600 PRINT; "N"
7610 PRINT; "USERDATA"
7620 PRINT; "ADVEV"
7630 PRINT; "MDLMAT ANLYT"
7640 PRINT; "MDLBAT ACTRNO"
7650 PRINT; "NAMBAT " + LPRINT "NAMBAT"
7660 RETURN
7750 RETURN  
7760 '/+++++++++++++++++++++++++++++++
7770 '/  
7780 REM SUBROUTINE PARAMVAR  
7790 '  
7800 '+++++++++++++++++++++++++++++++
7810 PRINT; "PARAMVAR"
7820 PRINT; "NAMCYC"
7830 PRINT; "N"
7840 RETURN
7850 '/+++++++++++++++++++++++++++++++
7860 '  
7870 REM SUBROUTINE CYCLE - 1  
7880 '  
7890 '/+++++++++++++++++++++++++++++++
7900 PRINT; "U81(1)+U81(2)"
7910 PRINT; "park 1.9hr"
7920 PRINT; "1.9hr"
7920 PRINT1, "park 21.90hr"
7940 PRINT1, "END"
7950 PRINT1, "RUN"
7960 PRINT1, "N"
7970 GOSUB 14250
7980 PRINT1, "END"
7990 RETURN
8000 ' ____________________________________________________________
8010 ' 8020 REM SUBROUTINE CYCLE - 2
8030 ' 8040 ' ____________________________________________________________
8050 PRINT1, UC1.66
8060 PRINT1, "park 5.01hr"
8070 PRINT1, UC7.166
8080 PRINT1, U8(17)
8090 PRINT1, "park 18.60hr"
8100 PRINT1, "END"
8110 PRINT1, "RUN"
8120 RETURN
8130 ' ____________________________________________________________
8140 ' 8150 REM SUBROUTINE CYCLE - 3
8160 ' 8170 ' ____________________________________________________________
8180 PRINT1, U6(1)
8190 PRINT1, "park 5.16hr"
8200 PRINT1, U6(2)+U6(3)+U6(4)+U6(5)+U6(6)
8210 PRINT1, "park 0.75hr"
8220 PRINT1, UC7.166
8230 PRINT1, U6(17)
8240 PRINT1, "park 2.77hr"
8250 PRINT1, UC1.66
8260 PRINT1, U6(7)+U6(8)+U6(9)
8270 PRINT1, "park 14.73hr"
8280 PRINT1, "END"
8290 PRINT1, "RUN"
8300 RETURN
8310 ' ____________________________________________________________
8320 ' 8330 REM SUBROUTINE CYCLE - 4
8340 ' 8350 ' ____________________________________________________________
8360 PRINT1, U6(1)
8370 PRINT1, "park 0.95hr"
8380 PRINT1, U6(2)
8390 PRINT1, "park 3.44hr"
8400 PRINT1, "federal 1"
8410 PRINT1, "park 18.79hr"
8420 PRINT1, "END"
8430 PRINT1, "RUN"
8440 RETURN
8450 ' ____________________________________________________________
8460 ' 8470 REM SUBROUTINE CYCLE - 5
8480 ' 8490 ' ____________________________________________________________
8500 PRINT1, UC1.66
8510 PRINT1, "park 7.15hr"
8520 PRINT1, UC7.166
8530 PRINT1, U6(17)
8540 PRINT1, "park 1.56hr"
8550 PRINT1, "federal 1"

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6360 PRINT1: "Park 6.87hr"
6370 PRINT1: "federal 1"
6380 PRINT1: "park 7.25hr"
6390 PRINT1: "END"
6400 PRINT1: "RUN"
6410 RETURN
6420 '******************************************************************************
6430 '
6440 REM SUBROUTINE CYCLE - 6
6450 '
6460 '******************************************************************************
6470 PRINT1: "federal 2"
6480 PRINT1: "park 1.04hr"
6490 PRINT1: UC1.66
6500 PRINT1: U6(7)+U6(8)+U6(9)
6510 PRINT1: "park 0.87hr"
6520 PRINT1: U6(1)+U6(2)
6530 PRINT1: "park 6.83hr"
6540 PRINT1: UC3.116
6550 PRINT1: UC12.176
6560 PRINT1: "park 0.63hr"
6570 PRINT1: "federal 1"
6580 PRINT1: "park 11.89hr"
6590 PRINT1: "END"
6600 PRINT1: "RUN"
6610 RETURN
6620 '******************************************************************************
6630 '
6640 REM SUBROUTINE CYCLE - 7
6650 '
6660 '******************************************************************************
6670 PRINT1: "federal 2"
6680 PRINT1: "park 4.57hr"
6690 PRINT1: U6(1)
6700 PRINT1: "park 0.60hr"
6710 PRINT1: "federal 2"
6720 PRINT1: "park 2.57hr"
6730 PRINT1: "federal 1"
6740 PRINT1: "park 1.36hr"
6750 PRINT1: "federal 1"
6760 PRINT1: "park 12.35hr"
6770 PRINT1: "END"
6780 PRINT1: "RUN"
6790 RETURN
6800 '******************************************************************************
6810 '
6820 REM SUBROUTINE CYCLE - 8
6830 '
6840 '******************************************************************************
6850 PRINT1: "federal 2"
6860 PRINT1: "park 0.82hr"
6870 PRINT1: "federal 2"
6880 PRINT1: "park 0.15hr"
6890 PRINT1: "federal 2"
6900 PRINT1: "park 3.73hr"
6910 PRINT1: U6(1)+U6(2)
6920 PRINT1: "park 0.216hr"
6930 PRINT1: "END"
6940 PRINT1: "RUN"
6950 '******************************************************************************
6960 '
6970 PRINT1: "END"
6980 PRINT1: "RUN"
6990 '******************************************************************************
9190 '******************************************************************************
9200 '
9210 REM SUBROUTINE CYCLE - 9
9220 '
9230 '******************************************************************************
9240 PRINT1, "hiway 4"
9250 PRINT1, "park 7.04hr"
9260 PRINT1, "frederal 1"
9270 PRINT1, "hiway 1"
9280 PRINT1, "frederal 1"
9290 PRINT1, "park 0.66hr"
9300 PRINT1, "frederal 1"
9310 PRINT1, "park 14.09hr"
9320 PRINT1, "END"
9330 PRINT1, "RUN"
9340 RETURN
9350 '******************************************************************************
9360 '
9370 REM SUBROUTINE CYCLE - 10
9380 '
9390 '******************************************************************************
9400 PRINT1, "hiway 4"
9410 PRINT1, "park 6.5hr"
9420 PRINT1, "frederal 1"
9430 PRINT1, "hiway 4"
9440 PRINT1, "frederal 1"
9450 PRINT1, "park 15.04hr"
9460 PRINT1, "END"
9470 PRINT1, "RUN"
9480 RETURN
9490 '******************************************************************************
9500 '
9510 REM SUBROUTINE CYCLE - 11
9520 '
9530 '******************************************************************************
9540 PRINT1, "hiway 15"
9550 PRINT1, "park 2.61hr"
9560 PRINT1, US(1)+US(2)
9570 PRINT1, "park 0.57hr"
9580 PRINT1, UC3.84H/8(9)
9590 PRINT1, "park 17.42hr"
9600 PRINT1, "END"
9610 PRINT1, "RUN"
9620 RETURN
9630 '******************************************************************************
9640 '
9650 REM SUBROUTINE CYCLE - 12
9660 '
9670 '******************************************************************************
9680 PRINT1, "frederal 1"
9690 PRINT1, "hiway 16"
9700 PRINT1, "park 1.0hr"
9710 PRINT1, "hiway 7"
9720 PRINT1, "frederal 1"
9730 PRINT1, "park 17.35hr"
9740 PRINT1, "END"
9750 PRINT1, "RUN"
9760 RETURN
9770 '******************************************************************************
9780 '
9790 REM SUBROUTINE CYCLE - VAN
9800 '
9810 '******************************************************************************
9820 PRINT01, U8(1)+UC3.110
9830 PRINT01, UC12.170
9840 PRINT01, "Park 1.5hr"
9850 PRINT01, U8(1)+UC3.110
9860 PRINT01, UC12.170
9870 RETURN
9900 '*****************************************************************************
9910  
9920 REM SUBROUTINE VEHICLE - DATA
9930  
9940  '*****************************************************************************
9950 OPEN "VEHICLE.DAT" FOR OUTPUT AS #2
9960 WRITE #2, TWo CAM VEH%• ICMT• ORAN• NUM%s SNUMXv CDA• CNUM%• WWI * BMF•
9970 CLOSE #2
9980 RETURN
9990 '*****************************************************************************
1000 '  
1001 REM SUBROUTINE CH - READ
1002  
10030 '*****************************************************************************
10040 FOR I=1 TO 3
10050 READ CH(I)
10060 NEXT I
10070 RETURN
10080 '*****************************************************************************
10090 '  
10100 REM SUBROUTINE DATNS- READ
10110  
10120 '*****************************************************************************
10130 FOR I=1 TO 4
10140 READ DATNS(I)
10150 NEXT I
10160 RETURN
10170 '*****************************************************************************
10180 '  
10190 REM SUBROUTINE ACTUAL - RANGE
10200  
10210 '*****************************************************************************
10220 ERRORF=0
10230 IF NUM% = 1 THEN 10360 'BRANCH TO AL-AIR DATA SET
10240 IF NUM% = 2 THEN 10450 'BRANCH TO FE-AIR DATA SET
10250 IF NUM% = 3 THEN 10620 'BRANCH TO LI-FE-S DATA SET
10260 IF NUM% = 4 THEN 11190 'BRANCH TO LI-FE-S2 DATA SET
10270 IF NUM% = 5 THEN 11280 'BRANCH TO NA-S DATA SET
10280 IF NUM% = 6 THEN 11650 'BRANCH TO NI-TE DATA SET
10290 IF NUM% = 7 THEN 12020 'BRANCH TO NI-IN DATA SET
10300 IF NUM% = 8 THEN 12110 'BRANCH TO PB-ACID DATA SET
10310 IF NUM% = 9 THEN 12480 'BRANCH TO PB-ACID/EP DATA SET
10320 IF NUM% = 10 THEN 12850 'BRANCH TO ZN-BR2 DATA SET
10330 IF NUM% = 11 THEN 13220 'BRANCH TO ZN-CL2 DATA SET
10340 '  
10350 REM DATA TAKEN FROM SPECIFIC POWER X DOD CHARTS FOR THE ELEVEN BATTERY TYP
10360 'ES
10370 N=2
10380 DATA 0.157
10390 DATA 100.90
10400 STORE 10380
10410 GOSUB 13420
10420 RESTORE 10380
10430 GOSUB 13690
10440 GOTO 13760
10450 ' FE-AIR DATA SET
10460 IF SNAUX1=1 THEN 10500
10470 IF SNAUX2=2 THEN 10580
10480 IF SNAUX3=3 THEN 10660
10490 IF SNAUX4=4 THEN 10740
10500 N = 5 1 ' P/E=1.0
10510 DATA 0.102,107,110,112
10520 DATA 100.90.70.90.40
10530 RESTORE 10510
10540 GOSUB 13620
10550 RESTORE 10520
10560 GOSUB 13690
10570 GOTO 13760
10580 N = 4 1 ' P/E=2.1
10590 DATA 0.115,125,131,140,143
10600 DATA 100.90.70.70.50.40
10610 RESTORE 10590
10620 GOSUB 13620
10630 RESTORE 10600
10640 GOSUB 13690
10650 GOTO 13760
10660 N = 4 1 ' P/E=2.4
10670 DATA 0.136,145,150,157,159
10680 DATA 100.90.70.70.50.40
10690 RESTORE 10670
10700 GOSUB 13620
10710 RESTORE 10680
10720 GOSUB 13690
10730 GOTO 13760
10740 N = 4 1 ' P/E=2.3
10750 DATA 0.146,156,162,165,167
10760 DATA 100.90.70.70.50.40
10770 RESTORE 10750
10780 GOSUB 13620
10790 RESTORE 10760
10800 GOSUB 13690
10810 GOTO 13760
10820 ' LIF-E-S DATA SET
10830 IF SNAUX1=1 THEN 10870
10840 IF SNAUX2=2 THEN 10950
10850 IF SNAUX3=3 THEN 11030
10860 IF SNAUX4=4 THEN 11110
10870 N = 6 1 ' P/E=1.0
10880 DATA 0.99,126,161,177
10890 DATA 100.90.70.70.50.40
10900 RESTORE 10880
10910 GOSUB 13620
10920 RESTORE 10890
10930 GOSUB 13690
10940 GOTO 13760
10950 N = 6 1 ' P/E=2.1
10960 DATA 0.90,110,140,165,172
10970 DATA 100.90.70.70.50.40
10980 RESTORE 10960
10990 GOSUB 13620
11000 RESTORE 10970
11010 GOSUB 13690
11020 GOTO 13760
11030 N = 6 1 ' P/E=2.4
11040 DATA 0.90,110,140,165,172
11050 DATA 100.90.70.70.50.40

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11060 RESTORE 11040
11070 GOSUB 13620
11080 RESTORE 11060
11090 GOSUB 13690
11100 GOTO 13760
11110 N = S 'P/E=3.3
11120 DATA 0.107.137.175.178
11130 DATA 100.90.70.50.40
11140 RESTORE 11120
11150 GOSUB 13620
11160 RESTORE 11130
11170 GOSUB 13690
11180 GOTO 13760
11190 'Li-FE-82 DATA SET
11200 N = S 'DATA = ""
11210 DATA 0.0.110.0.142.5.165.0.180.0
11220 DATA 100.0.90.0.80.0.60.0.60.0.50.0
11230 RESTORE 11210
11240 GOSUB 13620
11250 RESTORE 11220
11260 GOSUB 13690
11270 GOTO 13760
11280 'NA-8 DATA SET
11290 IF SNUMX=1 THEN 11330
11300 IF SNUMX=2 THEN 11410
11310 IF SNUMX=3 THEN 11490
11320 IF SNUMX=4 THEN 11570
11330 N = S 'P/E=1.0
11340 DATA 0.129.135.141.148.150
11350 DATA 100.90.80./0.50.40
11360 RESTORE 11340
11370 GOSUB 13620
11380 RESTORE 11350
11390 GOSUB 13690
11400 GOTO 13760
11410 N = S 'P/E=2.1
11420 DATA 0.180.192.199.200
11430 DATA 100.90.70.50.40
11440 RESTORE 11420
11450 GOSUB 13620
11460 RESTORE 11430
11470 GOSUB 13690
11480 GOTO 13760
11490 N = S 'P/E=2.4
11500 DATA 0.180.210.224.228
11510 DATA 100.90.70.50.40
11520 RESTORE 11500
11530 GOSUB 13620
11540 RESTORE 11510
11550 GOSUB 13690
11560 GOTO 13760
11570 N = S 'P/E=3.3
11580 DATA 0.220.234.244.246
11590 DATA 100.90.70.50.40
11600 RESTORE 11580
11610 GOSUB 13620
11620 RESTORE 11590
11630 GOSUB 13690
11640 GOTO 13760
11650 'Ni-FE DATA SET
11660 IF SNUMX=1 THEN 11700
11670 IF SNUMX=2 THEN 11780
11680 IF SNUMX=3 THEN 11860
11690 IF SNUN%-4 THEN 11940
11700 N = 6 : ' P/E=1.0
11710 DATA 0.45,75,105,120,124
11720 DATA 100,97,90,70,50,40
11730 RESTORE 11710
11740 GOSUB 13620
11750 RESTORE 11720
11760 GOSUB 13690
11770 GOTO 13760
11780 N = 6 : ' P/E=2.1
11790 DATA 0.75,90,120,141,150
11800 DATA 100,95,90,70,50,40
11810 RESTORE 11790
11820 GOSUB 13620
11830 RESTORE 11800
11840 GOSUB 13690
11850 GOTO 13760
11860 N = 6 : ' P/E=2.1
11870 DATA 0.75,90,120,141,150
11880 DATA 100,95,90,70,50,40
11890 RESTORE 11870
11900 GOSUB 13620
11910 RESTORE 11880
11920 GOSUB 13690
11930 GOTO 13760
11940 N = 6 : ' P/E=3.3
11950 DATA 0.90,110,140,160,163
11960 DATA 100,97,90,70,50,40
11970 RESTORE 11950
11980 GOSUB 13620
11990 RESTORE 11960
12000 GOSUB 13690
12010 GOTO 13760
12020 'NZ-2N DATA SET
12030 N = 8
12040 DATA 0.0,110,0.140,0.160,0.170,0.180,0.195,0.199,0
12050 DATA 100,0,92.2,88,0,82.5,78.3,72.7,76.0,50.0
12060 RESTORE 12040
12070 GOSUB 13620
12080 RESTORE 12050
12090 GOSUB 13690
12100 GOTO 13760
12110 'PB-ACID DATA SET
12120 IF SNUN%-1 THEN 12160
12130 IF SNUM%-2 THEN 12240
12140 IF SNUM%-3 THEN 12320
12150 IF SNUM%-4 THEN 12400
12160 N = 7 : ' P/E=1.0
12170 DATA 0.50,80,93,105,120,124
12180 DATA 100,98,90,82,70,50,40
12190 RESTORE 12170
12200 GOSUB 13620
12210 RESTORE 12180
12220 GOSUB 13690
12230 GOTO 13760
12240 N = 6 : ' P/E=2.1
12250 DATA 0.70,90,115,135,145
12260 DATA 100,96,90,70,50,40
12270 RESTORE 12250
12280 GOSUB 13620
12290 RESTORE 12260
12300 GOSUB 13690
12310 GOTO 12240

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12320 N = 6 1 ' P/E=2.4
12330 DATA 0.70, 90, 115, 135, 145
12340 DATA 100, 97.90, 70, 50, 40
12350 RESTORE 12330
12360 GOSUB 13620
12370 RESTORE 12340
12380 GOSUB 13690
12390 GOTO 13760
12400 N = 6 1 ' P/E=3.3
12410 DATA 0.85, 100, 125, 145, 155
12420 DATA 100, 97, 90, 70, 50, 40
12430 RESTORE 12410
12440 GOSUB 13620
12450 RESTORE 12420
12460 GOSUB 13690
12470 GOTO 13760
12480 IF PB-ACID/BP DATA SET
12490 IF SNUMX=1 THEN 12530
12500 IF SNUMX=2 THEN 12610
12510 IF SNUMX=3 THEN 12690
12520 IF SNUMX=4 THEN 12770
12530 N = 5 1 ' P/E=1.0
12540 DATA 0.275, 345, 400, 426
12550 DATA 100, 97, 90, 70, 50, 40
12560 RESTORE 12540
12570 GOSUB 13620
12580 RESTORE 12550
12590 GOSUB 13690
12600 GOTO 13760
12610 N = 5 1 ' P/E=1.0
12620 DATA 0.275, 345, 400, 426
12630 DATA 100, 97, 90, 70, 50, 40
12640 RESTORE 12620
12650 GOSUB 13620
12660 RESTORE 12630
12670 GOSUB 13690
12680 GOTO 13760
12690 N = 5 1 ' P/E=1.0
12700 DATA 0.275, 345, 400, 426
12710 DATA 100, 97, 90, 70, 50, 40
12720 RESTORE 12700
12730 GOSUB 13620
12740 RESTORE 12710
12750 GOSUB 13690
12760 GOTO 13760
12770 N = 5 1 ' P/E=1.0
12780 DATA 0.275, 345, 400, 426
12790 DATA 100, 97, 90, 70, 50, 40
12800 RESTORE 12780
12810 GOSUB 13620
12820 RESTORE 12790
12830 GOSUB 13690
12840 GOTO 13760
12850 IF ZN-BK2 DATA SET
12860 IF SNUMX=1 THEN 12900
12870 IF SNUMX=2 THEN 12990
12880 IF SNUMX=3 THEN 13060
12890 IF SNUMX=4 THEN 13140
12900 N = 6 1 ' P/E=1.0
12910 DATA 0.35, 52, 69, 83, 89
12920 DATA 100, 97, 90, 70, 50, 40
12930 RESTORE 12910
12940 GOSUB 13920

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12950 RESTORE 12920
12960 GOSUB 13690
12970 GOTO 13760
12980 N = 6 : 'P/E=2.1
12990 DATA 0.55, 72, 96, 115, 125
13000 DATA 100, 97, 90, 70, 50, 40
13010 RESTORE 12990
13020 GOSUB 13620
13030 RESTORE 13000
13040 GOSUB 13690
13050 GOTO 13760
13060 N = 6 : 'P/E=2.4
13070 DATA 0.65, 85, 113, 135, 147, 13080 DATA 100, 98, 90, 70, 50, 40
13090 RESTORE 13070
13100 GOSUB 13620
13110 RESTORE 13080
13120 GOSUB 13690
13130 GOTO 13760
13140 N = 6 : 'P/E=3.3
13150 DATA 0.85, 94, 125, 150, 160
13160 DATA 100, 95, 90, 70, 50, 40
13170 RESTORE 13150
13180 GOSUB 13620
13190 RESTORE 13160
13200 GOSUB 13690
13210 GOTO 13760
13220 'IN-CL2 DATA SET
13230 IF SNUMX=1 THEN 13270
13240 IF SNUMX=2 THEN 13350
13250 IF SNUMX=3 THEN 13430
13260 IF SNUMX=4 THEN 13510
13270 N = 3 : 'P/E=1.0
13280 DATA 0.80, 84, 88, 87
13290 DATA 100, 90, 70, 50, 40
13300 RESTORE 13280
13310 GOSUB 13620
13320 RESTORE 13290
13330 GOSUB 13690
13340 GOTO 13760
13350 N = 6 : 'P/E=2.1
13360 DATA 0.90, 96, 103, 110, 114
13370 DATA 100, 90, 82, 70, 50, 40
13380 RESTORE 13360
13390 GOSUB 13620
13400 RESTORE 13370
13410 GOSUB 13690
13420 GOTO 13760
13430 N = 6 : 'P/E=2.4
13440 DATA 0.110, 116, 121, 127, 131
13450 DATA 100, 90, 81, 70, 50, 40
13460 RESTORE 13440
13470 GOSUB 13620
13480 RESTORE 13450
13490 GOSUB 13690
13500 GOTO 13760
13510 N = 6 : 'P/E=3.3
13520 DATA 0.115, 121, 128, 130, 131
13530 DATA 100, 90, 85, 70, 50, 40
13540 RESTORE 13520
13550 GOSUB 13620
13560 RESTORE 13530
13570 'FIN GOSUB 13640
13380 GOTO 13760
13390
13400 REM SUBROUTINE FOR READING THE SPECIFIC POWER DATA INTO THE D(I) ARRAY.
13410
13420 FOR I = 1 TO N
13430 READ DOM(I)
13440 NEXT I
13450 RETURN
13460
13470 REM SUBROUTINE FOR READING THE DOD DATA INTO THE R(I) ARRAY.
13480
13490 FOR I = 1 TO N
13500 READ RAN(I)
13510 NEXT I
13520 RETURN
13530
13540 IF STAX•l THEN IF WKO < 0 OR WKO > DOM(N) THEN ERRORFX-1
13550 IF STAX•l THEN IF WKO < 0 OR WKO > DOM(N) THEN 13890
13560
13570 REM INTERPOLATION ALGORITHM.
13580
13590 FOR I = 1 TO N-1
13600 IF WKO < DOM(I+1) AND WKO > DOM(I) THEN 13840
13610 NEXT I
13620 DOD = (RAN(I+1)-RAN(I))/(DOM(I+1)-DOM(I))*WKO+DOM(I)
13630 RETURN
13640 REM COMPUTE ACTUAL RANGE.
13650
13660 ACTRAN = DOD/RAN/100
13670 RETURN
13680
13690 REM SUBROUTINE WEIGHT
13700
13710 WTERM1=WTH+PANDPL+WTERM2=BMF*WMOD1+WMOD1+WMOD1
13720 WT=WTERM1/(1-(1.3*WTERM2))
13730 MB=BMF+WT / PACC=RACC+NB
13740 WC=WT-PANPL
14000 WPWT=-.9000001*GRADE/MOSSW)*WT
14010 IF CAPK=4 OR CAPK=5 THEN WCON=(GRADE/CONS)/WT
14020 IF CAPK=5 THEN WFF=(GRADE/TRFSW)*WT
14030 IF CAPK=6 THEN WCON=(CYCLE/CONS)/WT
14040 IF CAPK=2 OR CAPK=6 THEN WFF=(CYCLE/TRFSW)*WT
14050 IF CAPK=4 THEN WFF=(GRADE/TRFSW)*WT
14060 IF CAPK=4 AND VEH%=2 THEN WRTT=(GRADE/TPRTS)#WT
14070 IF CAPK=5 AND VEH%=2 THEN WRTT=(GRADE/TPRTS)#WT
14071 IF CAPK=2 OR CAPK=6 THEN ETKW=CYCLE#WT/1000
14072 IF CAPK=4 THEN ETKW=GRAD3#WT/1000
14073 IF CAPK=5 THEN ETKW=GRAD3#WT/1000
14074 IF VEH%=2 ANU CAPK=4 THEN EPM=GRADE#WT/1000
14075 IF VEH%=2 AND CAPK=5 THEN EPM=GRADE#WT/1000
14076 IF VEH%=2 THE ' EPM=GRADE/EPW
14077 IF VEH%=2 THEN ENW#EPW=.7460001
14078 IF VEH%=2 OR CAPK=6 THEN CKW=CYCLE#WT/1000
14079 IF CAPK=4 OR CAPK=5 THEN CKW=GRADE#WT/1000
14080 IF VEH%=1 THEN WRTT=0 ELSE WRTT=(GRADE/TPRTS)#WT
14081 PEFPW=.9*GRADE#WT/1000
14090 IF VEH%=2 THEN WHE=(GRADE/HESW)#WT ELSE WHE=0


REM DATA ON WH/L ARE FROM SYMONS EQUATIONS
REM AL-AIR WH/L WAS TAKEN FROM GREY REPORT
REM NI-iN WH/L WAS TAKEN FROM OBEY REPORT
B=+(PSC+WE)/1000
RETURN

REM SUBROUTINE HYBRID
PRINT "U8t'ȒDATA"
PRINT "ADVICE"
PRINT "NAME AUU1700"
PRINT "FUELCP 100AL"
PRINT "EFFBC 0.9"
PRINT "EFCVRT 0.9"
PRINT "WT" " INT" "WB" " IWB"
PRINT "CDA" " ICDA"
PRINT "CRDIAL" " CRDIAL"
PRINT "PTIRE" " IPTIRE"
PRINT "CH(2) CH(3)"
IF NUMU>4 THEN PRINT "CH(1)
RETURN
BLOCK DIAGRAM
INPUT: DO YOU WISH TO RUN:
1. NEW VEHICLE USING URBAN OR HIGHWAY CYCLE?
2. PREVIOUS VEHICLE USING 24-h CYCLE?
3. REDESIGN OF VEHICLE BY CHANGING BMF?

START

1. (NEW VEHICLE) 1, 2 OR 3?

A

OPEN THE FILE: VEHICLE.DAT FOR INPUT AS #2

2. (24-h CYCLE) 3. (REDESIGN)

2 OR 3?

B

INPUT:
ENTER BMF

3

A1

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INPUT: ENTER TITLE OF RUN

IS VEHICLE 2-PASSENGER OR VAN?

YES

INPUT: ENTER VEHICLE TYPE (1 OR 2)
(1 = ELECTRIC, 2 = HYBRID)

NO

INPUT: ENTER DESIRED RANGE
ENTER BATTERY TYPE NUMBER
1. AL-AIR 4. LI-FE-S,\(^a\) 7. NI-ZN
2. FE-AIR 5. NA-S 8. PB-AC/ADV
10. ZN-BR 11. ZN-CL\(_2\)

ENTER POWER-TO-ENERGY RATIO NUMBER
1.0 2.1 2.4 3.3

\(^a\) THIS BATTERY IS NOT OPERATIONAL IN THIS VERSION OF THE PROGRAM

B
INPUT: DO YOU WISH TO RUN ELVEC IN
1. DEMAND
2. BATCH
ENTER TYPE OF RUN (1 OR 2)

24-h CYCLE ?

YES

INPUT: ENTER FILENAME
OF 24-h INPUT FILE

NO

5 PAS ?

YES

INPUT: ENTER VEHICLE
RANGE NO. (1, 2, OR 3)
100 mi
150 mi
250 mi

BATCH ?

YES

NO

BRANCH TO BATTERY DATA SET:
(NAME, EFFCD, SLFD, ACC, RANGE-BMF COEFFICIENTS,
Q1, Q2, PBC, CH-COEFFICIENTS)

C
C

DEFINE VEHICLE PARAMETERS

REDESIGN?

YES

SET BMF TO INPUT VALUE

NO

COMPUTE BMF AS A FUNCTION OF ELVEC RANGE

COMPUTE SPECIFIC POWER

COMPUTE ACTUAL RANGE (CALL SUBROUTINE ACTUAL RANGE)

IS ACTUAL RANGE CONVERGED?

NO

COMPUTE NEW ELVEC RANGE

YES

IS ITERATION LIMIT EXCEEDED?

NO

D
D

FINAL CHECK FOR ACTUAL RANGE CONVERGENCE

D

DETERMINE IF BMF IS 1. RANGE 2. GRADE

DI

COMPUTE SPECIFIC POWER

D

COMPUTE ACTUAL RANGE (CALL SUBROUTINE Actual Range)

F1

COMPUTE WEIGHTS AND WEIGHT-DEPENDENT VARIABLES

F

PRINT OUTPUT REPORT
DO YOU WISH TO MAKE ANOTHER RUN?

YES

NEW VEHICLE

NEW VEHICLE OR REDESIGN

REDESIGN

NO

DO YOU WISH TO RUN ELVEC FOR THE VEHICLE SIZED IN THE LAST RUN?

YES

NO

END

COMPUTE CDA

COMPUTE PTIRE

PKEFF

CRDIAL

SOME COMMON CYCLES

F
1. NEW VEHICLE
2. REDesign
3. 24-h CYCLE

1 OR 3

1. FEDERAL
2. HIGHWAY
3. VAN

WRITE 24-h CYCLE TO DISK

WRITE CHOSEN CYCLE TO DISK
CALL SUBR VEHICLE DATA (WRITES DATA TO DISK)

THE FILE WRITTEN TO DISK IS LOCAL.DAT. (REGARDLESS WHETHER ELVEC IS TO BE RUN IN DEMAND OR BATCH)

WRITE DATA TO THE FILES OF THE FORM XXX.ENG, XXX.COS

IF ELVEC IS TO BE RUN IN DEMAND, THE FILE WRITTEN TO DISK IS STAREL.DAT.
IF BATCH, IT IS XXX.DAT WHERE XXX IS FILENAME OF 24-h INPUT FILE

END
$ TYPE MAX.COM

$ set noverify
$ ON CONTROL-Y THEN $GOTO EXIT
$ inq rsp "Do you want to see 1 July message? "
$ if rsp.eqv."Y" then TYPE SIAO:[GRCUSER,STORE]MSG284,LIS
$ inq rsp "BULK DATA FILE TO BE USED(NULL RETURN FOR DEFAULT)? "
$ if rsp.eqv."" then goto default
$ assign/user 'rsp'
$ goto continue
$ default:
$ assign/user SIAO:[GRCUSER]bulk.dat for009
$ continue:
$ assign/user sav.dat for012
$ assign/user STAREL.COM for005
$ assign/user sys$command for006
$ ON ERROR THEN $ GOTO EXIT
$ run SIAO:[GRCUSER]ELV.EXE
$ EXIT:
$ del sav.dat:*

$ TYPE RUNELVEC.COM

$ set noverify
$ ON CONTROL-Y THEN $GOTO EXIT
$ inq rsp "Do you want to see 1 Jul message? "
$ if rsp.eqv."Y" then TYPE SIAO:[GRCUSER,STORE]MSG284,LIS
$ inq rsp "BULK DATA FILE TO BE USED(NULL RETURN FOR DEFAULT)? "
$ if rsp.eqv."" then goto default
$ assign/user 'rsp'
$ goto continue
$ default:
$ assign/user SIAO:[GRCUSER]bulk.dat for009
$ continue:
$ assign/user sav.dat for012
$ assign/user sys$command for005
$ assign/user sys$command for006
$ ON ERROR THEN $ GOTO EXIT
$ run SIAO:[GRCUSER]ELV.EXE
$ EXIT:
$ del sav.dat:*
## Glossary

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Coefficient of the battery mass fraction (BMF) - ELVEC range (R) equation. viz., BMF = AR + B</td>
</tr>
<tr>
<td>ACC</td>
<td>Defined by PACC = ACC*WB</td>
</tr>
<tr>
<td>ACCN</td>
<td>Acceleration power (kw)</td>
</tr>
<tr>
<td>ACTRAN</td>
<td>Actual range (miles)</td>
</tr>
<tr>
<td>ANS$</td>
<td>String variable which obtains the response to question &quot;DO YOU WISH TO MAKE ANOTHER RUN? If not Y or N (including lower case forms) then try again.</td>
</tr>
<tr>
<td>ANS1$</td>
<td>String variable which obtains the response to the question &quot;DO YOU WISH TO RUN ELVEC FOR THE VEHICLE SIZED IN THE LAST RUN?&quot; If not Y or N (including lower case forms) then try again.</td>
</tr>
<tr>
<td>B</td>
<td>Coefficient of the battery mass fraction (BMF) - ELVEC range (R) equation viz., BMF = AR + B</td>
</tr>
<tr>
<td>BATN$ (I)</td>
<td>Battery name</td>
</tr>
<tr>
<td>BMF</td>
<td>Battery mass fraction</td>
</tr>
<tr>
<td>BMFIN</td>
<td>Battery mass fraction input by the user in the redesign mode.</td>
</tr>
<tr>
<td>BMF1</td>
<td>AMP$ = GRAGE/PD</td>
</tr>
<tr>
<td>BMF2</td>
<td>BMF value in the file VEHICLE.DAT</td>
</tr>
<tr>
<td>BVOL</td>
<td>Battery volume (l)</td>
</tr>
</tbody>
</table>
CAP%  Vehicle capacity
CDA    Drag coefficient
CH(I)  CH-coefficients
CKW    controller power (kw)
CNUM%  Cycle type number:
       1 = Federal cycle
       2 = Highway cycle
       3 = Van cycle
CONSW  Controller specific weight
CRDIAL ELVEC variable
CYCLE  Cycle power
CYCLE% Sets number of cycles in
       24-hour cycle
CY$$(I) String variable used to label
       cycle number in the TITLE
       field of the ELVEC program
DOB%   Flag which determines whether
       24-hr. cycle will be run in
       demand or batch. (If set to
       1 then demand; if set to
       2 then batch).
DOD    Cut off depth of discharge
DOM(I) Specific power values for
       the tables in the subroutine
       which computes actual range.
DRAN   Desired range (miles)
EFCVRTEfficiency of CVT
EFFBCBattery charger efficiency
EFFCDCharge-discharge efficiency
ENGHPDefined by: $\text{ENGHP} = \frac{\text{ENGKW}}{0.746}$
ENGKWFor hybrids defined by $\text{ENGKW} = \text{EPOW}$
ENGVOLEngine volume (l)
EPOWDefined by: $\text{EPOW} = \frac{\text{GRADE} \times \text{WT}}{1000}$
ERROR$\%$Flag set equal to 1 if the specific power is out of range
ETKWEqual to $\frac{\text{GRADE} \times \text{WT}}{1000}$ or $\frac{\text{CYCLE} \times \text{WT}}{1000}$
FBRKSFraction of braking energy dissipated by friction
FUELCPFuel capacity
GRADEGrade power (kw)
GTRANVOLICE transmission volume (l)
HESWHeat engine specific power (w/kg)
LIMPRT$\%$Flag set equal to 1 if the iteration limit is exceeded in the iteration procedure for actual range.
MOTSWMotor specific power (w/kg)
MTMotor type (not operational in this version of the program)
the number of points used to define the SPECIFIC POWER X DOD functions. The value of N is dependent upon battery type. However, it is fixed for each run.

String variable which obtains the current battery name.

Battery type number. An integer input variable which directs the program's branching to the correct data set for the desired battery. Must obtain a value between 1 and 11 (inclusive) or try again.

Accessory power (kw)

Passenger and payload wt (kg)

Battery power (kw)

Constant in battery power equation

Power density

Power/energy ratio

Pressure of tires (lbs/sq.in.)

Value of the variable TOR% for "previous" run.

Constant in battery volume equation

Constant in battery volume equation

Cut off DOD values for the tables in the subroutine which computes actual range.
RFZ

Internal integer variable such that if it is equal to zero then the header of the output report is printed. If it is equal to one then the header is not printed.

SLFD

Self discharge (kw-hr)

SNUMZ

Integer variable which sets the power to energy ratio according to:

1 means P/E = 1.0
2 means P/E = 2.1
3 means P/E = 2.4
4 means P/E = 3.3

TLE$

Title of run

TORX

Integer variable with the following settings:
1 means new vehicle
2 means 24-hr. cycle using previous vehicle
3 means redesign by entering BMF.

TRCVT$W

CVT specific weight

TRFSW

Fixed transmission specific weight

VCT

Controller volume (1)

VEHZ

Vehicle type number
1 = electric
2 = hybrid

VMOT

Motor volume (1)

VTT$1F

EV transmission volume (1)

WCON

Controller weight (kg)

WCON1

term in basic weight equation
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHE</td>
<td>weight of the heat engine (kg)</td>
</tr>
<tr>
<td>WHE1</td>
<td>term in basic weight equation</td>
</tr>
<tr>
<td>WKG</td>
<td>specific power (W/kg)</td>
</tr>
<tr>
<td>WMOT</td>
<td>Motor weight (kg)</td>
</tr>
<tr>
<td>WSH</td>
<td>shell weight (kg)</td>
</tr>
<tr>
<td>WTCVT</td>
<td>CVT weight (kg)</td>
</tr>
<tr>
<td>WTCVT1</td>
<td>term in basic weight equation</td>
</tr>
<tr>
<td>WTF</td>
<td>Fixed transmission weight (kg)</td>
</tr>
<tr>
<td>WTF1</td>
<td>term in basic weight equation</td>
</tr>
<tr>
<td>WTR1</td>
<td>term in basic weight equation</td>
</tr>
</tbody>
</table>
LISTINGS FOR AVENERGY AND AVCOST
0 " Avenery.001 - Combined Program for 2, 4, 5 Passenger and Van
10 ' Subroutine Listing
200 INPUT "Enter file name of the form XXX.ENO: " , ENO$
385 ' 390 OOSUB 25000 ' Initialization Routine
395 ' 400 OPEN ENO$ FOR INPUT AS #5
410 INPUT#3, WMT, TIT, VEH
420 CLOSE#3
430 ' 440 REM Request ELC vector output file
450 ' 460 INPUT "Enter ELC vector output file name (null if no file is being used): " , JRB$
470 IF JRB$="" THEN ELFLAG=0 ELSE ELFLAG=1
475 IF ELFLAG=1 THEN OPEN JRB$ FOR INPUT AS 02
480 IF ELFLAO=1 THEN INPUT02, DUMMY1+DUMMY2+RANGE(1)+ACTRNO(1)+DUMDI+PDMA(1),
510 WHPM(1)+OPM(1)+DAT(1)+TIM(1)
490 CLOSE#2
510 PRINT "SELECT THE VEHICLE AS FOLLOWS:"
520 PRINT "1 - Two-Passenger - 9 Cycles"
530 PRINT "2 - Four-Passenger 225w - 12 Cycles"
540 PRINT "3 - Five-Passenger 100w - 10 Cycles"
550 PRINT "4 - Five-Passenger 150w - 11 Cycles"
560 PRINT "5 - Five-Passenger 250w - 12 Cycles"
570 PRINT "6 - Van - 4 Cycles"
580 PRINT "0 - Exit program - Return to BASIC"
590 INPUT "Pick a number", NPAS
600 IF NPAS=0 THEN CLOSE#1 END
610 IF NPAS=2 OR NPAS>5 THEN CLS1000 510
620 OOSUB 23000 ' Vehicle Type and Info Subroutine
625 RESTORE
630 ON NPAS GOSUB 1000,2000,3000,4000,5000,6000
640 CLS1000 510
1000 'S 1000 Subroutine - 2 Passenger - 9 Cycle
1010 J=9
1020 OOSUB 10000 ' Read Car Data
1030 IF ELFLAG=0 THEN GOSUB 1100 ELSE GOSUB 27000
1040 IF VEH=1 THEN GOSUB 1100
1050 IF VEH=2 THEN GOSUB 1150
1060 RETURN
1100 '2 Passenger - 9 Cycle - Veh = 1
1110 GOSUB 14000 ' Print 1 Subroutine
1120 GOSUB 16000 ' Print 3 Subroutine
1130 GOSUB 17000 ' Print 4 Subroutine
1140 GOSUB 18000 ' Print 5 Subroutine
1150 GOSUB 24000 ' Closing Subroutine
1160 RETURN
1170 '2 Passenger - 9 Cycle - Veh = 2
1180 GOSUB 15000 ' Print 2 Subroutine
1190 GOSUB 16000 ' Print 3 Subroutine
1200 GOSUB 17000 ' Print 4 Subroutine
1210 GOSUB 18000 ' Print 5 Subroutine
1220 GOSUB 24000 ' Closing Subroutine
1230 RETURN
2000 'S 2000 Subroutine - 4 Passenger - 12 Cycle - 225w
2010 Z=12
2020 OOSUB 10000 ' Read Car Data
2030 IF ELFLAG=0 THEN GOSUB 1100 ELSE GOSUB 27000
2040 IF VEH=1 THEN GOSUB 2100
2050 IF VEH=2 THEN GOSUB 2900
2060 RETURN
2100 '4 Passenger - 12 Cycle - 225w - Veh = 1

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M-119 PAGE M-115 INTENTIONALLY BLANK
2110 GOSUB 14000 ' PRINT 1 SUBROUTINE
2120 GOSUB 16000 ' PRINT 3 SUBROUTINE
2130 'GOSUB 17000 ' PRINT 4 SUBROUTINE
2150 GOSUB 19000 ' PRINT 5 SUBROUTINE
2160 GOSUB 24000 ' CLOSING SUBROUTINE
2170 RETURN
2500 '4 PASSENGER - 12 CYCLE - 250m - VEH = 2
2510 GOSUB 15000 ' PRINT 2 SUBROUTINE
2520 GOSUB 16000 ' PRINT 3 SUBROUTINE
2530 GOSUB 17000 ' PRINT 4 SUBROUTINE
2550 GOSUB 18000 ' PRINT 5 SUBROUTINE
2560 GOSUB 20000 ' PRINT 6 SUBROUTINE
2570 GOSUB 24000 ' CLOSING SUBROUTINE
2580 RETURN
3000 '5 3000 SUBROUTINE - 5 PASSENGER - 10 CYCLE - 100m
3010 Z=10
3020 GOSUB 10000 ' READ CAR DATA
3030 IF ELFLAG=0 THEN GOSUB 13000 ELSE GOSUB 27000
3040 IF VEH=1 THEN GOSUB 3100
3050 IF VEH=2 THEN GOSUB 3500
3060 RETURN
3100 '5 PASSENGER - 10 CYCLE - 100m - VEH = 1
3110 GOSUB 14000 ' PRINT 1 SUBROUTINE
3120 GOSUB 16000 ' PRINT 3 SUBROUTINE
3130 'GOSUB 17000 ' PRINT 4 SUBROUTINE
3150 GOSUB 18000 ' PRINT 5 SUBROUTINE
3160 GOSUB 24000 ' CLOSING SUBROUTINE
3170 RETURN
3500 '5 PASSENGER - 10 CYCLE - 100m - VEH = 2
3510 GOSUB 15000 ' PRINT 2 SUBROUTINE
3520 GOSUB 16000 ' PRINT 3 SUBROUTINE
3530 GOSUB 17000 ' PRINT 4 SUBROUTINE
3550 GOSUB 18000 ' PRINT 5 SUBROUTINE
3560 GOSUB 20000 ' PRINT 6 SUBROUTINE
3570 GOSUB 24000 ' CLOSING SUBROUTINE
3580 RETURN
4000 '5 4000 SUBROUTINE - 5 PASSENGER - 11 CYCLE - 150m
4010 Z=11
4020 GOSUB 10000 ' READ CAR DATA
4030 IF ELFLAG=0 THEN GOSUB 13000 ELSE GOSUB 27000
4040 IF VEH=1 THEN GOSUB 4100
4050 IF VEH=2 THEN GOSUB 4500
4060 RETURN
4100 '5 PASSENGER - 11 CYCLE - 150m - VEH = 1
4110 GOSUB 14000 ' PRINT 1 SUBROUTINE
4120 GOSUB 16000 ' PRINT 3 SUBROUTINE
4130 'GOSUB 17000 ' PRINT 4 SUBROUTINE
4150 GOSUB 18000 ' PRINT 5 SUBROUTINE
4160 GOSUB 24000 ' CLOSING SUBROUTINE
4170 RETURN
4500 '5 PASSENGER - 11 CYCLE - 150m - VEH = 2
4510 GOSUB 15000 ' PRINT 2 SUBROUTINE
4520 GOSUB 16000 ' PRINT 3 SUBROUTINE
4530 GOSUB 17000 ' PRINT 4 SUBROUTINE
4550 GOSUB 18000 ' PRINT 5 SUBROUTINE
4560 GOSUB 20000 ' PRINT 6 SUBROUTINE
4570 GOSUB 24000 ' CLOSING SUBROUTINE
4580 RETURN
5000 '5 5000 SUBROUTINE - 5 PASSENGER - 12 CYCLE - 250m
5010 Z=12
5020 GOSUB 10000 ' READ CAR DATA
5030 IF ELFLAG=0 THEN GOSUB 13000 ELSE GOSUB 27000
5040 IF VEH=1 THEN GOSUB 5100

ORIGINAL PAGE IS OF POOR QUALITY

5500 IF VEH=2 THEN GOSUB 5500
5540 RETURN
5550 '5 PASSENGER - 12 CYCLE - 250M - VEH = 1
5570 GOSUB 14000 'PRINT 1 SUBROUTINE
5570 GOSUB 16000 'PRINT 3 SUBROUTINE
5530 'GOSUB 17000 'PRINT 4 SUBROUTINE
5560 GOSUB 18000 'PRINT 5 SUBROUTINE
5580 GOSUB 24000 'CLOSING SUBROUTINE
5570 RETURN
5590 '5 PASSENGER - 12 CYCLE - 250M - VEH = 2
5610 GOSUB 15000 'PRINT 2 SUBROUTINE
5650 GOSUB 16000 'PRINT 3 SUBROUTINE
5630 GOSUB 17000 'PRINT 4 SUBROUTINE
5660 GOSUB 18000 'PRINT 5 SUBROUTINE
5680 GOSUB 24000 'CLOSING SUBROUTINE
5670 RETURN
6100 '5 6000 SUBROUTINE - VAN - 4 CYCLE
6100 GOSUB 11000 'READ VAN DATA
6100 IF ELFLAG=0 THEN GOSUB 13000 ELSE GOSUB 27000
6140 IF VEH=1 THEN GOSUB 6100
6150 IF VEH=2 THEN GOSUB 6500
6140 RETURN
6500 'VAN - 4 CYCLE - VEH = 1
6510 GOSUB 14000 'PRINT 1 SUBROUTINE
6540 GOSUB 16000 'PRINT 3 SUBROUTINE
6530 GOSUB 17000 'PRINT 4 SUBROUTINE
6560 GOSUB 18000 'PRINT 5 SUBROUTINE
6580 GOSUB 24000 'CLOSING SUBROUTINE
6570 RETURN
6580 'VAN - 4 CYCLE - VEH = 2
6510 GOSUB 15000 'PRINT 2 SUBROUTINE
6550 GOSUB 16000 'PRINT 3 SUBROUTINE
6540 GOSUB 17000 'PRINT 4 SUBROUTINE
6570 GOSUB 18000 'PRINT 5 SUBROUTINE
6590 GOSUB 24000 'CLOSING SUBROUTINE
6580 RETURN
10000 'CAR DATA READ SUBROUTINE
10010 FOR I=1 TO 2
10030 READ M(I),DAYS(I) NEXT 1
10020 DATA 4.2,57
10040 DATA 7.45,50
10050 DATA 8.2,43
10060 DATA 16.86,32
10070 DATA 22.35,63
10080 DATA 27.27
10090 DATA 45.4,29
10100 DATA 59.6,18
10110 DATA 3.6,19
10120 DATA 105.3,9
10130 DATA 136.4,7
10140 DATA 250.4
10150 RETURN
10160 'VAN DATA READ SUBROUTINE
10160 M(1)=DAYS(1)*16.3
10180 M(2)=DAYS(2)*6.2
10160 M(3)=DAYS(3)*25
10160 M(4)=DAYS(4)*12
10190 'FOR I=1 TO 2
10200 'READ M(I),DAYS(I) NEXT 1
10300 DATA 25,163
11040 DATA 25,62
11050 DATA 45,25
11060 DATA 55,12
11070 RETURN
13000 'VEHICLE CONSUMPTION AND RANGE SUBROUTINE
13010 PRINT "INPUT THE RANGE, ENERGY CONSUMPTION AND MPG FOR EACH CYCLE"
13020 LPRINT "CYCLE", "RANGE", "WH/MILE", "MPG"
13030 FOR I=1 TO 2
13040 PRINT "CYCLE", "RANGE", "WH/MILE", "MPG"
13050 I=1
13060 NEXT I
13070 RETURN
14000 'PRINT 1 SUBROUTINE
14010 FOR I=1 TO 2
14020 MILES(I)=M(1)*DAYS(I)
14030 EL(I)=WHPM(I)*MILES(I)/1000
14040 IF M(I)>RANGE(I) THEN MILES(I)=RANGE(I)*DAYS(I)
14050 DOD(I)=M(I)/RANGE(I)
14060 IF M(I)>RANGE(I) THEN DOD(I)=DAYS(I)
14070 D=D+MILES(I)*E+EL(I)
14080 CYCLES(I)=DOD(I)*DAYS(I)
14090 NEXT I
14100 RETURN
14110 LPRINT "cycle", "wh/mile", "miles/day", "days", "cum miles", "kwh", "dod", "cycles"
14120 FOR I=1 TO 2
14130 PRINT I,WHPM(I),M(I),DAYS(I),MILES(I),EL(I),DOD(I),CYCLES(I)
14140 LPRINT I,WHPM(I),M(I),DAYS(I),MILES(I),EL(I),DOD(I),CYCLES(I)
14150 NEXT I
14160 RETURN
15000 'PRINT 2 SUBROUTINE
15010 FOR I=1 TO 2
15020 K=RANGE(I)+DODMX*MILES(I)=DAYS(I)*M(1)
15030 IF M(I)>K THEN GOSUB 15500 ELSE GOSUB 15100
15040 NEXT I
15050 UOSUM
15060 'PRINT 2-1 SUBROUTINE
15100 GM(I)=EM(I)=M(1)=EL(I)=WHPM(I)=M(1)=DAYS(I)/1000
15120 DOD(I)=M(I)/RANGE(I)
15130 CYCLES(I)=DOD(I)*DAYS(I)
15140 RETURN
15150 'PRINT 2-2 SUBROUTINE
15200 GM(I)=M(1)-K=EL(I)=WHPM(I)=DAYS(I)/1000
15210 EM(I)=K+DOD(I)=DAYS(I)
15220 RETURN
15230 'PRINT 2-3 SUBROUTINE
15280 FOR I=1 TO 2
15300 PRINT GM(I)=EM(I)=M(1)=EL(I)=WHPM(I)=DAYS(I)=EM(I)=M(1)=DAYS(I)
15350 NEXT I
15360 RETURN
16000 'PRINT 3 SUBROUTINE
16010 LPRINT "---------------------------------------------------------------"
16020 PRINT DI="miles",EL="kwh",Y="cycles",P="FUEL MILES",P="miles on electric"
16030 I=PRINT DI="miles",EL="kwh",Y="cycles",P="FUEL MILES",P="miles on electric"
I W40 I-UEL:

16050 LPRINT "Electric..."+TENK:" Fuel...";FUEL
16060 PRINT "Electric..."+TENK:" Fuel...";FUEL
16070 LPRINT "Annual travel in km"=1DL.6
16080 DCON=0.1&ETERN=100DCON=1=1/36L1GAS=0
16090 "LPRINT "MPG-UH"+INPUT"MPU-HH"1MPH"1MPH
16100 RETURN
17000 'PRINT 4 SUBROUTINE
17100 FOR I=1 TO 2
17101 GM(1)=21.4
17102 GM(1)=18.4
17103 GM(1)=106.2
17104 GM(1)=197.6
17105 IF I<9 THEN GM(1)=0
17106 IF I<9 THEN FC(1)=0
17107 THE FOLLOWING ASSUMES METHANOIL MPG INPUT - UNADJUSTED FROM ELVE
17108 IF I<9 THEN FC(1)=0
17109 "LPRINT "Vehicle Curb weight in km"=1MC."weight of the Battery="1WB
17110 RETURN
16000 'PRINT 5 SUBROUTINE
16100 LPRINT "Battery Cycle Life="1BC.1"Cycles"
16100 LPRINT "Depth of discharge, Average Daily"=1X/365
18040 X.163X/36
18090 RETURN
16090 RETURN
20000 'PRINT 6 SUBROUTINE
20100 LPRINT "ANNUAL GAS CONSUMPTIONS"10A61"DALLON1i"
20200 LPRINT "M_43 DUD"1X/363
20300 RETURN
20030 'PRINT 7 SUBROUTINE
21010 REM * INPUT "PRINT THE TITLE"ITITS
21010 REM * INPUT "SELECT VEHICLE - 1 FOR EV • 2 FOR HV"IVEH
21010 REM * INPUT "PRINT 11r.WB"1WT.f1B
21010 REM * INPUT "BATTERY CYCLE LIFE"1BCL
21010 REM * INPUT "ELFUGD=0 THEN INPUT "MAI DUD"1DUMAX
21010 'CLOSING SUBROUTINE
24000 'CLOSING SUBROUTINE
24010 OPEN "ENERGY. DAT" FOR OUTPUT AS E1
24020 WRITE 01. LTKM.E•ENER•FUEL. DCON.LITM.B(:L•X363.WB*11$.
24030 CLOSE 01
24040 'INITIALIZATION SUBROUTINE
25010 'INITIALIZATION SUBROUTINE
25020 LPRINT "LP111".160
25030 LPRINT "X"1
25040 LPRINT "X"1
25050 'CLOSING SUBROUTINE
25060 CLOSE 02
25070 RETURN
27000 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27010 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27020 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27030 CLOSE 02
27040 CLOSE 02
27050 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27060 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27070 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27080 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27090 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27100 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27110 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27120 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27130 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
27140 'SUBROUTINE AUTOMATIC INPUT OF RANGE, ENERGY, DUMAX AND MPG
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10 'ACOSJ.BAS
20 KEQ OFFILS
30 LPRINT CHR$(12)
40 LPRINT CHR$(27)+"5"
50 LPRINT CHR$(27)+"7"
60 OPEN "ENERGY.DAT" FOR INPUT AS #1
70 INPUT#1, TKN, AEL, EULY, RILE, KMYR, AFUS, CYCB, ADDU, MB, PHUS, IVTYP
80 IF IVTYP=1 THEN VTYPE=2 ELSE VTYPE=1
90 CLOSE #1
100 'TMY=128480 'KMY=133721 'RICE=0 'KMYR=128481 'AFUS=0 'CYCB=800
100 IF ADDU=. THEN 'ADDU=.329
105 LPRINT "ENTER ONE OF THE NAME OF THE FORM XXX.US;": CST$
110 OPEN CST# FOR INPUT AS #3
120 INPUT#3, MKW, CKW, ETKW, EPOW, BATTE, CURBWT
130 CLOSE #3
140 'PEE=PKM-31CKW=351ETKW=351EPOW=40
150 LPRINT "TYPE THE PAGE HEADING. "PHD$
160 REM ** INPUT "TYPE THE NAME OF THE BATTERY. "BATTE
70 IDUL=1982
80 IF IDUL=0 THEN IDUL=1982
190 REM * INPUT "Enter 1 for hybrid, 2 for electric, 3 for ice vehicle":IVTYP
200 PRINT "Type the number of passengers as follows!"
210 PRINT "1 - TWO-PASSENGER"
220 PRINT "2 - FOUR-PASSENGER 2500m";
230 PRINT "3 - FIVE-PASSENGER 2500m";
240 PRINT "4 - FIVE-PASSENGER 1000m";
250 PRINT "5 - FIVE-PASSENGER 1500m";
260 PRINT "6-VAN"
270 INPUT "Enter the vehicle curb weight in KG."CURBWT
280 ON NPAS GOTO 20, 300, 310, 320, 330, 340
290 PASS=4 "2-PASS" IF PANPL=1381 GOTO 350
300 PASS=4 "5-PASS" IF PANPL=1381 GOTO 350
310 PASS=5 "5-PASS" IF PANPL=1381 GOTO 350
320 PASS=5 "5-PASS" IF PANPL=1381 GOTO 350
330 PASS=5 "5-PASS" IF PANPL=1381 GOTO 350
340 PASS=5 "5-PASS" IF PANPL=1381 GOTO 350
350 REM
360 W=200
370 REM -- INPUT "Type the vehicle curb weight in KG."CURBWT
380 IF NPAS=6 THEN GOTO 410
390 W=CURBWT+136
400 GOTO 415
410 W=CURBWT+205
415 IF VTYPE=3 THEN GOTO 482
420 'PRINT "Input section for battery data"
430 REM * INPUT "Type battery weight in kg.":MB
440 'PRINT "Type the cost of electricity in C/KW-H."PELEC
450 PELEC=PELEC/100
460 'PRINT "Type the battery shelf life in years."BLYIF
470 'PRINT "Type the depth of a deep discharge (usually .8)."IDDCG
480 IF IDDCG=. THEN IDDCG=.8
482 'PRINT "Type the vehicle maintenance factor--default=1"MFAC
490 IF MFAC=0 THEN MFAC=1
490 'PRINT "Enter the life of the vehicle in years" YEAR
495 IF VTYPE=2 THEN RICE=0 EULY=1 DOLO 580
497 IF VTYPE=3 THEN RICE=1 EULY=0 DOLO 700
500 PRINT
500 PRINT "Motor data"
502 'PRINT "enter motor type=1 for ac,2 for dc brushless,3 for dc brush":MTYP
504 MTYP="ac"
506 IF MTYP=2 THEN MTYP="dc brushless"
508 IF MTYP=3 THEN MTYP="dc brush"
590 PRINT

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600 REM ** INPUT "Type the power of the motor in kw.":MKW
620 'MKW=PEFPWR
630 REM=MKW/.49
652 IF CTYP=2 THEN MONT=MKW/.64
654 IF CTYP=3 THEN MONT=MKW/.22
636 INPUT "Enter controller type: 1 for ac, 2 for dc brushless, 3 for dc brush";CTYP
638 CTYP="ac"
640 IF CTYP=2 THEN CTYP="dc brushless"
641 IF CTYP=3 THEN CTYP="dc brush"
645 REM ** INPUT "Type the controller rated power in kw.";CKW
650 CKW=MONT/2.5
652 IF CTYP=2 THEN CKW=MONT/1.47
660 REM ** INPUT "TYPE THE EV TRANSMISSION POWER IN KW";EIKW
670 EIKW="ac" IF CTYP=2 THEN EIKW="DC"
680 PRINT
690 IF VTYP=1 THEN NTRAN=1100
700 PRINT "Input section for engine"
710 PRINT
720 REM ** INPUT "Type the engine power in kw.";EPOW
730 EPOW=EIKW/2.5
740 REM ** INPUT "TYPE THE ICE TRANSMISSION POWER IN KW";IIPW
750 'INPUT "Type tank volume volume in L. ";VGRAS
760 INPUT "1 TRANSMISSION ON 2";NTRAN
770 REM
775 TKM=YEAR*KMWR
800 INPUT "Type the vehicle salvage value as percent of new.";ISLBV
810 ISLBV=SLBV/2.5
812 ' IF VTYP=3 THEN GOTO 814
814 'INPUT "ENTER THE ANNUAL TRAVEL IN KM/yr";KMWR
815 'IF VTYP=3 THEN GOTO 816
816 'INPUT "ENTER THE ANNUAL FUEL USE IN LITERS";AFUS
820 IF VTYP=2 THEN GOTO 870
830 INPUT "Type the cost of fuel for 1992 in 1982$/L";PFUEL
840 INPUT "Type 1 for gasoline fuel, 2 for diesel, 3 for methanol.";FTYP
850 FTYP="GASOLINE" IF FTYP=2 THEN FTYP="DIESEL"
860 IF FTYP=3 THEN FTYP="METHANOL"
870 INPUT "TYPE PERCENT REAL INTEREST RATE.";IRINTR
880 INPUT "TYPE PERCENT REAL DISCOUNT RATE.";IRDISR
890 INPUT "Type the number of years to finance over.";IFYEAR
900 RINTR=IRINTR/100
910 RKISR=IRDISR/100
920 REM
960 REM
970 REM
980 IF VTYP=3 THEN GOTO 1270
990 IF NTRTRAN=2 THEN GOTO 1150
1000 PRINT "TYPE EV TRANSMISSION TYPE. "
1010 PRINT "1 - CVT"
1020 IF NTRAN=2 THEN NTRAN=1270
1030 PRINT "3 - FIXED RATIO"
1035 INPUT "4 - 2 speed auto";NTRAN
1040 ON NTRAN GOTO 1050,1060,1070,1080
1050 TRANS="CVT" IF TRANS=11 THEN GOTO 1090
1060 TRANS="4-speed" IF TRANS=11 THEN GOTO 1090
1070 TRANS="fixed ratio" IF TRANS=11 THEN GOTO 1090
1080 TRANS="2 speed auto" IF TRANS=11 THEN GOTO 1090
1090 ON TRANS GOTO 1090,1100,1110,1120,1125
1100 COSTRAN=EIKW/1.11 GOTO 1090
1110 COSTRAN=EIKW/1.61 GOTO 1090
1120 COSTRAN=EIKW/1.42 GOTO 1090
1125 COSTRAN=EIKW/1.86 GOTO 1090
1130 ON COSTRAN GOTO 1140,1150,1160,1170,1180
1140 ON COSTRAN GOTO 1140
1150 ON COSTRAN GOTO 1150
1160 ON COSTRAN GOTO 1160
1170 ON COSTRAN GOTO 1170
1180 ON COSTRAN GOTO 1180
ORIGINAL PAGE IS OF POOR QUALITY
1680 IF BATT$="ZN-CL2/1.0" THEN CWBT=(10*(89/1000)*Wb)+(45*(166/1000)*Wb)+1150
1690 IF BATT$="ZN-CL2/2.1" THEN CWBT=(10*(54/1000)*Wb)+(45*(110/1000)*Wb)+1150
1700 IF BATT$="ZN-CL2/2.4" THEN CWBT=(10*(54/1000)*Wb)+(45*(127/1000)*Wb)+1150
1710 IF BATT$="ZN-CL2/3.3" THEN CWBT=(10*(54/1000)*Wb)+(45*(130/1000)*Wb)+1150
1720 IF BATT$="FE-AIR1.0" THEN CWBT=(8*(109/1000)*Wb)+(25*(140/1000)*Wb)+700
1730 IF BATT$="FE-AIR2.1" THEN CWBT=(8*(168/1000)*Wb)+(25*(197/1000)*Wb)+700
1740 IF BATT$="FE-AIR2.4" THEN CWBT=(8*(168/1000)*Wb)+(25*(197/1000)*Wb)+700
1750 IF BATT$="FE-AIR3.3" THEN CWBT=(8*(152/1000)*Wb)+(25*(165/1000)*Wb)+700
1760 IF BATT$="LI- FE-S1.0" THEN CWBT=(70*(102/1000)*Wb)+(10*(161/1000)*Wb)+750
1770 IF BATT$="LI- FE-S2.3" THEN CWBT=(70*(81/1000)*Wb)+(10*(165/1000)*Wb)+750
1780 IF BATT$="LI- FE-S2.4" THEN CWBT=(70*(81/1000)*Wb)+(10*(165/1000)*Wb)+750
1790 IF BATT$="LI- FE-S3.3" THEN CWBT=(70*(81/1000)*Wb)+(10*(165/1000)*Wb)+750
1800 IF BATT$="NA-S1.0" THEN CWBT=(25*(121/1000)*Wb)+(45*(148/1000)*Wb)+1000
1810 IF BATT$="NA-S2.1" THEN CWBT=(25*(87/1000)*Wb)+(45*(199/1000)*Wb)+1000
1820 IF BATT$="NA-S2.4" THEN CWBT=(25*(83/1000)*Wb)+(45*(224/1000)*Wb)+1000
1830 IF BATT$="NA-S3.3" THEN CWBT=(25*(71/1000)*Wb)+(45*(244/1000)*Wb)+1000
1840 IF BATT$="PBAC/AO1.0" THEN CWBTH=1.16*CWBT
1850 IF BATT$="PBAC/A112.1" THEN CWBTH=1.35*CWBT
1860 IF BATT$="PBAC/A22.4" THEN CWBTH=1.2*CWBT
1870 IF BATT$="PBAC/A23.3" THEN CWBTH=1.2*CWBT
1880 IF BATT$="PB- AC/BIPL" THEN CWBTH=1.5*CWBTH
1890 IF BATT$="NI-FE1.0" THEN CWBTH=0.9099999*CWBTH
1900 IF BATT$="NI-FE2.1" THEN CWBTH=0.87*CWBTH
1910 IF BATT$="NI-FE2.4" THEN CWBTH=0.9000001*CWBTH
1920 IF BATT$="NI-FE3.3" THEN CWBTH=1.01*CWBTH
1930 IF BATT$="PBAC/AD1.0" THEN CWBTH=1.16*CWBTH
1940 IF BATT$="PBAC/AD2.1" THEN CWBTH=1.35*CWBTH
1950 IF BATT$="PBAC/AD2.4" THEN CWBTH=1.2*CWBTH
1960 IF BATT$="PBAC/AD3.3" THEN CWBTH=1.2*CWBTH
1970 IF BATT$="PBAC/AD2.4" THEN CWBTH=1.2*CWBTH
1980 IF BATT$="PBAC/AD3.3" THEN CWBTH=1.2*CWBTH
1990 IF BATT$="PAC-D2/1.0" THEN CWBTH=1.16*CWBTH
2000 IF BATT$="PAC-D2/2.1" THEN CWBTH=2.02*CWBTH
2010 IF BATT$="PAC-D2/2.4" THEN CWBTH=1.72*CWBTH
2020 IF BATT$="PAC-D2/3.3" THEN CWBTH=1.83*CWBTH
2030 IF BATT$="PAC-D2/3.3" THEN CWBTH=1.83*CWBTH
2040 IF BATT$="PAC-D2/2.1" THEN CWBTH=1.04*CWBTH
2050 IF BATT$="PAC-D2/2.4" THEN CWBTH=1.04*CWBTH
2060 IF BATT$="PAC-D2/3.3" THEN CWBTH=1.01*CWBTH
2070 IF BATT$="FE-AIR1.0" THEN CWBTH=1.83*CWBTH
2080 IF BATT$="FE-AIR2.1" THEN CWBTH=2.57*CWBTH
2090 IF BATT$="FE-AIR2.4" THEN CWBTH=1.83*CWBTH
2100 IF BATT$="FE-AIR3.3" THEN CWBTH=2.03*CWBTH
2110 IF BATT$="NA-S1.0" THEN CWBTH=1.36*CWBTH
2120 IF BATT$="NA-S2.1" THEN CWBTH=1.24*CWBTH
2130 IF BATT$="NA-S2.4" THEN CWBTH=0.95*CWBTH
2140 IF BATT$="NA-S3.3" THEN CWBTH=9.9999999*CWBTH
2150 IF BATT$="LI-FE-S1.0" THEN CWBTH=1.20*CWBTH
2160 IF BATT$="LI-FE-S2.1" THEN CWBTH=9.3*CWBTH
2170 IF BATT$="LI-FE-S2.4" THEN CWBTH=1.19*CWBTH
2180 IF BATT$="LI-FE-S3.3" THEN CWBTH=9.8*CWBTH
2190 IF BATT$="AL-AIR" THEN CWBTH=1.5*CWBTH
2200 REM LOW AND HIGH BATTERY COST
2210 IF CWBTH>CWBTH THEN GOTO 2270
2220 XXX=CWBTH
2230 GOTO 2270
2240 CWBT=WBT
2250 CWBT=XXX
2260 REM INITIAL COST
2270 REM INITIAL COST
2280 INIT=CWH+VBC+CHOT+CCON+ECOST+ENUC+OCUST+ACUST+GUST+GUST
2290 INIT=LWH+VBC+CHOT+CCON+ECOST+ENUC+OCUST+ACUST+GUST
2295 IF VYPS THEN GOTO 3040
2300 REM REPLACEMENT BATTERIES
2310 IF BATT$="AL-AIR" THEN 2240
REM THIS TAKES FRACTIONAL BATTERIES AND MAKES THEM WHOLE NUMBERS FOR BATTERY REPLACEMENT, THE DIFFERENCE BETWEEN THE WHOLE NUMBER AND THE FRACTION IS CONSIDERED AS BATTERY SALVAGE

IRBAT=INT(IRBAT+.5)

DRBAT=IRBAT-RBAT

IF DRBAT=0 THEN DRBAT=0

CWRB=IRBAT*CHBT+TI

CHRM=IRBAT*CHBT*LI

UOTO 2460

REM DETERMINATION OF BATTERY MATERIAL SALVAGE COST PER KWH

IF BATTS=PBAC/AD1.0 OR BATTS=PBAC/AD2.1 THEN MCPKWH=1.66

IF BATTS=PBAC/AD2.2 OR BATTS=PBAC/AD3.3 THEN MCPKWH=1.66

IF BATTS=PB/AC/BIPL THEN MCPKWH=1.66

IF BATTS=NI-FE1.0 OR BATTS=NI-FE2.1 THEN MCPKWH=6.56

IF BATTS=NI-FE2.4 OR BATTS=NI-FE3.3 THEN MCPKWH=6.56

IF BATTS=ZIR2/1.0 OR BATTS=ZIR2/2.1 THEN MCPKWH=6.0

IF BATTS=ZIR2/2.4 OR BATTS=ZIR2/3.3 THEN MCPKWH=6.0

IF BATTS=FE-AIR1.0 OR BATTS=FE-AIR2.1 THEN MCPKWH=6.0

IF BATTS=FE-AIR2.4 OR BATTS=FE-AIR3.3 THEN MCPKWH=6.0

IF BATTS=LI-FE-S1.0 OR BATTS=LI-FE-S2.1 THEN MCPKWH=2

IF BATTS=LI-FE-S2.4 OR BATTS=LI-FE-S3.3 THEN MCPKWH=2

IF BATTS=NA-S1.0 OR BATTS=NA-S2.1 THEN MCPKWH=0

IF BATTS=NA-S2.4 OR BATTS=NA-S3.3 THEN MCPKWH=0

IF BATTS=NI-ZIR2.0 THEN MCPKWH=10.23

IF BATTS=LI-FE-S1.0 THEN MCPKWH=2

REM SPECIFIC ENERGY VALUES ARE SUBSTITUTED IN THE FOLLOWING EQUATIONS

IF BATTS=PBAC/AD1.0 THEN KWHR=(45/1000)*WB

IF BATTS=PBAC/AD2.1 THEN KWHR=(43/1000)*WB

IF BATTS=PBAC/AD2.2 THEN KWHR=(41/1000)*WB

IF BATTS=PB/AC/AD3.3 THEN KWHR=(38/1000)*WB

IF BATTS=PB/AC/BIPL THEN KWHR=(50/1000)*WB

IF BATTS=NI-FE1.0 THEN KWHR=(56/1000)*WB

IF BATTS=NI-FE2.1 THEN KWHR=(54/1000)*WB

IF BATTS=NI-FE2.4 THEN KWHR=(52/1000)*WB

IF BATTS=NI-FE3.3 THEN KWHR=(48/1000)*WB

IF BATTS=ZIR2/1.0 THEN KWHR=(67/1000)*WB

IF BATTS=ZIR2/2.1 THEN KWHR=(65/1000)*WB

IF BATTS=ZIR2/2.4 THEN KWHR=(63/1000)*WB

IF BATTS=ZIR2/3.3 THEN KWHR=(61/1000)*WB

IF BATTS=FE-AIR1.0 THEN KWHR=(109/1000)*WB

IF BATTS=FE-AIR2.1 THEN KWHR=(65/1000)*WB

IF BATTS=FE-AIR2.4 THEN KWHR=(63/1000)*WB

IF BATTS=FE-AIR3.3 THEN KWHR=(52/1000)*WB

IF BATTS=LI-FE-S1.0 THEN KWHR=(102/1000)*WB

IF BATTS=LI-FE-S2.1 THEN KWHR=(81/1000)*WB

IF BATTS=LI-FE-S2.4 THEN KWHR=(81/1000)*WB

IF BATTS=LI-FE-S3.3 THEN KWHR=(71/1000)*WB

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2940 REM BATTERY SALVAGE VALUE IS THE SUM OF SALVAGE FROM REPLACEMENT BATTERIES AND BATTERY SALVAGE MATERIAL
2950 SVB1=MCPKWH*TI*KWHR*LI
2960 SVB1H=(MCPKWH*TI*KWHR)*LI
2970 IF IRBAT=2 THEN IRBATH=2*RBATYH:GOTO 2990
2980 GOTO 3035
2990 SI=1/(1+RIN1')*IRBATYR
3000 ZI=1/(1+RIN1')*IRBATYR
3010 IF IRBATYR<10 THEN SVB2=(MCPKWH*SI*KWHR)*ZI
3020 IF IRBATYR<10 THEN GOTO 3035
3030 SVB=(MCPKWH*SI*KWHR)*ZI
3035 SVB=SVB1+SVB2
3036 SVBH=SVB1+SVB2
3039 REM ALL OPERATING COSTS ARE DISCOUNTED TO PRESENT VALUES
3040 REM REPAIRS AND MAINTENANCE
3050 TKM=YEAR*KMYR
3060 IF VTYP=2 THEN MICE=0:GOTO 3080
3070 MICE=136.22
3080 MICE=81.7301
3090 RPM= (ME+(1.14/100*KMYR*EOLY*MFAC))+(MICE+(1.91/100*KMYR*RI
3100 RPM=0
3110 FOR N=1 TO YEAR
3120 TEMP1=RPM*CI
3130 RPM=TEMPC1
3140 NEXT N
3150 IF VTYP=2 THEN MICE=0:GOTO 3170
3160 MICE=131.11
3170 MICE=78.67
3180 IF NPAS=5 THEN RPM= (ME+(1.23/100*KMYR*EOLY*MFAC))+(MICE+(2.05/100*KMYR*RI
3190 RPM=0
3200 FOR N=1 TO YEAR
3210 TEMPC2=RPM*CI
3220 RPM=TEMPC2
3230 NEXT N
3240 REM REPLACEMENT TIRES
3250 RTKM=TKM-64374!
3260 RTIR=(RTKM*(368.74+(.18086*CURBWT))/(128748!))
3270 REM INSURANCE
3280 IRNSR=0
3290 FOR N=1 TO YEAR
3300 TEMPC3=243*CI
3310 IRNSR=IRNSR+TEMPC3
3320 NEXT N
3330 IRNSR=IRNSR+748
3340 IF NPAS=5 THEN GOTO 3345
3345 IRNSR=0
3350 FOR N=1 TO YEAR
3360 TEMPC4=256*CI
3370 IRNSR=IRNSR+TEMPC4
3380 NEXT N
3390 IRNSR=IRNSR+919
3400 REM GARAGING, PARKING AND TOLL
3410 PIE=0
3420 FOR N=1 TO YEAR
3430 TEMPC5=78.25*CI
3440 PIE=PIE+TEMPC5
3450 NEXT N
REM TITLE: REGISTRATION
TRLE=0
FOR N=1 TO YEAR
    TEMP=N+30:CI
    TRLE=TRLE+TEMP
    NEXT N
    TRLE=TRLE+1.05*INIT
    TRLEH=0
    FOR N=1 TO YEAR
        TEMP=N+30:CI
        TRLEH=TRLEH+TEMP
        NEXT N
    TRLEH=TRLEH+(.05*INIT)

REM FUEL AND OIL COST
CFU=AFU*PFUEL*1.03
CFUL=0
FOR N=1 TO YEAR
    TEMP=CFUL+CI
    CFUL=CFUL+TEMP
    NEXT N
REM ELECTRICITY COST
CEL=ALC*PELEC
CELE=0
FOR N=1 TO YEAR
    TEH=PO*CEL*CI
    CELE=CELE+TEH
    IF BATWAL = AIR THEN ANOD=-.0625*KMYR*CI
    IF BATWAL = AL—AIR THEN CELE=CELE+ANOD
    NEXT N
REM ANNUAL PRINCIPAL AND INTEREST PAYMENT
    APINT=.B*(INIT)*((RINTR*(1+RINTR)^FYEAR)/((1+RINIR)^FYEAR-1))
    FI=((1+RDISP)^FYEAR)
    PAPINT=APINT*F1/O1
    APINTH=.B*(INITH)*((RINITH*(1+RINITH)^FYEAR)/((1+RINITH)^FYEAR-1))
    PAPINTH=APINTH*F1/O1
GO TO 3950
REM OPERATING COSTS
OPER=CEL+CFUL+TRLE+PTE+INSR+RTIR+RPMN+CWRB+PAPINT

REM CUMULATIVE CALCULATIONS COMPLETE
FORMAT$=" "*SPACE$(24)+""
FORMAT1=""*SPACE$(24)+"
GO TO REM
REM ** PRINT HEADER INFORMATION.
REM
4040 I=(AO-EN(PHINT))1/2
4070 LPRINT I LPRINT SPACE(10)"INPUTS" I LPRINT
4090 LPRINT "GENERAL -"TAB(40)"YEARS" "10DUL
4100 LPRINT "VEHICLE SIZE:" "PASS#="TAB(40)
4110 LPRINT "REAL INTEREST RATE:" "INTER#1001%"
4120 LPRINT "Curb Weight:" "CURBW#."TAB(40)
4130 LPRINT "VEHICLE SALVAGE VALUE:" "SLBV#1001%"
4140 LPRINT "VEHICLE WEIGHT - WT:" "WT
4150 LPRINT "LIFE:" "TKM#."TAB(40)"ACCESSORY COST:" "CACC
4160 LPRINT "BATTERY:" "TAB(40)"NAME:" "BATT$
4170 LPRINT "BATTERY WEIGHT:" "W#."TAB(40)
4190 LPRINT "BATTERY CYCLE LIFE:" "CYC$
4200 LPRINT "ELECTRICITY COST:" "PEL#-"/KM-H"TAB(40)
4210 LPRINT "MAXIMUM SHELF LIFE:" "BLIF$YEARS"
4220 LPRINT "AVERAGE DAILY DEPTH OF DISCHARGE:" "ADDITAB(40)
4230 LPRINT "DEPTH OF A DEEP DISCHARGE:" "IDDC$
4240 LPRINT "MAINTENANCE FACTOR:" "MFA$
4250 LPRINT
4260 IF VYP-2 THEN GOTO 4310
4270 LPRINT "ENGINE --"TAB(40)
4280 LPRINT "FUEL COSTS:" "PFUELI"/L"
4290 LPRINT "TANK CAPACITY:" "VQAS#"TAB(40)"FUEL TYPE:" "FYP$
4300 IF NTRAN-2 THEN GOTO 4350
4310 LPRINT "TRANSMISSION TYPE:" "TRAN$
4320 IF VYP-2 THEN GOTO 4340
4330 LPRINT "TAB(40)"RATED POWER:" "EPW"KW$
4340 GOTO 4360
4350 LPRINT "ICE TRANSMISSION TYPE:" "TRAN#"TAB(40)"POWER:" "TPW$"KW$
4360 LPRINT "MOTOR:" "MKW$"KW$
4370 LPRINT "CONTROLLER:" "CKW$"KW$
4380 LPRINT "EV TRANSMISSION TYPE:" "ETRAN$"TAB(40)"POWER:" "ETPW$"KW$
4390 LPRINT "DRIVING --"TAB(40)"AMOUNT:" "KMYRI"KM/YEAR"
4400 REM
4410 IF NTRAN-1 THEN GOTO 4430
4420 LPRINT "EV FRACTIONAL RANGE:" "RICE$1001"%"TAB(40)
4430 LPRINT "EV FRACTIONAL RANGE:" "EOLY$1001"%
4440 LPRINT "ANNUAL FUEL USE:" "AFUSI" L"TAB(40)
4450 LPRINT "ANNUAL ELEC USE:" "AEUSI"/KW-H$
4460 REM
4470 A=100/TKM
4480 REM "PRINT OUTPUT INFORMATION.
4500 LPRINT LPRINT TAB(32)"OUTPUTS --" LPRINT LPRINT
4520 LPRINT TAB(24)"COST ITEMS--"
4540 LPRINT "COST ITEMS--" I LPRINT I LPRINT
4550 LPRINT TAB(24)"
4560 LPRINT A/C/KM$
4570 LPRINT USING FORMATOSI "BASIC VEHICLE COST"
4590 LPRINT USING FORMATOSI "ENGINE COST"
4610 LPRINT USING FORMATOSI "ICE TRANSMISSION COST"
4630 LPRINT USING FORMATOSI "MOTOR COST"
4650 LPRINT USING FORMATOSI "CONTROLER COST"
4670 LPRINT USING FORMATOSI "CUMULATIVAA"
4690 IF NTRAN=1 THEN GOTO 4730
4700 LPRINT USING FORMAT$1 "EV TRANSMISSION COST"
4710 LPRINT USING FORMAT$1 ECOSTRAN=ECOSTRAN
4720 GOTO 4750
4730 LPRINT USING FORMAT$1 "EV TRANSMISSION COST"
4740 LPRINT USING FORMAT$1 COSTRAN=ECOSTRAN
4750 LPRINT USING FORMAT$1 "BATTERY LOW"
4760 LPRINT USING FORMAT$1 CBTBICBTA
4770 LPRINT "HIGH"
4780 LPRINT USING FORMAT$1 CBTBICBTA
4790 LPRINT TAB(28)
4800 LPRINT "-------- -------- ")
4810 LPRINT
4820 LPRINT "INITIAL COST LOW"
4830 LPRINT USING FORMAT$1 INITINITA
4840 LPRINT "HIGH"
4850 LPRINT USING FORMAT$1 INITINITA
4860 LPRINT "DOWNPAYMENT LOW"
4870 LPRINT USING FORMAT$1 DPMIDPMHA
4880 LPRINT "HIGH"
4890 LPRINT USING FORMAT$1 DPMIDPMHA
4900 LPRINT "REPLACEMENT BATT'S LOW"
4910 LPRINT USING FORMAT$1 CRBBICRBA
4920 LPRINT USING FORMAT$1 CRBBICRBA
4930 LPRINT "HIGH"
4940 LPRINT USING FORMAT$1 CRBBICRBA
4950 LPRINT "Number!
4960 LPRINT USING FORMAT$1 "REPAIRS & MAINTENANCE"
4970 LPRINT USING FORMAT$1 RPTNAPMA
4980 LPRINT USING FORMAT$1 "REPLACEMENT TIRES"
4990 LPRINT USING FORMAT$1 RTIRIRHA
5000 LPRINT USING FORMAT$1 "INSURANCE"
5010 LPRINT USING FORMAT$1 INSRINSRA
5020 LPRINT USING FORMAT$1 "GARAGING, PARK, TOLL"
5030 LPRINT USING FORMAT$1 PTEIPTEA
5040 LPRINT USING FORMAT$1 "TITLE, REG, LIC, LOW"
5050 LPRINT USING FORMAT$1 TRLEITLRA
5060 LPRINT "HIGH"
5070 LPRINT USING FORMAT$1 TRELITLRA
5080 IF VTYP=2 THEN GOTO 5110
5090 LPRINT USING FORMAT$1 "FUEL-OIL"
5100 LPRINT USING FORMAT$1 CFULICFULA
5110 LPRINT USING FORMAT$1 "ELECTRICITY"
5120 LPRINT USING FORMAT$1 CELEICELA
5130 LPRINT USING FORMAT$1 "FUEL & INT LOW"
5140 LPRINT USING FORMAT$1 PAPINTPAPINTA
5150 LPRINT "HIGH"
5160 LPRINT USING FORMAT$1 PAPINTPAPINTA
5170 GOTO 5180
5180 LPRINT TAB(28)
5190 LPRINT "-------- -------- ")
5200 LPRINT
5210 LPRINT "OPERATING COST LOW"
5220 LPRINT USING FORMAT$1 OPEHIOPERHA
5230 LPRINT "HIGH"
5240 LPRINT USING FORMAT$1 OPEHIOPERHA
5250 LPRINT 1 LPRINT 1 LPRINT
5260 LPRINT USING FORMAT$1 "VEHICLE SALVAGE VALUE LOW"
5270 LPRINT USING FORMAT$1 SVSVSVVA
5280 LPRINT "HIGH"
5290 LPRINT USING FORMAT$1 SVSVSVVA
5300 LPRINT USING FORMAT$1 "BATTERY SALVAGE LOW"
5320 LPRINT "HIGH"
5330 LPRINT USING FORMAT161  SVBH1SVBH#A
5340 LPRINT
5350 LPRINT
5360 LPRINT "TOTAL LIFE CYCLE COST  LOW"
5370 LPRINT USING FORMAT161  TTL1TTL#A.
5380 LPRINT "HIGH"
5390 LPRINT USING FORMAT161  TILH1TILH#A
5400 LPRINT CHR$(12) & LPRINT CHR$(27) + "6"
5410 LPRINT CHR$(27) + "4"
5420 ENU
## CONTENTS

<table>
<thead>
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<th>Page</th>
</tr>
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<td>M-139</td>
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<tr>
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</table>

**PRECEDING PAGE BLANK NOT FILMED**
A. INTRODUCTION

Advanced Vehicle Energy Program (AVENERGY) is a computer program written in the IBM version of Microsoft Basic.

The purpose of the AVENERGY Program is for use in calculating such information as electrical energy expended, fuel consumed, and depths of discharges on various cycles of the 24-hour cycles. Information derived from the results of this program is used as part of the input into the Advanced Vehicle Cost Program (AVCOST). In its present form the program is interactive and it is designed to accept inputs from ELVEC and provide inputs into AVCOST.

B. INPUT AND OUTPUT

The following list is the input required to run the program.

1. Input
   Type of vehicle (electric or hybrid)
   Weight of vehicle
   Weight of battery
   Battery cycle life
   Maximum depth of discharge
   Fuel economy, both federal and highway, when using the internal combustion engine (ICE)
   Energy consumption and range for each cycle
   A representative distance travelled on each of twelve cycles per day and corresponding number of days in the year that cycle is used

The following is a list of the output from the program:

2. Output
   Annual travel in miles
   Annual travel in kilometers
   Electric energy use in kW/h
   Annual cycles expended
   Fuel miles travelled
   Electric miles travelled
Fraction of mileage on electric
Fraction of mileage on engine/ICE
Miles per gallon on federal and highway
Vehicle weight
Battery weight
Battery cycle life
Average daily depth of discharge for hybrid vehicle
Annual gasoline consumption
Liters of methanol
Gallons of methanol

C. ENERGY CALCULATIONS

The following are equations and calculations needed for energy and depth-of-discharge statistics.

1. Total Distance Travelled on any Cycle
   The distance travelled on any cycle is given by
   
   \[ MILES = M \times DAYS \]
   
   where
   
   \[ MILES \] = total distance travelled on any cycle
   \[ M \] = miles per day travelled
   \[ DAYS \] = number of days in the year travelled on a given cycle

2. Electrical Energy Used on any Cycle
   The electrical energy used on each cycle is obtained by multiplying the energy per mile (Wh/mi) by the miles travelled on that cycle, as follows:
   
   \[ EL = WHPM \times MILES \]
where

\[ WHFM = \text{Watt hours per mile} \]

\[ MILES = \text{Total distance travelled on any cycle} \]

\[ EL = \text{Watt hours on that cycle} \]

3. Depth of Discharge

The depth of discharge is calculated by using the relationship

\[ DOD = \frac{M}{RANGE} \]

where

\[ M = \text{miles per day} \]

\[ RANGE = \text{distance vehicle travels to zero state of charge} \]

\[ DOD = \text{depth of discharge} \]

Average daily depth of discharge = \( \frac{\text{total annual depth of discharge}}{365} \)

4. Battery Cycles per Year

The number of battery cycles per year on any specific driving cycle is given by:

\[ CYCLES = DOD \times DAYS \]

where

\[ CYCLES \text{ is the battery cycles per year; the other variables are as previously defined above.} \]

5. Total Distance Travelled per Year

Total distance travelled in a year is the summation of the cumulative distance travelled on each cycle.

6. Total Electrical Energy

Total electrical energy usage is the summation of the energy used on each cycle.
7. Total Number of Battery Cycles

Total number of battery cycles is the summation of the battery cycles on each driving cycle.

8. Fraction of Mileage on ICE

This is the fraction of miles driven as an ICE vehicle on gas only and is given by

\[ \text{FUEL} = \frac{G}{D} \]

where

- \( G \) = the fuel miles driven on gas
- \( D \) = the total distance in miles

9. Fraction of Mileage on Electric

This is the fraction of miles driven as electric car only and is given by

\[ \text{ENER} = \frac{P}{D} \]

where

- \( P \) = the mileage driven as electric
- \( D \) = total distance in miles

10. Annual Travel

This is the sum of miles travelled on electric and that on the heat engine.

11. Amount of Fuel Used on Highway and Urban Cycles

Amount of fuel used on highway is given by

\[ \text{FC} = \text{DAYS} \times \text{GM/MPGH} \]
where

\[
\begin{align*}
\text{DAYS} & = \text{number of days in the year travelled on a given cycle} \\
\text{GM} & = \text{miles per day on gas} \\
\text{MPGH} & = \text{miles per gallon on highway} \\
\text{FC} & = \text{total fuel used for highway driving} \\
\end{align*}
\]

Amount of fuel used on urban cycle is given by

\[
\text{FC} = \text{DAYS} \times \text{GM}/\text{MPGU}
\]

where

\[
\begin{align*}
\text{FC} & = \text{total fuel used for urban driving} \\
\text{MPGU} & = \text{miles per gallon on urban} \\
\text{DAYS} & = \text{number of days in the year travelled on a given cycle} \\
\end{align*}
\]

12. Total Fuel Miles

This is the sum of the mileage on each of the cycles covered by the ICE vehicle.

13. Total Electric Miles

This is the sum of the mileage on each of the cycles covered by the vehicle when it runs on electric only. Note that:

- gallons of methanol = 1.8 x gallons of gas
- liters of methanol = 3.8 x gallons of methanol

D. SAMPLE TEST CASE

Three test cases follow: a five-passenger baseline ICE, a five-passenger, 400-km Metal Disulphide (Li-fe-S2) all-electric, and a five-passenger, 400-km Lead Acid (Pb-Ac) hybrid vehicle. The input and output results are as shown.
ELECTRIC AND HYBRID VEHICLE COST MODEL

**100-M1 BIPOLAR 5-P EV**

**—INPUTS—**

<table>
<thead>
<tr>
<th>GENERAL</th>
<th>YEAR: 1982</th>
</tr>
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<tbody>
<tr>
<td>VEHICLE SIZE: 5-PASS</td>
<td></td>
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<tr>
<td>CURB WEIGHT: 1998 KG</td>
<td></td>
</tr>
<tr>
<td>VEHICLE HEIGHT: MT: 1634</td>
<td></td>
</tr>
<tr>
<td>LIFE: 13143.9 KM</td>
<td>ACCESSORY COST: 9200</td>
</tr>
<tr>
<td>BATTERY —</td>
<td>NAME: PB-AC/DIPL</td>
</tr>
<tr>
<td>BATTERY WEIGHT: 404 KG</td>
<td>BATTERY CYCLE LIFE: 750</td>
</tr>
<tr>
<td>ELECTRICITY COST: .05 9/KW-H</td>
<td>MAXIMUM SHELF LIFE: 10 YEARS</td>
</tr>
<tr>
<td>AVERAGE DAILY DEPTH OF DISCHARGE: .2217449</td>
<td>DEPTH OF A DEEP DISCHARGE: .8</td>
</tr>
<tr>
<td>MAINTENANCE FACTOR: .5</td>
<td></td>
</tr>
<tr>
<td>TRANSMISSION TYPE: fixed ratio</td>
<td></td>
</tr>
<tr>
<td>MOTOR —</td>
<td>TYPE: AC</td>
</tr>
<tr>
<td>RATED POWER: 41.2 KW</td>
<td></td>
</tr>
<tr>
<td>CONTROLLER: 45.7 KW</td>
<td></td>
</tr>
<tr>
<td>DRIVING —</td>
<td>AMOUNT: 13143.49 MW/H YEAR</td>
</tr>
<tr>
<td>ANNUAL ELEC USE: 2128.121 KW/H</td>
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</table>

**—OUTPUTS—**

<table>
<thead>
<tr>
<th>COST ITEMS</th>
<th>6 C/100</th>
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<tr>
<td>BASIC VEHICLE COST</td>
<td>6846.21</td>
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<td>MOTOR COST</td>
<td>782.80</td>
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<td>CONTROLLER COST</td>
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<td>EV TRANSMISSION COST</td>
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<tr>
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<tr>
<td>INITIAL COST - LOW</td>
<td>12123.65</td>
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<tr>
<td>DOWNPAYMENT LOW</td>
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<tr>
<td>REPLACEMENT BATTERIES LOW</td>
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<td>REPAIRS &amp; MAINTENANCE</td>
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<td>REPLACEMENT TIRES</td>
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<tr>
<td>INSURANCE</td>
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<td>OPERATING COST LOW</td>
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<td>VEHICLE SALVAGE VALUE LOW</td>
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<tr>
<td>TOTAL LIFE CYCLE COST</td>
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<td>1044.06</td>
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<td>PRIN &amp; INT LOW</td>
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<td>OPERATING COST HIGH</td>
<td>19993.27</td>
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<tr>
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<tr>
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<td>33.53</td>
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<tr>
<td>TOTAL LIFE CYCLE COST</td>
<td>20704.01</td>
</tr>
</tbody>
</table>

**M-144**
ELECTRIC AND HYBRID VEHICLE COST MODEL

5 PAX BASELINE ICE 100M 1992 07-18-1964

++ INPUTS ++

GENERAL —

VEHICLE SIZE: 5-PASS
CURB WEIGHT: 895 KG
VEHICLE WEIGHT + MT: 1031
LIFE: 132365.9 KM

YEAR: 1982
REAL INTEREST RATE: 10 %
VEHICLE SALVAGE VALUE: 10 %
ACCESSORY COST: $200

BATTERY —

BATTERY WEIGHT: 0 KG
BATTERY WEIGHT: 0 KG
ELECTRICITY COST: .05 $/KW-H
MAXIMUM SHELF LIFE: 10 YEARS
AVERAGE DAILY DEPTH OF DISCHARGE: .11 DEPTH OF A DEEP DISCHARGE: .6

NAME: III
MAXIMUM SHELF LIFE: 750

MAINTENANCE FACTOR: 1

ENGINE —

FUEL COST: .373 $/L
ICE TRANSMISSION TYPE: CVT

ENGINE FUEL CMT: .373
FUEL TYPE: METHANOL
POWER: 31 KW

DRIVING —

ICE TRANSMISSION TYPE: fixed ratio

ICE FRACTIONAL RANGE: 100 %
EV FRACTIONAL RANGE: 0 %

ANNUAL FUEL USE: 1302 L
ANNUAL ELECTRIC USE: 0 KW-H

++ OUTPUTS ++

COST ITEMS

$ C/KM

BASIC VEHICLE COST 5745.61 4.341
ENGINE COST 1118.03 0.845
ICE TRANSMISSION COST 346.27 0.262
MOTOR COST 0.00 0.000
CONTROLLER COST 0.00 0.000
EV TRANSMISSION COST 0.00 0.000
BATTERY LOW 0.00 0.000 HIGH 0.00 0.000
INITIAL COST LOW 7209.90 5.447 HIGH 7209.90 5.447
DOWNPAYMENT LOW 1441.98 1.089 HIGH 1441.98 1.089
REPLACEMENT BATTERIES LOW 0.00 0.000 HIGH 0.00 0.000
REPAIRS & MAINTENANCE 4707.69 3.527
REPLACEMENT TIRES 260.22 0.212
TAXES 3479.00 2.626
SHEETING, PARK, TOLL 782.50 0.591
TITLE, REG, LIC, LOW 560.50 0.423 HIGH 560.50 0.423
FUEL-OIL 5002.15 3.779
ELECTRICITY 0.00 0.000
FAX & INT LOW 5767.92 4.358 HIGH 5767.92 4.358
OPERATING COST LOW 20579.98 15.548 HIGH 20579.98 15.548

VEHICLE SALVAGE VALUE LOW 277.97 0.210 HIGH 277.97 0.210
BATTERY SALVAGE LOW 0.00 0.000 HIGH 0.00 0.000

TOTAL LIFE CYCLE COST LOW 21743.98 16.427 HIGH 21743.98 16.427
**Electric and Hybrid Vehicle Cost Model**

**PB/ACID Hybrid**

**Inputs**

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
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<tbody>
<tr>
<td>Year</td>
<td>1982</td>
</tr>
<tr>
<td>Real Interest Rate</td>
<td>10%</td>
</tr>
<tr>
<td>Vehicle Salvaage Value</td>
<td>10%</td>
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<td>Vehicle Weight</td>
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<td>Life</td>
<td>166106.7 KM</td>
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<tr>
<td>Battery Weight</td>
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<td>Maximum Shelf Life</td>
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<td>Engine Power</td>
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<td>Controller COST</td>
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<td>Motor Type</td>
<td>AC</td>
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<td>Transmission Type</td>
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<tr>
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<td>Rated Power</td>
<td>47.5 KW</td>
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<td>Transmission Type</td>
<td>CVT</td>
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<tr>
<td>Driving</td>
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<tr>
<td>Ice Fractional Range</td>
<td>22.15056%</td>
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<tr>
<td>EV Fractional Range</td>
<td>74.33632%</td>
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<tr>
<td>Annual Fuel Use</td>
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<tr>
<td>Electricity Use</td>
<td>16610.67 KWh/YEAR</td>
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<td>Vehicle Salvage Value</td>
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<td>Accessory COST</td>
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<td>Replacement Battery Cost</td>
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<td>Replacement Batts Low</td>
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<td>Repairs &amp; Maintenance</td>
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<td>Title, Reg. Lic. Low</td>
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<td>Fuel-Oil</td>
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<td>Battery Life</td>
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<td>Depth of a Deep Discharge</td>
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<td>Maintenance Factor</td>
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**Outputs**

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<th>Category</th>
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<th>High</th>
<th>Medium</th>
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<tbody>
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<td>Initial Cost</td>
<td>$14871.10</td>
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<td>Downpayment Low</td>
<td>$2974.22</td>
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<td>Replacement batteries Low</td>
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<td>Repairs &amp; Maintenance</td>
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<td>Replacement Tires</td>
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<td>Insurance</td>
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<td>Title, Reg. Lic. Low</td>
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<td>Fuel-Oil</td>
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<td>Property &amp; Int Low</td>
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<td>Operating Cost</td>
<td>$27946.31</td>
<td>$31946.31</td>
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</tr>
<tr>
<td>Vehicle Salvage Value Low</td>
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<td>$3157.63</td>
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<tr>
<td>Battery Salvage Low</td>
<td>$51.75</td>
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<tr>
<td>TOTAL LIFE CYCLE COST</td>
<td>$29778.33</td>
<td>$31946.31</td>
<td>$31946.31</td>
</tr>
</tbody>
</table>

*Note: The values are provided in thousands of dollars.*
# Glossary

**ABBREVIATIONS AND ACRONYMS**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCL</td>
<td>Battery-cycle life in cycles</td>
</tr>
<tr>
<td>CYCLES</td>
<td>Cycle based on depth of discharges and days</td>
</tr>
<tr>
<td>D</td>
<td>Total distance in miles</td>
</tr>
<tr>
<td>DAYS</td>
<td>Number of days</td>
</tr>
<tr>
<td>DOD</td>
<td>Depth of discharge</td>
</tr>
<tr>
<td>DODMX</td>
<td>Maximum depth of discharge</td>
</tr>
<tr>
<td>EL</td>
<td>Watt hours</td>
</tr>
<tr>
<td>EM</td>
<td>Miles per day on electric</td>
</tr>
<tr>
<td>ENER</td>
<td>Fraction of mileage on electric</td>
</tr>
<tr>
<td>FC</td>
<td>Total fuel used for urban or highway driving</td>
</tr>
<tr>
<td>FUEL</td>
<td>Fraction of mileage on fuel</td>
</tr>
<tr>
<td>G</td>
<td>Fuel miles</td>
</tr>
<tr>
<td>GALM</td>
<td>Gallons of methanol</td>
</tr>
<tr>
<td>GAS</td>
<td>Annual gasoline consumption in gallons</td>
</tr>
<tr>
<td>GM</td>
<td>Miles per day on gas</td>
</tr>
<tr>
<td>K</td>
<td>Cut-off range in miles</td>
</tr>
<tr>
<td>LITM</td>
<td>Liters of methanol</td>
</tr>
<tr>
<td>M</td>
<td>Miles per day</td>
</tr>
<tr>
<td>MILES</td>
<td>Total distance travelled in miles on any cycle</td>
</tr>
<tr>
<td>MPGH</td>
<td>Miles per gallon -- highway</td>
</tr>
<tr>
<td>MPGU</td>
<td>Miles per gallon -- urban</td>
</tr>
<tr>
<td>P</td>
<td>Miles on electric</td>
</tr>
<tr>
<td>RANGE</td>
<td>Range in miles</td>
</tr>
</tbody>
</table>
VEH: vehicle type, electric or hybrid
WB: battery weight in kilograms
WC: vehicle curb weight in kilograms
WHPM: watt hour per mile
WC: vehicle curb weight in kilograms
X: total annual depth of discharge on all cycles
Advanced Vehicle Cost Program (AVCOST)
**CONTENTS**

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   1. Initial Cost .................................................. M-156
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A. INTRODUCTION

The Advanced Vehicle Cost Program (AVCOST) is a computer program written in the IBM version of Microsoft Basic for use in computing initial, operating, and life-cycle costs of advanced vehicles. It is being used for the evaluation of candidate vehicles in the Advanced Vehicle Assessment study as part of the work performed by the Jet Propulsion Laboratory (JPL) for the Electric and Hybrid Vehicle (EHV) Division of the U.S. Department of Energy (DOE). In its present form the program is interactive, and the user is prompted for various inputs. Other inputs into the program are from files that have been previously created after running AVSIZING and AVENERGY programs.

The advanced vehicles that could be used with the program are all-electric two-, four-, and five-passenger vehicles or vans and four- and five-passenger hybrid vehicles and corresponding baseline internal combustion engine (ICE) vehicles. In the following pages, input, output, cost calculations, and an example test case are presented.

B. INPUT AND OUTPUT

The following paragraphs list the input required for the program; a sample output is also included.

1. Input

Input into the program depends on whether the vehicle is all-electric, a hybrid vehicle, or a baseline ICE. Sample input into each type of vehicle is listed below:

a. Input: All-Electric

The page heading

The name of the battery

Enter 1 for hybrid, 2 for electric only, or 3 for ICE vehicle

Type the number of passengers as follows:

1 - Two-passenger
2 - Four-passenger, 250-mi
3 - Five-passenger, 250-mi
4 - Five-passenger, 100-mi
5 - Five-passenger, 150-mi
6 - Van
Cost of electricity in £/kWh

Battery shelf life in years

Depth of a deep discharge (use cut-off DOD)

Vehicle maintenance factor—default=1

Vehicle life in years

Motor type: 1 for ac, 2 for dc brushless, and 3 for dc brush

Controller type: 1 for ac, 2 for dc brushless, and 3 for dc brush

Vehicle salvage value as percent of new

Percent real interest rate

Percent real discount rate

Number of years to finance over

b. **Input: Hybrid**

The page heading

The name of the battery

Enter 1 for hybrid, 2 for electric-only or 3 for ICE vehicles

Type the number of passengers as follows:

1 - Two-passenger
2 - Four-passenger, 250-mi
3 - Five-passenger, 250-mi
4 - Five-passenger, 100-mi
5 - Five-passenger, 150-mi
6 - Van

Cost of electricity in £/kWh

Battery shelf life in years

Depth of a deep discharge (use cut-off DOD)

Vehicle maintenance factor—default=1
Vehicle life in years

Motor type: 1 for ac, 2 for dc brushless, and 3 for dc brush

Controller type: 1 for ac, 2 for dc brushless, and 3 for dc brush

Vehicle salvage value as percent of new

Type 1 for gasoline fuel, 2 for diesel, 3 for methanol

Cost of fuel for 1992 in 1982$/liter

Percent real interest rate

Percent real discount rate

Number of years to finance over

c. Input: Baseline ICE

The page heading

Enter 1 for hybrid, 2 for electric, or 3 for ICE vehicle.

Type the number of passengers as follows:

1 - Two-passenger
2 - Four-passenger, 250-mi
3 - Five-passenger, 250-mi
4 - Five-passenger, 100-mi
5 - Five-passenger, 150-mi
6 - Van

Vehicle maintenance factor--default=1

Vehicle life in years

Vehicle salvage value as a percent

Type 1 for gasoline, 2 for diesel, 3 for methanol

Cost of fuel in 1992 in 1982$/liter

Percent real interest rate
Percent real discount rate

Number of years to finance over

The input is printed together with the output results as shown in the test case examples in Subsection D.

2. Output

Output results from the program, as well as the inputs into the program, are printed on the same page. This arrangement provides easy check on the input.

The output results from the program are categorized into initial, operating, and life-cycle costs. Initial cost is subdivided into basic vehicle, engine, electric transmission, motor, controller, engine transmission, and battery cost. Operating cost is subdivided into replacement batteries, repairs and maintenance, replacement tires, insurance, garage, park, toll, title, registration, license, fuel oil and electricity, and vehicle interest. Salvage value and life-cycle costs are also printed out. A sample output is as shown in the test-case examples for all-electric, hybrid, and a baseline ICE vehicle in Section D.

C. COST CALCULATIONS

The following paragraphs show the computation for initial, operating, and life-cycle costs.

1. Initial Cost

Initial cost is defined as the cost to the consumer. It is made up of the following costs: basic vehicle, engine, transmission, (one or two transmissions) motor, controller, and battery costs.

   a. Basic Vehicle Cost. This cost is computed as the product of the weight of the basic vehicle and a cost per weight of the basic vehicle. The basic-vehicle weight is obtained by removing the battery, motor, engine, controller, and transmission from the vehicle curb weight.

   Thus

   Basic Vehicle Weight (WBV) = Curb weight (CURBWT)
   - Battery weight (WB)
   - Motor weight (MOTWT)
   - Engine weight (ENGWT)
   - Controller weight (CONWT)
- Electric transmission weight (TRANWT EV case)
- Electric transmission weight (ETRANWT HV case)
- Engine transmission weight (GTRANWT).

User inputs are curb weight and battery weight. The other weights are calculated as functions of the rated power as follows:

Motor weight = $\frac{\text{Motor kW}}{0.49}$

when a specific weight of 490 W/kg is assumed for ac (Volume II, Subsystems Assessment), 640 W/kg for dc brushless, and 220 W/kg for dc brush.

Engine weight = $\frac{\text{Engine power kW}}{0.45}$

when a specific weight of 450 W/kg is assumed for engine (see Volume II)

Controller weight = $\frac{\text{Controller power kW}}{2.5}$

when a specific weight of 2500 W/kg is assumed for ac, 875 W/kg for dc brushless, and 1470 W/kg for dc brush.

Transmission weight = $\frac{\text{Power (CVT)}}{1.1}$

when a specific weight of 1100 W/kg is assumed for Belt CVT (see Volume II)

Transmission weight = $\frac{\text{Power*(fixed ratio)}}{1.42}$

when a specific weight of 1420 W/kg is assumed for fixed-gear reduction (see Volume II)

Transmission weight = $\frac{\text{Power*(4-speed manual)}}{1.06}$

*Note that power is peak power.
when a specific weight of 1060 W/kg is assumed for 4-speed manual (see Volume II)

\[
\text{Transmission weight} = \frac{\text{Power} \times \text{Power}^{0.33}}{0.86}
\]

when a specific weight of 860 W/kg is assumed for the 2-speed auto (see Volume II).

Basic Vehicle Cost (BVC) = basic vehicle weight (WBV) 
\(\times\) cost per kg of basic vehicle (BVCPKG) 
\(\text{+ accessory cost (CACC)}\)

Basic vehicle cost (BVC) = WBV \(\times\) BVCPKG + CACC

where

WBV = the basic vehicle weight calculated as shown above

BVCPKG = the cost per kg of basic vehicle weight. This is representative of the cost per kg of a 1981 Chevrolet Citation (Wayne Carrier, General Research Corporation). The cost of accessories is assumed to be $200.

b. **Engine Cost.** Engine cost is given by the following:

\[
\text{Engine cost} = 1.5 \times 240 \times (\text{Engine Power in kW})^{0.33}
\]

for gas engine from Volume II

\[
1.5 \times 260 \times (\text{Engine Power in kW})^{0.33}
\]

for diesel engine from Volume II

Engine maximum-rated power is an input

1.5 represents the mark-up from OEM cost to sale price

c. **Transmission Cost.** Transmission cost is a function of rated power. Transmission cost is related to the rated power by

Transmission cost = 11.17 \(\times\) Power (CVT)

Transmission cost = 5.58 \(\times\) Power (4-Speed)

*Note that power is peak power.*
Transmission cost = 4.65 x Power (fixed ratio)
Transmission cost = 5.40 x Power (2-Speed Auto)
Transmission rated power is an input.

d. **Motor Cost.** Motor cost is given by

Motor cost = 19 x Motor Power kW (ac)
= 26.5 x Motor Power kW (dc brushless)
= 79 x Motor Power kW (dc brush)

Cost includes the mark-up of 1.5 (see Volume II)
Motor-rated power is an input.

e. **Controller Cost.** Controller cost is related to controller power by:

Controller cost = 45 x controller power kW for ac (see Volume II)
= 90 x controller power kW for dc brushless (see Volume II)
= 62.5 x controller power, kW dc brushless (see Volume II)

The cost for the controller includes the mark-up of 1.5.
Controller-rated power is an input.

f. **Battery Cost.** Battery cost is calculated using Symon's Equation of the form:

Cost (1983$) = A x kWh + B x kW + C

where A is the specific energy specified, B is the specific power specified, and C is a constant for the battery.

Battery cost for each battery type and design is listed in the program. The high battery cost represents the upper-bound cost of that battery.

As mentioned before, initial cost is the sum of the following cost: basic vehicle, engine, transmission, (one or two transmissions) motor, controller, and battery.
2. Operating Cost

Operating costs include the following: replacement batteries, replacement tires, insurance, repairs and maintenance, insurance, garage, parking, toll, title, registration, license, fuel and oil, electricity, and equivalent road tax. Each one of these is as discussed below. It may be noted that each of these annual values is discounted to present values.

a. ReplacementBattery Cost. The cost of replacement batteries is the product of the unit cost of battery and the number of replacement batteries. The number of replacement batteries may be a fraction. In such a case the price of a whole battery is determined and the difference between the whole number and fraction is taken as battery salvage. The appropriate discount factor is applied.

b. Repairs and Maintenance Cost. For all cars except five-passenger cars, repairs and maintenance cost is given by

\[
RPM = \left[ 81.73 + \left( \frac{1.14}{100} \times KMYR \times EOLY \times MFAC \right) \right] + \left[ MICE + \left( \frac{0.91}{100} \times KMYR \times RICE \right) \right]
\]

For five-passenger cars

\[
RPM = \left[ 78.67 + \left( \frac{1.23}{100} \times KMYR \times EOLY \times MFAC \right) \right] + \left[ MICE + \left( \frac{2.05}{100} \times KMYR \times RICE \right) \right]
\]

where

- MFAC = maintenance factor
- EOLY = decimal fraction of operation time with electric propulsion operating
- RICE = decimal fraction of operation time with ICE propulsion operating

The appropriate discount factor is applied.

c. Replacement Tires.

\[
RTIR = \left[ RTKM \times (368.74 + \frac{0.18086 \times CURBWT}{128748}) \right]
\]

where

- RTIR = total cost of replacement tires over the vehicle life
- RTKM = TKM - 64374
CURBWT = curb weight of the vehicle

TKM = vehicle life in km or total km driven over the vehicle life.

The appropriate discount factors at the times of replacement are applied.

d. Insurance.

\[ \text{INSR} = 748 + 243 \text{ CI} \text{ for 2-, 4-passenger and vans} \]
\[ = 919 + 256 \text{ CI} \text{ for 5-passenger} \]

where

INSR = total cost of insurance over the vehicle life

CI = discount factor

e. Garage, Parking, and Toll.

\[ \text{PTE} = 78.25 \times \text{CI} \]

where

PTE = total cost of garaging, parking, toll, etc. over the vehicle life

CI = discount factor

f. Title, Registration, and License.

\[ \text{TRLE} = 20 \times \text{CI} + (0.05 \times \text{INIT}) \]

where

TRLE = total cost of title, registration, license, etc. over the vehicle life

CI = discount factor

INIT = initial cost of the vehicle
g. Fuel and Oil.

\[ \text{CFUL} = \text{AFUS} \times \text{PFUEL} \times 1.03 \times \text{CI} \]

where

- \text{CFUL} = \text{total cost of fuel and oil over the ICE or hybrid vehicle life}
- \text{AFUS} = \text{annual fuel use in liters}
- \text{PFUEL} = \text{cost of fuel in $/liters}
- \text{CI} = \text{discount factor}

The factor of 1.03 is used to allow for the cost of oil rather than just the cost of gas or diesel.

h. Electricity Cost:

\[ \text{CELE} = \text{AELC} \times \text{PELEC} \times \text{CI} \]

where

- \text{CELE} = \text{total cost of electricity over the vehicle life}
- \text{PELEC} = \text{electricity price in $ per kWh}
- \text{AELC} = \text{annual electricity use kWh}
- \text{CI} = \text{discount factor}

i. Annual Principal and Interest Payment. After the initial cost of the vehicle has been calculated, a down payment of 20 percent is assumed. The difference is capitalized over the life of the vehicle and added to the annual operating costs. This annual cost is calculated using

\[ \text{APINT} = 0.8 \times \text{INIT} \times \frac{i(1+i)^n}{(1+i)^n-1} \]

where

- \text{APINT} = \text{the annual principal and interest payment}
- \text{i} = \text{interest rate}
\[ n = \text{vehicle life} \]

\[ \text{INIT} = \text{initial cost of the vehicle} \]

Total operating cost is the sum of the costs of replacement batteries, repairs and maintenance, replacement tires, insurance, garage, parking, tolls, title, registration, license, fuel and oil, electricity, and annual principal and interest payment. Salvage value is made up of salvage from vehicle and from battery material.

Total life-cycle cost is the sum of initial cost and operating cost, less salvage value.

D. SAMPLE TEST CASE

Three test cases are presented below:

A 5-passenger baseline ICE, a 5-passenger 400-km lithium metal disulphide (Li-fe-S\textsubscript{2}) all-electric, and a 5-passenger 400-km lead acid (Pb-Ac) hybrid vehicles. The input and output results are as shown.
ELECTRIC AND HYBRID VEHICLE COST MODEL

5 PAX BASELINE ICE 250K  07-18-1984

---INPUTS---

**GENERAL**

- YEAR: 1982
- VEHICLE SIZE: 5-PASS
- VEHICLE WEIGHT: 875 KG
- VEHICLE LIFE: 1031 166106 KM
- REAL INTEREST RATE: 10%
- VEHICLE SALVAGE VALUE: 10%

**BATTERY**

- BATTERY WEIGHT: 0 KG
- BATTERY CYCLE LIFE: 1
- ELECTRICITY COST: .05 $/KW-H
- MAINTENANCE FACTOR: 1
- AVERAGE DAILY DEPTH OF DISCHARGE: 1
- DEPTH OF A DEEP DISCHARGE: .6

**ENGINE**

- TANK CAPACITY: 40 L
- ICE TRANSMISSION TYPE: CVT
- FUEL TYPE: METHANOL
- POWER: 31 KW

**MOTOR**

- RATED POWER: 0 KW
- CONTROLLER: 0 KW
- EV TRANSMISSION TYPE: fixed ratio

**DRIVING**

- ICE FRACTIONAL RANGE: 100%
- EV FRACTIONAL RANGE: 0%
- ANNUAL FUEL USE: 1610 L
- ANNUAL ELECTRIC USE: 0 KW-H

---OUTPUTS---

<table>
<thead>
<tr>
<th>COST ITEMS</th>
<th>LOW</th>
<th>$/KM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASIC VEHICLE COST</td>
<td>5745.61</td>
<td>3.459</td>
</tr>
<tr>
<td>ENGINE COST</td>
<td>1118.03</td>
<td>0.673</td>
</tr>
<tr>
<td>ICE TRANSMISSION COST</td>
<td>346.27</td>
<td>0.208</td>
</tr>
<tr>
<td>MOTOR COST</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>CONTROLLER COST</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>EV TRANSMISSION COST</td>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>BATTERY LOW</td>
<td>0.00</td>
<td>0.000</td>
</tr>
</tbody>
</table>

| INITIAL COST          | LOW    | 7209.90| 4.341|
| DOWNSHIFT LOW         | 1441.98| 0.868|

| REPLACEMENT BATTERIES | LOW    | 0.00   | 0.000|
| REPAIRS & MAINT.     | 5352.12| 3.222|
| REPLACEMENT TIRES    | 419.27 | 0.252|
| INSURANCE            | 3179.00| 2.094|
| GARAGING, PARK, TOLL | 762.50 | 0.471|
| TITLE, REG LIC, POLICE | 560.50 | 0.337|
| FUEL-OIL             | 6105.46| 3.724|
| ELECTRICITY          | 0.00   | 0.000|
| PRIN & INT LOW       | 5767.92| 2.472|

| OPERATING COST        | LOW    | 22546.77| 13.574|

| VEHICLE SALVAGE VALUE | LOW    | 277.97  | 0.167|
| BATTERY SALVAGE       | 0.00   | 0.000|

| TOTAL LIFE CYCLE COST | LOW23710.78 | 14.274|

M-164
ELECTRIC AND HYBRID VEHICLE COST MODEL

250-MI LI/FES 5-P EV  08-29-1984

--- INPUTS ---

**GENERAL**

- YEAR: 1982
- VEHICLE SIZE: 5-PASS
- Curb Weight: 1804 KG
- VEHICLE HEIGHT, MT: 1940
- LIFE: 166106.7 KI
- ACCESSORY COST: $200

**BATTERY**

- BATTERY WEIGHT: 615 KG
- BATTERY CYCLE LIFE: 750
- ELECTRICITY COST: $.05/kWh
- MAXIMUM SHELF LIFE: 10 YEARS
- AVERAGE DAILY DEPTH OF DISCHARGE: .100048
- DEPTH OF A DEEP DISCHARGE: .8

**MAINTENANCE FACTOR**: 1.25

**TRANSMISSION TYPE**: fixed ratio

**MOTOR**

- RATED POWER: 46.9 KW
- TYPE: AC

**CONTROLLER**

- 54.3 KW

**DRIVING**

- ANNUAL AVERAGE DEPTH OF DISCHARGE: .100048
- DEPTH OF A DEEP DISCHARGE: .8

--- OUTPUTS ---

**COST ITEMS**

- BASIC VEHICLE COST: 7553.25
- MOTOR COST: 929.10
- CONTROLLER COST: 2443.30
- EV TRANSMISSION COST: 252.50
- BATTERY: 830.44
- LOW: 19339.14
- HIGH: 21680.16
- DOWNPAYMENT: 3867.83
- LOW: 1144.96
- HIGH: 1294.01
- REPLACEMENT BATTERIES: 0.00
- REPAIRS & MAINTENANCE: 3184.32
- REPLACEMENT TIRES: 549.18
- INSURANCE: 3479.00
- GARAGING, PARK, TOLL: 762.50
- TITLE, REG, LIC: 1144.96
- ELECTRICITY: 2240.23
- PRIN & INT LOAN: 15471.31
- OPERATING COST LOW: 2673.31
- VEHICLE SALVAGE VALUE: 423.26
- BATTERY SALVAGE LOW: 125.44
- TOTAL LIFE CYCLE COST: 30192.62

--- M-165 ---
## ELECTRIC AND HYBRID VEHICLE COST MODEL

### Inputs

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td><strong>YEAR</strong></td>
<td>1992</td>
</tr>
<tr>
<td><strong>REAL INTEREST RATE</strong></td>
<td>10%</td>
</tr>
<tr>
<td><strong>VEHICLE SALVAGE VALUE</strong></td>
<td>10%</td>
</tr>
<tr>
<td><strong>ACCESSORY COST</strong></td>
<td>$200</td>
</tr>
<tr>
<td><strong>BATTERY NAME</strong></td>
<td>PbAC/003.2</td>
</tr>
<tr>
<td><strong>BATTERY CYCLE LIFE</strong></td>
<td>750</td>
</tr>
<tr>
<td><strong>ELECTRICITY COST</strong></td>
<td>$0.05/kWh</td>
</tr>
<tr>
<td><strong>MAXIMUM SHELF LIFE</strong></td>
<td>10 YEARS</td>
</tr>
<tr>
<td><strong>AVERAGE DAILY DEPTH OF DISCHARGE</strong></td>
<td>0.3336073</td>
</tr>
<tr>
<td><strong>DEPTH OF A DEEP DISCHARGE</strong></td>
<td>0.8</td>
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### Engine

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>FUEL TYPE</strong></td>
<td>Methanol</td>
</tr>
<tr>
<td><strong>FUEL COST</strong></td>
<td>$0.373/L</td>
</tr>
<tr>
<td><strong>TANK CAPACITY</strong></td>
<td>40 L</td>
</tr>
<tr>
<td><strong>ICE TRANSMISSION TYPE</strong></td>
<td>CVT</td>
</tr>
<tr>
<td><strong>PWR: 32.7 KW</strong></td>
<td></td>
</tr>
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</table>

### Motor

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RATED POWER</strong></td>
<td>47.5 KW</td>
</tr>
<tr>
<td><strong>POWER: 52.7 KW</strong></td>
<td></td>
</tr>
<tr>
<td><strong>EV TRANSMISSION TYPE</strong></td>
<td>Fixed ratio</td>
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</table>

### Driving

<table>
<thead>
<tr>
<th>Category</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td><strong>AMOUNT: 16610.67 Kwh/Year</strong></td>
<td>15336.32</td>
</tr>
<tr>
<td><strong>ICE FRACTIONAL FADS</strong></td>
<td>74.33 %</td>
</tr>
<tr>
<td><strong>EV FRACTIONAL FADS</strong></td>
<td>25.67 %</td>
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### Outputs

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<thead>
<tr>
<th>Category</th>
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<tr>
<td><strong>BASIC VEHICLE COST</strong></td>
<td>$7267.10</td>
</tr>
<tr>
<td><strong>ENGINE COST</strong></td>
<td>$1331.99</td>
</tr>
<tr>
<td><strong>ICE TRANSMISSION COST</strong></td>
<td>$388.66</td>
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<tr>
<td><strong>MOTOR COST</strong></td>
<td>$922.50</td>
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<tr>
<td><strong>CONTROLLER COST</strong></td>
<td>$2371.50</td>
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<tr>
<td><strong>EV TRANSMISSION COST</strong></td>
<td>$2455.06</td>
</tr>
<tr>
<td><strong>BATTERY LOW</strong></td>
<td>$2144.30</td>
</tr>
<tr>
<td><strong>INITIAL COST</strong></td>
<td>$10811.10</td>
</tr>
<tr>
<td><strong>DOWNPAYMENT LOW</strong></td>
<td>$2974.22</td>
</tr>
<tr>
<td><strong>REPLACEMENT BATTERIES LOW</strong></td>
<td>$4326.60</td>
</tr>
<tr>
<td><strong>REPAIRS &amp; MAINTENANCE</strong></td>
<td>$4289.90</td>
</tr>
<tr>
<td><strong>REPLACEMENT TIRES</strong></td>
<td>$411.03</td>
</tr>
<tr>
<td><strong>INSURANCE</strong></td>
<td>$3479.00</td>
</tr>
<tr>
<td><strong>MATING-PARK, TOLL</strong></td>
<td>$762.50</td>
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<tr>
<td><strong>TITLE, REG. LIC. LOW</strong></td>
<td>$943.56</td>
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<tr>
<td><strong>FUEL-OIL</strong></td>
<td>$1067.27</td>
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<tr>
<td><strong>ELECTRICITY</strong></td>
<td>$1317.56</td>
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<tr>
<td><strong>PAV &amp; INT LOW</strong></td>
<td>$1199.68</td>
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<td><strong>OPERATING COST LOW</strong></td>
<td>$29446.31</td>
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### Total Life Cycle Cost

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<th>Value</th>
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<tr>
<td><strong>VEHICLE SALVAGE VALUE</strong></td>
<td>Low $2590.48</td>
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<tr>
<td><strong>BATTERY SALVAGE LOW</strong></td>
<td>$51.73</td>
</tr>
<tr>
<td><strong>TOTAL LIFE CYCLE COST</strong></td>
<td>Low $29776.33</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>ADOD</td>
<td>average daily depth of discharge</td>
</tr>
<tr>
<td>AELC</td>
<td>annual electricity use in kWh</td>
</tr>
<tr>
<td>AFUS</td>
<td>annual fuel use in liters</td>
</tr>
<tr>
<td>APINT</td>
<td>annual principal and interest payment (low)</td>
</tr>
<tr>
<td>APINTH</td>
<td>annual principal and interest payment (high)</td>
</tr>
<tr>
<td>AUP</td>
<td>mark-up OEM to sale price</td>
</tr>
<tr>
<td>BATT</td>
<td>battery name</td>
</tr>
<tr>
<td>BI</td>
<td>inflation factor</td>
</tr>
<tr>
<td>BLIF</td>
<td>battery shelf life</td>
</tr>
<tr>
<td>BVC</td>
<td>basic vehicle cost</td>
</tr>
<tr>
<td>BVCPRG</td>
<td>basic vehicle cost per kg</td>
</tr>
<tr>
<td>CACC</td>
<td>accessories cost $</td>
</tr>
<tr>
<td>CCON</td>
<td>controller cost</td>
</tr>
<tr>
<td>CEL</td>
<td>total cost of electricity</td>
</tr>
<tr>
<td>CFU</td>
<td>total cost of fuel and oil</td>
</tr>
<tr>
<td>CI</td>
<td>ratio of inflation to discount factor</td>
</tr>
<tr>
<td>CKW</td>
<td>power of controller</td>
</tr>
<tr>
<td>CMOT</td>
<td>motor cost</td>
</tr>
<tr>
<td>CONWT</td>
<td>controller weight</td>
</tr>
<tr>
<td>COSTRAN</td>
<td>cost of EV transmission $</td>
</tr>
<tr>
<td>CURBWT</td>
<td>vehicle curb weight kg</td>
</tr>
<tr>
<td>CWBT</td>
<td>battery cost $ (low)</td>
</tr>
<tr>
<td>CWBTH</td>
<td>battery cost $ (high)</td>
</tr>
</tbody>
</table>
CWRB  cost of replacement batteries (low) $
CWRBH  cost of replacement batteries (high) $
CYCB  battery cycle life in cycles
DDCG  depth of a deep discharge
DI  discount factor
DNBAT  difference between integer value of number of batteries and number of batteries
DPMH  downpayment (high)
DPML  downpayment (low)
DRBAT  difference between integer value of number of replacement batteries and number of replacement batteries
ECOSTRAIN  cost of EV transmission
ENGW  engine weight
EOLY  EV fractional use of vehicle
EPW  engine power
ETKW  EV transmission power
ETRAN  EV transmission type
ETRAN$  EV transmission type
ETRANWT  EV transmission weight
FI  inflation factor
FTYP  fuel type
FYEAR  number of years to finance over
GCOSTRAN  ICE transmission cost
GTRAN  ICE transmission type
GTRAN$  ICE transmission type
GTRANWT  ICE transmission weight
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDOL</td>
<td>1982</td>
</tr>
<tr>
<td>INBAT</td>
<td>integer value of the number of batteries</td>
</tr>
<tr>
<td>INIT</td>
<td>Initial cost (low $)</td>
</tr>
<tr>
<td>INITH</td>
<td>initial cost (high $)</td>
</tr>
<tr>
<td>INSR</td>
<td>cost of insurance $</td>
</tr>
<tr>
<td>IRBAT</td>
<td>integer value of number of replacement batteries</td>
</tr>
<tr>
<td>KMYR</td>
<td>annual travel in km per year</td>
</tr>
<tr>
<td>KWHR</td>
<td>kilowatt hour</td>
</tr>
<tr>
<td>LI</td>
<td>inflation factor</td>
</tr>
<tr>
<td>MCPKWH</td>
<td>battery material cost per kWh</td>
</tr>
<tr>
<td>ME</td>
<td>maintenance constant</td>
</tr>
<tr>
<td>MFAC</td>
<td>maintenance factor</td>
</tr>
<tr>
<td>MICE</td>
<td>maintenance constant</td>
</tr>
<tr>
<td>MKW</td>
<td>motor power</td>
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<tr>
<td>MOTWT</td>
<td>motor weight</td>
</tr>
<tr>
<td>MTYP$</td>
<td>Motor type</td>
</tr>
<tr>
<td>NBAT</td>
<td>number of batteries</td>
</tr>
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<td>NTRAN</td>
<td>number of transmissions</td>
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<tr>
<td>OPER</td>
<td>operating cost (low $)</td>
</tr>
<tr>
<td>OPERH</td>
<td>operating cost (high $)</td>
</tr>
<tr>
<td>PANDPL</td>
<td>passenger and payload</td>
</tr>
<tr>
<td>PAPINT</td>
<td>present value of principal and interest</td>
</tr>
<tr>
<td>PELEC</td>
<td>price of electricity</td>
</tr>
<tr>
<td>PFUEL</td>
<td>price of fuel</td>
</tr>
<tr>
<td>PTE</td>
<td>parking and toll</td>
</tr>
<tr>
<td>RBAT</td>
<td>number of replacement batteries</td>
</tr>
</tbody>
</table>
RBATYR  year of first replacement batteries
RDISR  real discount rate
RICE  fraction of ICE mileage
RINTR  real interest rate
RPM  repair and maintenance cost
RTIR  cost of replacement tires
SI  inflation factor
SLBV  salvage value of vehicle
SVB  salvage value of battery
SVB1  battery material salvage value (low)
SVB2  battery material salvage value (high)
SVV  salvage value of vehicle (low)
SVVH  salvage value of vehicle (high)
TEMP1  temporary addition to a sum
TEMP2  temporary addition to a sum
TEMP3  temporary addition to a sum
TEMP4  temporary addition to a sum
TEMP5  temporary addition to a sum
TEMP7  temporary addition to a sum
TEMP8  temporary addition to a sum
TEMP9  temporary addition to a sum
TEMP10  temporary addition to a sum
TI  inflation factor
TKM  total travel during life of vehicle
TRAWT  EV transmission weight
TRBATYR  year of second battery replacement
TRLE  cost of title and registration (low)
<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRLEH</td>
<td>cost of title and registration (high)</td>
</tr>
<tr>
<td>TTL</td>
<td>total life-cycle cost (low)</td>
</tr>
<tr>
<td>TTLH</td>
<td>total life-cycle cost (high)</td>
</tr>
<tr>
<td>VGAS</td>
<td>tank volume in liters</td>
</tr>
<tr>
<td>VTYP</td>
<td>vehicle type (hybrid, electric, ICE)</td>
</tr>
<tr>
<td>WB</td>
<td>weight of battery</td>
</tr>
<tr>
<td>WBV</td>
<td>weight of basic vehicle</td>
</tr>
<tr>
<td>WT</td>
<td>test weight of vehicle</td>
</tr>
<tr>
<td>YEAR</td>
<td>life of vehicle in years</td>
</tr>
<tr>
<td>ZI</td>
<td>inflation factor</td>
</tr>
</tbody>
</table>
APPENDIX N

BATTERY DISCHARGE MODELS
BASED ON ASSESSMENT OF
AV BATTERY REVIEW BOARD
Battery model coefficient generator:

PB/ACID/1.0

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>47.99</td>
<td>4.799</td>
<td>2.30259</td>
<td>1.56841</td>
</tr>
<tr>
<td>20</td>
<td>45.06</td>
<td>2.253</td>
<td>2.99573</td>
<td>.812263</td>
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<tr>
<td>30</td>
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<td>1.39967</td>
<td>3.4012</td>
<td>.336234</td>
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<tr>
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<td>.96875</td>
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<tr>
<td>50</td>
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<td>31.48</td>
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<td>27.11</td>
<td>.387286</td>
<td>4.2485</td>
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<tr>
<td>80</td>
<td>21.38</td>
<td>.26725</td>
<td>4.38203</td>
<td>-1.31957</td>
</tr>
</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 3.66561 + -.705735 \times \ln(tau) + -.110161 \times [\ln(tau)]^2
\]

CH1 = 3.66561
CH2 = -.705735
CH3 = -.110161

Sum of the squares of the residuals = 2.26633E-03
Standard error estimate = .0194351
Coefficient of determination = .999346
ELVEF battery CH coefficient curve plot....

For battery: PB/ACID/1.0

CH-1 = 3.66561   Pdmax = 120
CH-2 = -0.705735
CH-3 = -0.110161
Battery model coefficient generator:

PB/ACID2.1

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>45.74</td>
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<tr>
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<td>43.01</td>
<td>2.1505</td>
<td>2.99573</td>
<td>.7657</td>
</tr>
<tr>
<td>30</td>
<td>40.2</td>
<td>1.34</td>
<td>3.4012</td>
<td>.29267</td>
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<tr>
<td>40</td>
<td>37.29</td>
<td>.93225</td>
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<tr>
<td>100</td>
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<tr>
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<td>4.90528</td>
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</tbody>
</table>

RESULTS -----

\[ \ln(Pd) = 3.62626 + -.717755 \ln(tau) + -.094989 [\ln(tau)]^2 \]

CH1 = 3.62626
CH2 = -.717755
CH3 = -.094989

Sum of the squares of the residuals = .016799?
Standard error estimate = .043204
Coefficient of determination = .997163
ELVEC battery CH coefficient curve plot....

For battery: PB/ACID2.1

\[
\begin{align*}
CH-1 &= 3.62626 & Pd_{max} &= 135 \\
CH-2 &= -0.717755 \\
CH-3 &= -0.094989
\end{align*}
\]

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:
PB/ACID/2.4

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
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<td>2.30259</td>
<td>1.44903</td>
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<tr>
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<td>2.99573</td>
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<tr>
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<tr>
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<tr>
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<td>34.22</td>
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<td>4.2485</td>
<td>-0.868522</td>
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<td>0.1965</td>
<td>4.60517</td>
<td>-1.62709</td>
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</table>

RESULTS -----

\[
\ln(Pd) = 3.62408 + -0.782033 \times \ln(tau) + -0.0989376 \times [\ln(tau)]^2
\]

CH1 = 3.62408
CH2 = -0.782033
CH3 = -0.0989376

Sum of the squares of the residuals = 3.30163E-03
Standard error estimate = .0203151
Coefficient of determination = .999317

N-7
ELVEC battery CH coefficient curve plot......

For battery: Pb/ACID/2.4

CH-1 = 3.62408  Pdmax = 135
CH-2 = -.782033
CH-3 = -.0989376
Battery model coefficient generator:
PB/ACID/3.3

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>39.43</td>
<td>3.943</td>
<td>2.30259</td>
<td>1.37194</td>
</tr>
<tr>
<td>20</td>
<td>37.86</td>
<td>1.893</td>
<td>2.99573</td>
<td>.638163</td>
</tr>
<tr>
<td>30</td>
<td>36.25</td>
<td>1.20833</td>
<td>3.4012</td>
<td>.189242</td>
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<td>34.57</td>
<td>.86425</td>
<td>3.68088</td>
<td>-.145893</td>
</tr>
<tr>
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<td>32.83</td>
<td>.6566</td>
<td>3.91202</td>
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RESULTS -----

\[ \ln(Pd) = 3.57472 + -.822528 \ln(tau) + -.0838422 \ln(tau)^2 \]

\begin{align*}
\text{CH}_1 &= 3.57472 \\
\text{CH}_2 &= -.822528 \\
\text{CH}_3 &= -.0838422
\end{align*}

Sum of the squares of the residuals = 1.94499E-03
Standard error estimate = .0155924
Coefficient of determination = .999598

N-9
ELVEC battery CH coefficient curve plot....

For battery: PB/ACID/3.3

CH-1 = 3.57472  Pdmax = 145
CH-2 = -0.822528
CH-3 = -0.083042

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:

BIP PB/ACID/10.0

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RESULTS -----

\[
\ln(Pd) = 3.84895 + -.890158 \times \ln(tau) + -.0380122 \times (\ln(tau))^2
\]

\[
\begin{align*}
&CH1 = 3.84895 \\
&CH2 = -.890158 \\
&CH3 = -.0380122
\end{align*}
\]

Sum of the squares of the residuals = 1.89471E-04
Standard error estimate = 4.86661E-03
Coefficient of determination = .999961
ELVEC battery CH coefficient curve plot......

For battery: BIP PB/ACID/10.0

CH-1 = 3.04895  \quad Pdmax = 400
CH-2 = -0.890158
CH-3 = -0.0380122
Battery model coefficient generator:

NI/FE/1.0

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RESULTS -----

\[ \ln(Pd) = 3.85854 + -.723694 \ln(tau) + -.0985473 \ln(tau)^2 \]

\[ \text{CH1} = 3.85854 \]
\[ \text{CH2} = -.723694 \]
\[ \text{CH3} = -.0985473 \]

Sum of the squares of the residuals = 1.34634E-03
Standard error estimate = .0164094
Coefficient of determination = .999522
ELVEC battery CH coefficient curve plot...

For battery: Ni/FE/1.0

\[ CH-1 = 3.05854 \quad P_{dmax} = 120 \]
\[ CH-2 = -0.72394 \]
\[ CH-3 = -0.0965473 \]
Battery model coefficient generator:  

NI/FE/2.1

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RESULTS -----

\[
\ln(Pd) = 3.9014 + -.802984 \times \ln(tau) + -.0824347 \times [\ln(tau)]^2
\]

CH1 = 3.9014  
CH2 = -.802984  
CH3 = -.0824347

Sum of the squares of the residuals = 2.69918E-03  
Standard error estimate = .0183684  
Coefficient of determination = .999442
ELVEC battery CH coefficient curve plot

For battery: NI/FE/2.1

CH-1 = 3.9014  Pdmax = 141
CH-2 = -0.802984
CH-3 = -0.0824347
Battery model coefficient generator:

NI/FE/2.4

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RESULTS -----

\[
\ln(Pd) = 3.87467 + -0.820591 \ln(tau) + -0.0747063 \times [\ln(tau)]^2
\]

\[
CH1 = 3.87467
\]
\[
CH2 = -0.820591
\]
\[
CH3 = -0.0747063
\]

Sum of the squares of the residuals = 1.75763E-03
Standard error estimate = .0148224
Coefficient of determination = .999637

N-17
ELVEC battery CH coefficient curve plot.....

For battery: NI/FE/2.4

\[ CH-1 = 3.87467 \quad P_{\text{dmax}} = 141 \]
\[ CH-2 = -0.820591 \]
\[ CH-3 = -0.0747063 \]
Battery model coefficient generator:

NI/FE/3.3

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OF POOR QUALITY

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RESULTS -----

\[ \ln(Pd) = 3.81662 + -.882478 \ln(tau) + -.0504292 \ln(tau)^2 \]

CH1 = 3.81662
CH2 = -.882478
CH3 = -.0504292

Sum of the squares of the residuals = 4.70245E-04
Standard error estimate = 7.66686E-03
Coefficient of determination = .999903
ELVEC battery CH coefficient curve plot.....

For battery: NI/FE/3.3

\[
\begin{align*}
CH-1 & = 3.01662 & P_{\text{dmax}} & = 160 \\
CH-2 & = -0.882478 \\
CH-3 & = -0.0504292 \\
\end{align*}
\]

Specific Energy, \( E_d \) (Wh/kg)
Battery model coefficient generator:
NI/ZN2.0

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RESULTS -----

ln(Pd) = 4.06488 + -.844001 * ln(tau) + -.0847194 * ln(tau)^2

CH1 = 4.06488
CH2 = -.844001
CH3 = -.0847194

Sum of the squares of the residuals = 4.020E-03
Standard error estimate = .0366089
Coefficient of determination = .79921
ELVEC battery CH coefficient curve plot.....

For battery: Ni/Zn2.0

CH-1 = 4.06488, Pdmax = 204
CH-2 = -0.844001
CH-3 = -0.084194
Battery model coefficient generator:

ZN/BR/1.0

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RESULTS ------

\[
\ln(P_d) = 4.00357 - 0.627864 \ln(tau) - 0.151306 \ln(tau)^2
\]

CH1 = 4.00357  
CH2 = -0.627864  
CH3 = -0.151306

Sum of the squares of the residuals = 5.80993E-03  
Standard error estimate = .0311179  
Coefficient of determination = .998322
ELVECore battery CH coefficient curve plot.....

For battery: ZN/BR/1.0

CH-1 = 4.00357  \( P_{d\text{max}} = 83 \)
CH-2 = -0.627864
CH-3 = -0.151306

Specific Energy, \( E_d \) (Wh/kg)
Battery model coefficient generator:

ZN/BE/2.1

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RESULTS ------

\[
\ln(Pd) = 3.80889 + -.819456 \ln(tau) + -.0951689 \ln(tau)^2
\]

\[
CH1 = 3.80889 \\
CH2 = -.819456 \\
CH3 = -.0951689
\]

Sum of the squares of the residuals = 1.13292E-03
Standard error estimate = .0119002
Coefficient of determination = .999766
ELVEC battery CH coefficient curve plot.....

For battery: ZN/BE/2.1

CH-1 = 3.80889  \( P_{d\text{max}} = 115 \)
CH-2 = -0.819456
CH-3 = -0.0951689

Specific Energy, \( E_d \) (Wh/kg)
Battery model coefficient generator:
ZN/BR/2.4

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RESULTS ------

\[ \ln(Pd) = 3.83512 + -.837169 \ln(tau) + -.0851764 \left(\ln(tau)\right)^2 \]

\[
\begin{align*}
CH1 &= 3.83512 \\
CH2 &= -.837169 \\
CH3 &= -.0851764
\end{align*}
\]

Sum of the squares of the residuals = 6.16919E-04
Standard error estimate = 8.78151E-03
Coefficient of determination = .999873
ELVEC battery CH coefficient curve plot......

For battery: ZN/BR/2.4

CH-1 = 3.83512   Pdmax = 135
CH-2 = -0.837169
CH-3 = -0.0851764

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:
ZN/BR/3.3

DATA -----

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RESULTS ------

\[ \ln(Pd) = 3.65918 + -.874489 * \ln(\tau) + -.0779032 * (\ln(\tau))^2 \]  

\[ CH1 = 3.65918 \]
\[ CH2 = -.874489 \]
\[ CH3 = -.0779032 \]

Sum of the squares of the residuals = 3.25496E-04  
Standard error estimate = 6.37863E-03  
Coefficient of determination = .999933
ELVEC battery CH coefficient curve plot....

For battery: ZN/BR/3.3

\[ CH-1 = 3.65918 \quad Pd_{\text{max}} = 150 \]
\[ CH-2 = -0.874489 \]
\[ CH-3 = -0.0779032 \]
Battery model coefficient generator:

ZN/CL/1.0

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RESULTS ------

\[ \ln(Pd) = 4.2577 + -.658475 \times \ln(tau) + -.117385 \times (\ln(tau))^2 \]

CH1 = 4.2577
CH2 = -.658475
CH3 = -.117385

Sum of the squares of the residuals = 2.3967E-03
Standard error estimate = .0185037
Coefficient of determination = .999421
ELVFC battery CH coefficient curve plot

For battery: ZN/CL/1.0

\[ CH-1 = 4.2577 \quad P_{d\text{max}} = 86 \]
\[ CH-2 = -0.658475 \]
\[ CH-3 = -0.117385 \]
Battery model coefficient generator:
ZN/CL/2.1

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RESULTS -----

\[
\ln(Pd) = 3.90924 + -.820198 \ln(tau) + -.0882068 \ln(tau)^2
\]

\[
\begin{align*}
CH1 &= 3.90924 \\
CH2 &= -.820198 \\
CH3 &= -.0882068 \\
\end{align*}
\]

Sum of the squares of the residuals = 1.09263E-03
Standard error estimate = .0116867
Coefficient of determination = .999774
ELVEC battery CH coefficient curve plot....

For battery: ZN/CL/2.1

\[ \text{CH-1} = 3.90924 \quad \text{PdMax} = 110 \]
\[ \text{CH-2} = -0.820198 \]
\[ \text{CH-3} = -0.0882068 \]
Battery model coefficient generator:
ZN/CL/2.4

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RESULTS ------

\[ \ln(Pd) = 3.9258 + -.848145 \ln(tau) + -.0752426 \ln(tau)^2 \]

CH1 = 3.9258
CH2 = -.848145
CH3 = -.0752426

Sum of the squares of the residuals = 4.84082E-04
Standard error estimate = 7.77883E-03
Coefficient of determination = .9999
ELVEC battery CH coefficient curve plot....

For battery: ZN/CL/2.4

\[
\begin{align*}
CH-1 & = 3.9250 & Pd_{\text{max}} & = 127 \\
CH-2 & = -0.848145 \\
CH-3 & = -0.0752426
\end{align*}
\]

![Graph showing specific energy and specific power against specific energy for ZN/CL/2.4 battery.](image)

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:

ZN/Cl./3.3

DATA -----

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RESULTS -----

\[ \ln(P_d) = 3.69598 - 0.878004 \ln(tau) - 0.0750732 (\ln(tau))^2 \]

\[ CH_1 = 3.69598 \]
\[ CH_2 = -0.878004 \]
\[ CH_3 = -0.0750732 \]

Sum of the squares of the residuals = 4.63915E-04
Standard error estimate = 7.61508E-03
Coefficient of determination = .999904
ELVEC battery CH coefficient curve plot......

For battery: ZN/CL/3.3

CH-1 = 3.69598 \quad \text{Pdmax} = 130
CH-2 = -0.878004
CH-3 = -0.0750732
Battery model coefficient generator:

FE/AIR/1.0

DATA -----

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RESULTS -----

\[
\ln(Pd) = 4.48115 + -.723875 \ln(tau) + -.0850794 \ln(tau)^2
\]

\[\begin{align*}
\text{CH1} &= 4.48115 \\
\text{CH2} &= -.723875 \\
\text{CH3} &= -.0850794
\end{align*}\]

Sum of the squares of the residuals = 7.24412E-04
Standard error estimate = 9.51585E-03
Coefficient of determination = .99985
ELVEC battery CH coefficient curve plot.....

For battery: FE/AIR/1.0

\[
\begin{align*}
    CH-1 &= 4.48115 \\
    PD_{\text{max}} &= 110 \\
    CH-2 &= -.723875 \\
    CH-3 &= -.0850794
\end{align*}
\]
Battery model coefficient generator:

FE/AIR/2.1

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RESULTS ----- 

\[ \ln(Pd) = 4.12545 + -.833583 \ln(tau) + -.0698404 \ln(tau)^2 \]

\[ \text{CH1 = 4.12545} \]
\[ \text{CH2 = -.833583} \]
\[ \text{CH3 = -.0698404} \]

Sum of the squares of the residuals = 3.64821E-04
Standard error estimate = 6.75297E-03
Coefficient of determination = .999925
ELVEC battery CH coefficient curve plot.....

For battery: FE/AIR/2.1

CH-1 = 4.12545  Pdmax = 540
CH-2 = -.833583
CH-3 = -.0698404

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:

FE/AIR/2.4

DATA -----

\[
\begin{array}{cccccc}
\text{Pd} & \text{Ed} & \text{tau} & \ln(Pd) & \ln(tau) \\
10 & 66.14 & 6.614 & 2.30259 & 1.88919 \\
20 & 67.72 & 3.386 & 2.99573 & 1.21965 \\
30 & 67.29 & 2.243 & 3.4012 & 0.807814 \\
40 & 66.29 & 1.65725 & 3.68808 & 0.50516 \\
50 & 65.01 & 1.3002 & 3.91202 & 0.262518 \\
60 & 63.55 & 1.05917 & 4.09435 & 0.0574824 \\
70 & 61.94 & 0.884857 & 4.2485 & -0.122329 \\
80 & 60.2 & 0.7525 & 4.38203 & -0.284354 \\
90 & 58.31 & 0.647889 & 4.49981 & -0.433036 \\
100 & 56.27 & 0.5627 & 4.60517 & -0.575009 \\
\end{array}
\]

RESULTS -----

\[
\ln(Pd) = 4.13931 + -0.858481 \times \ln(tau) - 0.0612641 \times (\ln(tau))^2
\]

\[\begin{align*}
\text{CH1} &= 4.13931 \\
\text{CH2} &= -0.858481 \\
\text{CH3} &= -0.0612641
\end{align*}\]

Sum of the squares of the residuals = \(1.87778\times10^{-4}\)

Standard error estimate = \(4.04481\times10^{-3}\)

Coefficient of determination = \(0.999961\)
ELVEC battery CH coefficient curve plot....

For battery: FE/AJR/2.4

\[ CH-1 = 4.13931 \quad Pd_{\text{Max}} = 157 \]
\[ CH-2 = -0.856481 \]
\[ CH-3 = -0.0612641 \]
Battery model coefficient generator:

FE/AIR/3.3

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<td>-7.01179</td>
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<td>.4312</td>
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<td>-8.41183</td>
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</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 3.90664 + .886569 \times \ln(tau) - .0563951 \times [\ln(tau)]^2
\]

\[
CH1 = 3.90664 \\
CH2 = -.886569 \\
CH3 = -.0563951
\]

Sum of the squares of the residuals = 1.87741E-04

Standard error estimate = 4.84434E-03

Coefficient of determination = .999961
ELVEC battery CH coefficient curve plot....

For battery: FE/AlR/3.3

- CH-1 = 3.90664  \( P_d \text{ max} = 165 \)
- CH-2 = -0.886569
- CH-3 = -0.0563951
Battery model coefficient generator:
LI/HS1.0

DATA ------

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<thead>
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<th>Pd</th>
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<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
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<tr>
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<td>1.62924</td>
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</table>

RESULTS ------

\[
\ln(P_d) = 4.37983 + -0.713407 \ln(tau) + -0.0835533 [\ln(tau)]^2
\]

\[CH_1 = 4.37983\]
\[CH_2 = -0.713407\]
\[CH_3 = -0.0835533\]

Sum of the squares of the residuals = 4.54747E-13
Standard error estimate = 6.74349E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.

For battery: Li/MSi 0

\( CH-1 = 4.37983 \quad P_{dmax} = 161 \)
\( CH-2 = -0.713407 \)
\( CH-3 = -0.0835533 \)
Battery model coefficient generator:

Li/MS2.1 - 2.4

DATA -----

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<thead>
<tr>
<th>Pd</th>
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<th>ln(tau)</th>
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<td>1.16667</td>
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<td>.15475</td>
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<td>100</td>
<td>57</td>
<td>.57</td>
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<td>-.562119</td>
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</table>

RESULTS -----

\[ \ln(Pd) = 4.21177 + -.748451 \times \ln(tau) + -.0864695 \times (\ln(tau))^2 \]

CH1 = 4.21177
CH2 = -.748451
CH3 = -.0864695

Sum of the squares of the residuals = 7.3896E-13
Standard error estimate = 8.5963E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot....

For battery: LI/MS2.1

CH-1 = 4.21177  \quad Pdmax = 165
CH-2 = -0.748451
CH-3 = -0.0864695

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:
LI/MS3.3

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
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<td>3.55</td>
<td>2.99573</td>
<td>1.24695</td>
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<td>60</td>
<td>63</td>
<td>1.85</td>
<td>4.09435</td>
<td>0.040792</td>
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<td>53</td>
<td>0.53</td>
<td>4.60517</td>
<td>-0.634078</td>
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</tbody>
</table>

RESULTS -----

\[ \ln(Pd) = 4.13332 - 0.79485 \ln(tau) - 0.081334 \ln(tau)^2 \]

CH1 = 4.13332
CH2 = -0.79485
CH3 = -0.081334

Sum of the squares of the residuals = 1.81899E-12
Standard error estimate = 1.3487E-06
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.

For battery: LI/MS3.3

\[ \begin{align*}
\text{CH-1} &= 4.13332 & \text{Pdmax} &= 175 \\
\text{CH-2} &= -0.79485 \\
\text{CH-3} &= -0.081334
\end{align*} \]
Battery model coefficient generator:

NA/S/1.0

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
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</thead>
<tbody>
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<td>12.33</td>
<td>2.30259</td>
<td>2.51204</td>
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<tr>
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<td>120.53</td>
<td>6.0765</td>
<td>2.99573</td>
<td>1.79417</td>
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<tr>
<td>30</td>
<td>117.69</td>
<td>3.923</td>
<td>3.4012</td>
<td>1.36686</td>
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<td>40</td>
<td>114.78</td>
<td>2.8695</td>
<td>3.68888</td>
<td>1.05414</td>
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<tr>
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<td>2.2356</td>
<td>3.91202</td>
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<td>1.09567</td>
<td>4.49981</td>
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<td>4.60517</td>
<td>-0.052136</td>
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</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 4.57375 - 0.790541 \ln(tau) - 0.0460973 \ln(tau)^2
\]

CH1 = 4.57375
CH2 = -0.790541
CH3 = -0.0460973

Sum of the squares of the residuals = 3.64e-04
Standard error estimate = 6.74657e-03
Coefficient of determination = .999925
ELVEC battery CH coefficient curve plot.....

For battery: NA/S/1.0

CH-1 = 4.57375  \( P_{d\text{max}} = 148 \)
CH-2 = -0.790541
CH-3 = -0.0460973
Battery model coefficient generator: NA/S/2.1

DATA -----

<table>
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<th>Ed</th>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
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<td>2.99573</td>
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<td>2.85567</td>
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<td>84.38</td>
<td>2.1095</td>
<td>3.68888</td>
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<td>50</td>
<td>83.04</td>
<td>1.6608</td>
<td>3.91202</td>
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<td>81.65</td>
<td>1.36083</td>
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RESULTS -----

\[
\ln(Pd) = 4.36547 + -.834152 \times \ln(tau) + -.0299432 \times [(\ln(tau)]^2
\]

CH1 = 4.36547
CH2 = -.834152
CH3 = -.0299432

Sum of the squares of the residuals = 1.43137E-04
Standard error estimate = 4.22991E-03
Coefficient of determination = .99997
ELVEC battery CH coefficient curve plot.....

For battery: NA/S/2.1

CH-1 = 4.36547    Pdmax = 199
CH-2 = -.884152
CH-3 = -.0299432

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:

NA/S/2.4

DATA -----

<table>
<thead>
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<th>Pd</th>
<th>Ed</th>
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<th>ln(tau)</th>
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</table>

RESULTS -----

\[ \ln(Pd) = 4.3308 + .894503 \ln(tau) + .0276968 \ln(tau)^2 \]

\[ CH1 = 4.3308 \]
\[ CH2 = .894503 \]
\[ CH3 = .0276968 \]

Sum of the squares of the residuals = 1.12011E-04
Standard error estimate = 3.74184E-03
Coefficient of determination = .999977
ELVEG battery CH coefficient curve plot.....

For battery: NA/S/2.4

CH-1 = 4.3308  
Pdmax = 224
CH-2 = -.894503
CH-3 = -.0276968
Battery model coefficient generator:

NA/S/3.3

DATA ------

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<thead>
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<th>Pd</th>
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<th>ln(tau)</th>
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</table>

RESULTS ------

\[
\ln(Pd) = 4.21601 + -0.902732 \ln(tau) + -0.0272804 \ln(tau)^2
\]

CH1 = 4.21601
CH2 = -0.902732
CH3 = -0.0272804

Sum of the squares of the residuals = 1.08422E-04
Standard error estimate = 3.68141E-03
Coefficient of determination = .999978
ELVEC battery CH coefficient curve plot......

For battery: NA/S/3.3

CH-1 = 4.21601  \hspace{1cm} Pdmax = 244
CH-2 = -.902732
CH-3 = -.0272804

- Specific Energy, Ed (Wh/kg)
- Specific Power, Pd (W/kg)

Specif 1000

1 10 100 1000

N-60
Battery model coefficient generator:
A/AIR/PRES W/IMPR SELF-DISCH

DATA -----

<table>
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<tr>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
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</thead>
<tbody>
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</tbody>
</table>

RESULTS -----

\[ \ln(Pd) = 4.9078 + -.723055 \ln(tau) + -.098440? \ln(tau)^2 \]

\[ CH1 = 4.9078 \]
\[ CH2 = -.723055 \]
\[ CH3 = -.0984402 \]

Sum of the squares of the residuals = 7.7307E-04
Standard error estimate = .0165814
Coefficient of determination = .999676
ELVEC battery CH coefficient curve plot.....

For battery: Al/AIR/PRES W/IMPR SELF-DISCH

CH-1 = 4.9078  \quad P_{\text{max}} = 157
CH-2 = -0.723055
CH-3 = -0.0984402
Table N-1. Battery Projections by Review Board

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Energy (Wh/kg @20W/kg)</th>
<th>Power (30-s W/kg @10% SOC)</th>
<th>Annual Efficiency (%)</th>
<th>Cycle Life</th>
<th>OEM Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb/Acid</td>
<td>38-45</td>
<td>80-100</td>
<td>75</td>
<td>750</td>
<td>43</td>
</tr>
<tr>
<td>bipolar Pb/Acid</td>
<td>50</td>
<td>275</td>
<td>85</td>
<td>750</td>
<td>80</td>
</tr>
<tr>
<td>Ni/Fe</td>
<td>48-56</td>
<td>75-110</td>
<td>58</td>
<td>1500</td>
<td>100</td>
</tr>
<tr>
<td>Ni/Zn</td>
<td>60</td>
<td>155</td>
<td>70</td>
<td>600</td>
<td>130</td>
</tr>
<tr>
<td>Zn/Br2</td>
<td>40-67</td>
<td>52-94</td>
<td>46</td>
<td>750</td>
<td>20</td>
</tr>
<tr>
<td>Zn/C12</td>
<td>42-89</td>
<td>80-115</td>
<td>48</td>
<td>1500</td>
<td>10</td>
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<tr>
<td>Fe/Air</td>
<td>52-109</td>
<td>102-146</td>
<td>50</td>
<td>500</td>
<td>8</td>
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<tr>
<td>Li/FeS</td>
<td>72-102</td>
<td>90-107</td>
<td>60</td>
<td>750</td>
<td>70</td>
</tr>
<tr>
<td>Na/S</td>
<td>73-121</td>
<td>129-220</td>
<td>66</td>
<td>750</td>
<td>25</td>
</tr>
<tr>
<td>Al/Air</td>
<td>158</td>
<td>157</td>
<td>18**</td>
<td>3000***</td>
<td>42</td>
</tr>
</tbody>
</table>

* OEM Costs in 1982* = a*kWh + b*kW + c (Symons equation), numbers listed are the review board’s low estimates
** Source energy
*** Life of air cathode-3000 cold starts, equivalent to 4 years

Table N-2. Battery Projections by Developers

<table>
<thead>
<tr>
<th>Battery Type</th>
<th>Energy (Wh/kg @20W/kg)</th>
<th>Power (30-s W/kg @10% SOC)</th>
<th>Annual Efficiency (%)</th>
<th>Cycle Life</th>
<th>OEM Cost*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb/Acid</td>
<td>38-45</td>
<td>80-100</td>
<td>75</td>
<td>f:00</td>
<td>$53/kWh</td>
</tr>
<tr>
<td>Ni/Fe</td>
<td>50-56</td>
<td>100-130</td>
<td>72</td>
<td>1500</td>
<td>130/kWh</td>
</tr>
<tr>
<td>Ni/Zn</td>
<td>60</td>
<td>155</td>
<td>70</td>
<td>600</td>
<td>130/kWh</td>
</tr>
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<td>Zn/Br2</td>
<td>40-67</td>
<td>52-94</td>
<td>56</td>
<td>750</td>
<td>40/kWh</td>
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<tr>
<td>Zn/C12</td>
<td>50-110</td>
<td>103-154</td>
<td>53</td>
<td>1500</td>
<td>61-81/kW</td>
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<td>500</td>
<td>21-25/kW</td>
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<td>Li/FeS</td>
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<td>65</td>
<td>1000</td>
<td>99-115/kW</td>
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<td>218</td>
<td>32</td>
<td>3000***</td>
<td>32/kW</td>
</tr>
</tbody>
</table>

* Equivalent values calculated from cost estimates of complete battery systems in some instances
** Surrogate for replacement of 25% of the cells in 1000 cycles
*** Life of air cathode-3000 cold starts, equivalent to 4 years
APPENDIX O

BATTERY DISCHARGE MODELS
BASED ON BATTERY DESIGN REPORTS
Battery model coefficient generator:

NI/FE 1.0, 2.1, 2.4

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
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<tbody>
<tr>
<td>10</td>
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<td>5.8</td>
<td>2.30259</td>
<td>1.75786</td>
</tr>
<tr>
<td>20</td>
<td>56</td>
<td>2.8</td>
<td>2.99573</td>
<td>1.02962</td>
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<tr>
<td>60</td>
<td>46</td>
<td>.76666</td>
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<td>-.265703</td>
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<tr>
<td>100</td>
<td>31</td>
<td>.31</td>
<td>4.60517</td>
<td>-1.17118</td>
</tr>
</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 3.8825 + .73727 \ln(tau) + -.0959177 \ln(tau)^2
\]

\[
\begin{align*}
CH1 &= 3.8825 \\
CH2 &= -.73727 \\
CH3 &= -.0959177
\end{align*}
\]

Sum of the squares of the residuals = 1.43249E-03
Standard error estimate = .0267628
Coefficient of determination = .999561
ELVEF battery CH coefficient curve plot.....

For battery: NI/FE 1.0, 2.1, 2.4

- CH-1 = 3.8825 \( P_{d_{max}} = 160 \)
- CH-2 = -.73727
- CH-3 = -.0959177

### Graph

- Specific Power, \( P_d \) (W/kg)
- Specific Energy, \( E_d \) (Wh/kg)
Battery model coefficient generator:

NI/FE 3.3

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
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<tbody>
<tr>
<td>10</td>
<td>52</td>
<td>5.2</td>
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<td>20</td>
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<td>2.5</td>
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<td>60</td>
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<td>.37</td>
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</table>

RESULTS -----

\[
\ln(Pd) = 3.8239 + -.842842 \ln(tau) + -.050693 \ln(tau)^2
\]

\[
CH1 = 3.8239 \\
CH2 = -.842842 \\
CH3 = -.050693
\]

Sum of the squares of the residuals = 4.50989E-04
Standard error estimate = .0150165
Coefficient of determination = .999862
ELVEC battery CH coefficient curve plot

For battery: NI/FE 3.3

\[ CH-1 = 3.8239 \quad P_{\text{Dmax}} = 190 \]
\[ CH-2 = -0.842842 \]
\[ CH-3 = -0.050693 \]
Battery model coefficient generator:

ZN/CL 1.0

DATA ------

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
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<tbody>
<tr>
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<td>85</td>
<td>.85</td>
<td>4.60517</td>
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</table>

RESULTS ------

\[
\ln(Pd) = 4.48906 - 0.728524 \ln(tau) - 0.0864971 \ln(tau)^2
\]

CH1 = 4.48906
CH2 = -0.728524
CH3 = -0.0864971

Sum of the squares of the residuals = 3.56072E-11
Standard error estimate = 6.05039E-06
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot

For battery: ZN/CL 1.0

CH-1 = 4.48906 \quad PdMax = 105
CH-2 = -0.728524
CH-3 = -0.0864971
Battery model coefficient generator:

ZN/CL 2.1

DATA -----

<table>
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<tr>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
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<tbody>
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<td>60</td>
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<td>55</td>
<td>.55</td>
<td>4.60517</td>
<td>-.597437</td>
</tr>
</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 4.09435 + -.876383 \ln(tau) + -.0366745 \ln(tau)^2
\]

CH1 = 4.09435
CH2 = -.876383
CH3 = -.0366745

Sum of the squares of the residuals = 9.66338E-13
Standard error estimate = 9.33026E-07
Coefficient of determination = 1.
ELVEC battery CH coefficient curve plot .

For battery: ZN/CL 2.1

CH-1 = 4.09435  \quad Pd_{\text{max}} = 130
CH-2 = -0.876383
CH-3 = -0.0366745
Battery model coefficient generator:

ZN/CL 2.4

DATA -----

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<tr>
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<td>1.17866</td>
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<td>60</td>
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<td>0.0165293</td>
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<tr>
<td>100</td>
<td>56</td>
<td>0.56</td>
<td>4.60517</td>
<td>-0.579819</td>
</tr>
</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 4.10899 + -.885019 \times \ln(tau) + -.0504766 \times [\ln(tau)]^2
\]

\[
\begin{align*}
CH1 &= 4.10899 \\
CH2 &= -.885019 \\
CH3 &= -.0504766
\end{align*}
\]

Sum of the squares of the residuals = 1.81899E-12
Standard error estimate = 1.3487E-06
Coefficient of determination = 1
ELVEG battery CH coefficient curve plot....

For battery: ZN/CL 2.4

CH-1 = 4.10899    Pdmax = 147
CH-2 = -.885019
CH-3 = -.0504766
Battery model coefficient generator:
ZN/CL 3.7

DATA -----

<table>
<thead>
<tr>
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<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
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<tr>
<td>100</td>
<td>44</td>
<td>.44</td>
<td>4.60517</td>
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</tbody>
</table>

RESULTS -----

ln(Pd) = 3.87103 - .923069 *ln(tau) - .035132 *[ln(tau)]^2

CH1 = 3.87103
CH2 = -.923069
CH3 = -.035132

Sum of the squares of the residuals = 9.66339E-13
Standard error estimate = 9.83026E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot......

For battery: ZN/CL 3.3

$CH-1 = 3.87103 \quad P_d\text{max} = 158$

$CH-2 = -0.923069$

$CH-3 = -0.035132$
Battery model coefficient generator:

FE/AIR 1.0

DATA -----

<table>
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<tr>
<th>Pd</th>
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<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
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<tbody>
<tr>
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<td>9.75</td>
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<td>2.27727</td>
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<tr>
<td>60</td>
<td>182</td>
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<td>1.10966</td>
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<td>100</td>
<td>167</td>
<td>1.67</td>
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<td>.512824</td>
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</table>

RESULTS -----

\[
\ln(Pd) = 5.01672 + (-0.777791) \ln(tau) + (-0.0481574) \ln(tau)^2
\]

CH1 = 5.01672  
CH2 = -0.777791  
CH3 = -0.0481574  

Sum of the squares of the residuals = 2.97917E-10  
Standard error estimate = 1.72603E-05  
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.

For battery: FE/AIR 1.0

CH-1 = 5.01672 \quad P_{\text{dmax}} = 181
CH-2 = -1.777791
CH-3 = -0.0481574
Battery model coefficient generator:

FE/AIR 2.1

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
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<td>134</td>
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<td>3.00241</td>
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<td>122</td>
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<td>4.60517</td>
<td>.198851</td>
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</table>

RESULTS -----

\[
\ln(Pd) = 4.78288 - 0.888354 \ln(tau) - 0.0269051 \ln(tau)^2
\]

CH1 = 4.78288
CH2 = -0.888354
CH3 = -0.0269051

Sum of the squares of the residuals = 2.84217E-13
Standard error estimate = 5.3312E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot....

For battery: FE/AIR 2.4

CH-1 = 4.78288  \( P_{\text{max}} = 262 \)
CH-2 = -0.888354
CH-3 = -0.0269051

1000

Specific Power, \( P_d \) (W/kg)

1  10  100  1000

Specific Energy, \( E_d \) (Wh/kg)
Battery model coefficient generator:

FE/AIR 2.4

DATA -----

\[
\begin{array}{cccccc}
P_d & E_d & \tau & \ln(P_d) & \ln(\tau) \\
20 & 123 & 6.15 & 2.99573 & 1.51645 \\
60 & 118 & 1.96667 & 4.09435 & .67634 \\
100 & 113 & 1.13 & 4.60517 & .122217 \\
\end{array}
\]

RESULTS -----

\[
\ln(P_d) = 4.7158 + -.902187 \ln(\tau) + -.0246366 \ln(\tau)^2
\]

CH1 = 4.7158
CH2 = -.902187
CH3 = -.0246366

Sum of the squares of the residuals = 1.1937E-12
Standard error estimate = 1.09257E-06
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.....

For battery: FE/AIR 2.4

CH-1 = 4.7158    Pdmax = 277
CH-2 = -.902187
CH-3 = -.0246366
Battery model coefficient generator:

FE/AIR 3.3

DATA ------

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>98</td>
<td>4.9</td>
<td>2.99573</td>
<td>1.58924</td>
</tr>
<tr>
<td>60</td>
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<tr>
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<td>91</td>
<td>.91</td>
<td>4.60517</td>
<td>-.0943106</td>
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</table>

RESULTS ------

\[
\ln(Pd) = 4.51707 - 0.935427 \ln(\tau) + 0.0137498 (\ln(\tau))^2
\]

CH1 = 4.51707
CH2 = -0.935427
CH3 = -0.0137498

Sum of the squares of the residuals = 1.18803E-11
Standard error estimate = 3.44678E-06
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.....

For battery: FE/AIR 3.3

\[\text{CH-1} = 4.51707 \quad \text{Pdmax} = 309\]
\[\text{CH-2} = -.935427\]
\[\text{CH-3} = -.0137498\]
Battery model coefficient generator:

LI/FES 1.0 AND 3.3 - BIPOLAR

DATA ------

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
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<td>6.8</td>
<td>2.99573</td>
<td>1.91692</td>
</tr>
<tr>
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</tr>
<tr>
<td>100</td>
<td>90</td>
<td>0.9</td>
<td>4.60517</td>
<td>-1.10536</td>
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</tbody>
</table>

RESULTS ------

\[
\ln(Pd) = 4.54047 + -0.624021 * \ln(tau) + -0.0948519 * [\ln(tau)]^2
\]

\[
CH1 = 4.54047 \\
CH2 = -0.624021 \\
CH3 = -0.0948519
\]

Sum of the squares of the residuals = 7.95808E-12
Standard error estimate = 2.82101E-06
Coefficient of determination = 1
For battery: LI/FES 1.0 AND 3.3 - BIPOLAR

\[ CH-1 = 4.54047 \quad \text{Pdmax} = 187 \]
\[ CH-2 = -0.624021 \]
\[ CH-3 = -0.0948519 \]
Battery model coefficient generator:

LI/FES 2.1 AND 2.4 - PRISMATIC

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
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</thead>
<tbody>
<tr>
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<td>1.47018</td>
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<td>60</td>
<td>75</td>
<td>1.25</td>
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</tr>
<tr>
<td>100</td>
<td>60</td>
<td>.6</td>
<td>4.60517</td>
<td>-.510826</td>
</tr>
</tbody>
</table>

RESULTS -----

\[ \ln(P_d) = 4.26029 + -0.722844 \ln(\tau) + -0.093389 \ln(\tau)^2 \]

\[
\begin{align*}
\text{CH1} &= 4.26029 \\
\text{CH2} &= -0.722844 \\
\text{CH3} &= -0.093389
\end{align*}
\]

Sum of the squares of the residuals = 2.27374E-13
Standard error estimate = 4.76837E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.....

For battery: LI/FES 2.1 AND 2.4 - PRISOMATIC

CH-1 = 4.26029  Pdmax = 170
CH-2 = -0.722844
CH-3 = -0.093389

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator.

NA/S 1.0

DATA -----

\[
\begin{array}{cccccc}
Pd & Ed & \tau & ln(Pd) & ln(\tau) \\
20 & 132 & 6.6 & 2.99573 & 1.88707 \\
60 & 121 & 2.01667 & 4.09435 & .701446 \\
100 & 107 & 1.07 & 4.60517 & .0676507 \\
\end{array}
\]

RESULTS -----

\[
ln(Pd) = 4.65656 + -.755 \times ln(\tau) + -.0662971 \times (ln(\tau))^2
\]

CH1 = 4.65656
CH2 = -.755
CH3 = -.0662971

Sum of the squares of the residuals = 0
Standard error estimate = 0
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot....

For battery: NA/S 1.0

\[ \begin{align*}
CH-1 &= 4.65656 & Pd_{max} &= 165 \\
CH-2 &= -0.755 \\
CH-3 &= -0.0662971
\end{align*} \]
Battery model coefficient generator:

NA/S 2.1

DATA ------

<table>
<thead>
<tr>
<th>Pd</th>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
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</table>

RESULTS ------

\[ \ln(P_d) = 4.41274 + \cdot .870809 \ln(tau) + \cdot .0378316 \ln(tau)^2 \]

CH1 = 4.41274
CH2 = -.870809
CH3 = -.0378316

Sum of the squares of the residuals = 1.87583E-12
Standard error estimate = 1.36961E-06
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.....

For battery: NA/S 2.1

CH-1 = 4.41274 \quad \text{Pdmax} = 209
CH-2 = -0.870809
CH-3 = -0.0378316

Specific Energy, $E_d$ (Wh/kg)
Battery model coefficient generator:
NA/S 2.4

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
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<td>1.42311</td>
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<td>79</td>
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<td>4.09435</td>
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<tr>
<td>100</td>
<td>74</td>
<td>.74</td>
<td>4.60517</td>
<td>-.301105</td>
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</table>

RESULTS ------

\[
\ln(Pd) = 4.34162 + -.887594 \ln(tau) + -.040855 * [\ln(tau)]^2
\]

\[CH_1 = 4.34162\]
\[CH_2 = -.887594\]
\[CH_3 = -.040855\]

Sum of the squares of the residuals = 6.82121E-13
Standard error estimate = 8.25906E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.

For battery: NA/S 2.4

CH-1 = 4.34162  \hspace{1cm} Pd_{\text{max}} = 224
CH-2 = -0.887594
CH-3 = -0.040855
Battery model coefficient generator:

NA/S 3.3

DATA -----

<table>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
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<tbody>
<tr>
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<td>2.99573</td>
<td>1.29473</td>
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<tr>
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<td>65</td>
<td>.65</td>
<td>4.60517</td>
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</table>

RESULTS -----

\[ \text{ln}(Pd) = 4.22143 + -.904752 \times \text{ln}(\tau) + -.0323847 \times [\text{ln}(\tau)]^2 \]

CH1 = 4.22143
CH2 = -.904752
CH3 = -.0323847

Sum of the squares of the residuals = 4.54747E-13
Standard error estimate = 6.74349E-07
Coefficient of determination = 1
ELVEC battery CH coefficient curve plot.....

For battery: Na/S 3.3

\[
\begin{align*}
CH-1 &= 4.22143 & Pd_{max} &= 244 \\
CH-2 &= -0.904752 \\
CH-3 &= -0.0323847
\end{align*}
\]
Battery model coefficient generator:

AL/ATR

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
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<th>ln(Pd)</th>
<th>ln(tau)</th>
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<tbody>
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<td>3.4</td>
<td>4.09435</td>
<td>1.22370</td>
</tr>
<tr>
<td>100</td>
<td>192</td>
<td>1.92</td>
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<tr>
<td>200</td>
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<td>.82</td>
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RESULTS -----

\[ \ln(Pd) = 5.14165 + -.803725 \ln(tau) + -.0397415 (\ln(tau))^2 \]

\[ \begin{align*}
  \text{CH1} &= 5.14165 \\
  \text{CH2} &= -.803725 \\
  \text{CH3} &= -.0397415 \\
\end{align*} \]

Sum of the squares of the residuals = 4.21929E-05
Standard error estimate = 4.59309E-03
Coefficient of determination = .999985
ELVEC battery CH coefficient curve plot.....

For battery: AL/AIR

CH-1 = 5.14165  Pdmax = 218
CH-2 = -.803725
CH-3 = -.0397415

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator: AL/AIR/PRES

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>1.9947</td>
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<tr>
<td>60</td>
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<td>.968251</td>
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<td>.680569</td>
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<td>.41211</td>
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<td>126</td>
<td>.802549</td>
<td>5.05625</td>
<td>-.219964</td>
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</tbody>
</table>

RESULTS -----

\[ \ln(Pd) = 4.91109 - .703742 \times \ln(\tau) - .129094 \times (\ln(\tau))^2 \]

CH1 = 4.91109
CH2 = -.703742
CH3 = -.129094

Sum of the squares of the residuals = 3.50653E-04
Standard error estimate = .0108113
Coefficient of determination = .999853
ELVEC battery CH coefficient curve plot...

For battery: AL/AIR/PRES

CH-1 = 4.91109  Pd_max = 157
CH-2 = -0.703742
CH-3 = -0.129094

Specific Energy, Ed (Wh/kg)
Battery model coefficient generator:
AL/AIR/ADV

DATA -----

<table>
<thead>
<tr>
<th>Pd</th>
<th>Ed</th>
<th>tau</th>
<th>ln(Pd)</th>
<th>ln(tau)</th>
</tr>
</thead>
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<td>.665138</td>
<td>5.3845</td>
<td>-1.407761</td>
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</tbody>
</table>

RESULTS -----

\[
\ln(Pd) = 5.11411 + -0.758579 * \ln(tau) + -0.0543494 * (\ln(tau))^2
\]

CH1 = 5.11411
CH2 = -0.758579
CH3 = -0.0543494

Sum of the squares of the residuals = 2.44835E-03
Standard error estimate = .0247404
Coefficient of determination = .999366
ELVEC battery CH coefficient curve plot.....

For battery: AL/AIR/ADV

\[ CH-1 = 5.11411 \]  \[ Pd_{max} = 218 \]
\[ CH-2 = -0.758579 \]
\[ CH-3 = -0.0543494 \]