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LIFE-CYCLE ENERGY ANALYSES OF ELECTRIC VEHICLE
STORAGE BATTERIES

Final Report

By
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December 1980

Work Performed Under Contract No. AC02-79ET25420

Hittman Associates, Inc.
Columbia, Maryland

U. S. DEPARTMENT OF ENERGY

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LIFE-CYCLE ENERGY ANALYSES
OF ELECTRIC VEHICLE STORAGE BATTERIES

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Contract No. DE-AC02-79ET25420.A000
FINAL REPORT

Submitted to:

U.S. Department of Energy
Division of Energy Storage

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December 1980

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I. EXECUTIVE SUMMARY

A. Introduction

This report presents the results of several life-cycle energy analyses of prospective electric vehicle batteries. The batteries analyzed are:

- (1) Nickel-zinc
- (2) Lead-acid
- (3) Nickel-iron
- (4) Zinc-chlorine
- (5) Sodium-sulfur (glass electrolyte)
- (6) Sodium-sulfur (ceramic electrolyte)
- (7) Lithium-metal sulfide
- (8) Aluminum-air.

A life-cycle energy analysis consists of evaluating the energy use of all phases of the battery's life, including the energy to build it, operate it, and any credits that may result from recycling of the materials in it. The analysis is based on the determination of three major energy components in the battery life cycle:

- (1) Investment Energy - The energy used to produce raw materials and to manufacture the battery.

- (2) Operational Energy - The energy consumed by the battery during its operational life. In the case of an electric vehicle battery, this energy is the energy required (as delivered to the vehicle's charging circuit) to power the vehicle for 100,000 miles.
- (3) Recycling Credit - The energy that could be saved from the recycling of battery materials into new raw materials.

The value of the life-cycle analysis approach is that it includes the various penalties and credits associated with battery production and recycling, which enables a more accurate determination of the system's ability to reduce the consumption of scarce fuels.

The analysis of the life-cycle energy requirements consists of identifying the materials from which each battery is made, evaluating the energy needed to produce these materials, evaluating the operational energy requirements, and evaluating the amount of materials that could be recycled and the energy that would be saved through recycling.

Detailed descriptions of battery component materials, the energy requirements for battery production, and credits for recycling appear in Chapters IV through XI. Operational energy for an electric vehicle, and the procedures used to determine it are discussed in Chapter III.

B. Results of the Analyses

The results of the analyses of the batteries are shown in Figures I-1 through I-16 and Tables I-1 through I-8. These show the basic results in three different ways.

Figures I-1 through I-8 show energy use in terms of the various elements in the life cycle. Energy amounts for each major raw material are given as well as for operation and recycling. In these figures and all of the other figures and tables in this report, electric energy is based on primary energy or the fuel input to the electric generation plant. An energy credit is shown in parentheses.

Figures I-9 through I-18 show the energy life-cycle in terms of an energy flow diagram. This diagram shows where the energy comes from and how it is used in the life cycle.

Tables I-1 through I-8 show the life-cycle data in tabular form. These tables give a breakdown of the energy use by source (electric, coal, oil, gas, and other) in addition to showing the energy associated with each stage of the battery life-cycle.

C. Comparisons Between Batteries

1. Measures of Performance

One of the major reasons for performing life-cycle analyses of batteries is to enable the various systems to be compared against each other. In order to compare the batteries

TABLE I-1. LIFE-CYCLE ENERGY USE FOR A NICKEL-ZINC ELECTRIC
VEHICLE BATTERY (THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Petroleum	Other	Total	Percent
Investment							
Nickel	3,120	0	1,904	277	1,152	6,453	2.1
Nickel hydroxide	4,406	611	3,359	865	1,925	11,166	3.7
Zinc oxide	2,982	1,830	436	96	825	6,169	2.0
Potassium hydroxide	209	125	125	125	(46)	538	0.2
Plastic	166	3	1,524	607	(190)	2,110	0.7
Copper	513	4	276	218	208	1,219	0.4
Steel	26	238	12	13	(16)	273	0.1
Fabrication	1,632	0	177	20	0	1,829	0.6
Subtotal	13,054	2,811	7,813	2,221	3,858	29,757	9.8
Operation	278,900	0	0	0	0	278,900	91.9
Recycling	(2,524)	(460)	(1,157)	(266)	(875)	(5,282)	(1.7)
TOTAL	289,430	2,351	6,656	1,955	2,983	303,375	100.0

TABLE I-2. LIFE-CYCLE ENERGY USE FOR A LEAD-ACID ELECTRIC VEHICLE BATTERY
(THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Petroleum	Other	Total	Percent
Investment							
Sulfuric acid	11	0	44	2	(55)	2	0.0
Primary lead	1,252	1,019	804	117	317	3,509	1.2
Secondary lead	129	344	284	17	336	1,110	0.4
Plastic	123	2	1,127	449	(141)	1,560	0.5
Fabrication	1,349	0	1,599	160	0	3,108	1.0
Subtotal	2,864	1,365	3,858	744	457	9,289	3.1
Operation	293,400	0	0	0	0	293,400	96.9
TOTAL	296,264	1,365	3,858	744	457	302,689	100.0

TABLE I-3. LIFE-CYCLE ENERGY USE FOR A NICKEL-IRON
ELECTRIC VEHICLE BATTERY.
(THOUSAND Btu/100,000 MILES)

	Electric	Natural Coal	Gas	Petroleum	Other	Total	Percent
Investment							
Nickel	3,891	0	2,375	345	1,437	8,048	2.4
Steel	256	2,383	117	131	(163)	2,724	0.8
Potassium hydroxide	267	160	161	160	(59)	689	0.2
Lithium hydroxide	66	400	0	41	58	565	0.2
Polyethylene	108	2	991	395	(124)	1,372	0.4
Copper	568	4	305	241	230	1,348	0.4
Ferric oxide	98	979	1,142	1,099	(809)	2,509	0.8
Process materials	13	64	264	145	0	486	0.1
Nickel nitrate	0	0	0	0	107	107	0.1
Cobalt nitrate	0	0	0	0	85	85	0.0
Fabrication	7,540	0	677	76	0	8,293	2.5
Subtotal	12,807	3,992	6,032	2,633	762	26,226	7.9
Operation	308,800	0	0	0	0	308,800	93.2
Recycling	(1,083)	(1,193)	(744)	(269)	(298)	(3,592)	(1.1)
TOTAL	320,519	2,799	5,288	2,364	464	331,434	100.0

TABLE I-4. LIFE-CYCLE ENERGY USE FOR A ZINC-CHLORINE
ELECTRIC VEHICLE BATTERY (THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Petroleum	Other	Total	Percent
Investment							
Graphite	2,067	0	717	1,716	0	4,500	1.3
Polyvinyl chloride	874	333	2,046	711	(277)	3,687	1.1
Titanium	712	0	38	78	378	1,206	0.3
Steel	5	44	2	2	(3)	50	0.0
Zinc chloride	861	382	440	337	189	2,209	0.6
Fabrication	1,295	0	1,295	1,295	0	3,885	1.1
Subtotal	5,814	759	4,538	4,139	287	15,537	4.4
Operation	338,600	0	0	0	0	338,600	95.8
Recycling	(215)	(96)	(110)	(84)	(47)	(552)	(0.2)
TOTAL	344,199	663	4,428	4,055	240	353,585	100.0

TABLE I-5. LIFE-CYCLE ENERGY USE FOR A SODIUM-SULFUR (GLASS ELECTROLYTE)
ELECTRIC VEHICLE BATTERY (THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Petroleum	Other	Total	Percent
Investment							
Sodium	2,421	87	87	88	(570)	2,113	0.8
Sulfur	1	0	93	3	2	99	0.0
Glass tubes	30	0	89	16	21	156	0.1
Tube sheet glass	60	0	180	33	49	322	0.1
Glass microspheres	23	0	72	12	3	110	0.1
Aluminum	10,547	32	1,507	1,920	1,017	15,023	5.6
Steel	52	487	24	27	(33)	557	0.2
Polyethylene	109	2	998	397	(125)	1,381	0.5
Copper	376	3	202	160	152	893	0.3
Fabrication	2,295	0	2,295	2,295	0	6,885	2.6
Subtotal	15,914	611	5,547	4,951	516	27,539	10.3
Operation	246,500	0	0	0	0	246,500	92.6
Recycling	(5,376)	(262)	(748)	(941)	(551)	(7,878)	(2.9)
TOTAL	257,038	349	4,799	4,010	(35)	266,161	100.0

TABLE I-6. LIFE-CYCLE ENERGY USE FOR A SODIUM-SULFUR (CERAMIC ELECTROLYTE)
ELECTRIC VEHICLE BATTERY (THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Oil	Other	Total	Percent
Investment							
Sulfur	1	0	108	4	2	115	0.0
Sodium	3,708	133	133	135	(873)	3,236	1.0
β -Alumina	15,182	0	180	138	43	15,543	4.8
α -Alumina	3	0	24	18	6	51	0.0
Steel	66	612	30	34	(42)	700	0.2
Aluminum	5,171	16	739	941	499	7,366	2.3
Graphite	365	0	127	303	0	795	0.3
Copper	393	3	211	167	159	933	0.3
Polyethylene	113	2	1,039	414	(130)	1,438	0.4
Glass microspheres	24	0	74	12	3	113	0.0
Fabrication	3,366	0	3,366	3,366	0	10,098	3.1
Subtotal	28,392	766	6,031	5,532	(333)	40,388	12.4
Operation	289,200	0	0	0	0	289,200	88.9
Recycling	(2,710)	(315)	(418)	(514)	(286)	(4,243)	(1.3)
TOTAL	314,882	451	5,613	5,018	(619)	325,345	100.0

TABLE I-7. LIFE-CYCLE ENERGY USE FOR A LITHIUM-METAL SULFIDE
ELECTRIC VEHICLE BATTERY (THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Petroleum	Other	Total	Percent
Investment							
Lithium sulfide	6,148	4,132	0	356	1,432	12,068	4.1
Aluminum	3,656	21	522	665	353	5,207	1.8
Pig iron	36	437	13	25	(76)	435	0.2
Lithium chloride	281	2,218	0	289	767	3,555	1.2
Potassium							
Chloride	27	0	2	0	33	62	0.0
Boron nitride	1,049	0	2,888	2	32	3,971	1.4
Steel	173	1,614	79	89	(111)	1,844	0.6
Glass insulation	127	0	389	64	15	595	0.2
Asbestos	15	0	0	11	3	29	0.0
Molybdenum oxide	37	0	9	3	8	57	0.0
Copper	327	2	175	139	132	775	0.3
Fabrication	3,178	0	3,178	3,178	0	9,534	3.3
Subtotal	15,054	8,414	7,255	4,821	2,588	38,132	13.1
Operation	256,800	0	0	0	0	256,800	88.1
Recycling	(1,854)	(811)	(316)	(405)	(123)	(3,509)	(1.2)
TOTAL	270,000	7,603	6,939	4,416	2,465	291,423	100.0

TABLE I-8. LIFE-CYCLE ENERGY USE FOR AN ALUMINUM-AIR
ELECTRIC VEHICLE BATTERY (THOUSAND Btu PER 100,000 MILES)

	Electric	Coal	Natural Gas	Petroleum	Other	Total	Percent
Investment							
Aluminum	12,045	37	1,721	2,192	1,162	17,157	1.8
Polyethylene	328	5	3,013	1,200	(377)	4,169	0.4
Steel	51	471	23	26	(32)	539	0.0
Sodium hydroxide	87	66	66	66	(30)	255	0.0
Alumina	22	188	128	150	47	535	0.1
Copper	783	6	421	332	317	1,859	0.2
Fabrication	2,723	0	2,723	2,723	0	8,169	0.9
Subtotal	16,039	773	8,095	6,689	1,087	32,683	3.4
Operation	680,600	3,400	64,700	101,400	73,500	923,600	96.7
Recycling	(532)	(239)	(1,217)	(1,320)	(507)	(3,815)	(0.1)
TOTAL	696,107	3,934	71,578	106,769	74,080	952,468	100.0

Figure I-1. Life-Cycle Energy Use for a Nickel-Zinc Electric Vehicle Battery
(Thousand Btu per 100,000 Vehicle Miles)

**Lead recycling is included in the investment step above.*

Figure I-2. Life-Cycle Energy Use for a Lead-Acid Electric Vehicle Battery
(Thousand Btu per 100,000 Miles)

Figure I-3. Life-Cycle Energy Use for a Nickel-Iron Electric Vehicle Battery
(Thousand Btu per 100,000 Miles)

Figure I-4. Life-Cycle Energy Use for a Zinc-Chlorine Electric Vehicle Battery
(Thousand Btu per 100,000 Miles)

Figure I-5. Life-Cycle Energy Use for a Sodium-Sulfur (Glass Electrolyte) Electric Vehicle Battery (Thousand Btu per 100,000 Miles)

Figure I-6. Life-Cycle Energy Use for a Sodium-Sulfur (Ceramic Electrolyte) Battery (Thousand Btu/100,000 Miles)

Figure I-7. Life-Cycle Energy Use for a Lithium-Metal Sulfide Electric Vehicle Battery (Thousand Btu per 100,000 Miles)

Figure I-8. Life-Cycle Energy Use for an Aluminum-Air Electric Vehicle Battery
(Thousand Btu per 100,000 Miles)

Figure I-9. Life-Cycle Energy Flow Chart for the Nickel-Zinc Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-10. Life-Cycle Energy Flow Chart for the Lead-Acid Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-11. Life-Cycle Energy Flow Chart for the Nickel-Iron Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-12. Life-Cycle Energy Flow Chart for the Zinc-Chlorine Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-13. Life-Cycle Energy Flow Chart for the Sodium-Sulfur (Glass Electrolyte) Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-14. Life-Cycle Energy Flow Chart for the Sodium-Sulfur (Ceramic Electrolyte) Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-15. Life-Cycle Energy Flow Chart for the Lithium-Metal Sulfide Electric Vehicle Battery (Million Btu per 100,000 Miles)

Figure I-16. Life-Cycle Energy Flow Chart for the Aluminum-Air Electric Vehicle Battery (Million Btu per 100,000 Miles)

with each other, several measures of performance have been defined. Each measure stresses a different aspect of performance, and a comparison based on these measures gives a good picture of each battery's strengths and weaknesses. Two basic classes of criteria for the comparison of batteries are (1) the total life-cycle energy use and, (2) the relative effectiveness of a battery in shifting energy use from scarce fuels such as gas and oil to relatively abundant fuels such as coal and nuclear power.

a. Total Life-Cycle Energy Use. The two measures of performance based on total energy use are:

- (1) Total Life-Cycle Energy Use - This measure is simply the sum of the investment energy and operational energy less any recycling credits that can be obtained. Its units are Btu/100,000 miles.
- (2) Equivalent Miles per Gallon - This measure converts the total life-cycle energy use into gallons of gasoline per mile. A value of 125,000 Btu/gallon is used as a conversion factor.

b. Fuel Shift Potential. The measures which relate the initial investment to the fuel shifted are somewhat more complex. In order to simplify the descriptions it is convenient to define two intermediate values.

The objective of a battery is to shift energy use from scarce fuels to abundant fuels by storing energy. The operational oil and gas shift is a measure of the amount of oil and gas usage that is shifted to other fuels. In computing the oil and gas shift, it is assumed that the battery in an electric vehicle replaces an internal combustion engine that achieves a fuel economy of 27.5 miles per gallon. It is also

assumed that there is a 10 percent refinery loss in gasoline production.

These assumptions give a base shift from petroleum of 505 million Btu per 100,000 miles due to the replacement of an internal combustion engine vehicle with an electric vehicle. Since some of the electricity used in the electric vehicle is produced from oil and gas, this amount of fuel must be subtracted to determine the actual fuel shift. This amount is 30.3 percent of the electric vehicle operational energy assuming the national electric generation fuel mix.

In short, the oil and gas shift can be given by the energy saved due to the replacement of an ICE-powered vehicle minus the oil and gas used to generate electricity for the electric vehicle.

The net investment energy is simply the investment energy minus the credit obtained for recycling. It, therefore, represents the net energy embodied in the battery for its production.

The two measures of performance based on the fuel shift potential of the battery are:

- (1) Oil and Gas Shift-to-Investment-Ratio - This number is the operational oil and gas shift divided by the net investment energy. It measures the ratio between the energy shifted from scarce fuels during the battery's life to the energy required to produce the battery.
- (2) Miles to Payback of Investment Energy - This measure is the number of miles that the electric vehicle must drive until the fuel shifted from

oil and gas (through the replacement of an ICE powered vehicle) just equals the net investment energy. It is computed by dividing the net investment energy by the oil and gas shifted for one mile of travel.

2. Results of Battery Comparisons

The results of the battery comparisons are shown in Table I-9. The information in this table reveals several facts concerning the batteries studied. The most important factor in determining the life-cycle energy use is the efficiency of the battery. Since investment energy varies between 4 and 12 percent of the total life cycle energy, it has much less of an effect on total life-cycle energy use than operational energy, which is controlled by the battery efficiency. The battery with the lowest life-cycle energy use is the sodium-sulfur (glass electrolyte) battery with an efficiency of 80 percent. The batteries with the highest life-cycle energy use are those with the lowest efficiencies, the zinc-chlorine battery and the aluminum-air battery.

In terms of the amount of fuel shifted from gas and oil to other fuels, all of the batteries are roughly equivalent except for the aluminum-air battery. The aluminum-air battery has a significantly lower shift of fuels for 100,000 miles because its operational energy use is higher over its lifetime. This again is due to the lower operational efficiency of the aluminum-air battery.

In terms of their performance on the oil and gas shift-to-investment ratio, the best batteries are the lead-acid and zinc-chlorine batteries which are built from materials not requiring large amounts of energy for their production.

TABLE I-9. COMPARISON BETWEEN ALTERNATIVE ELECTRIC VEHICLE BATTERIES

Battery	Operation Oil and Gas Shift (million Btu per 100,000 miles	Net Investment Energy (million Btu per 100,000 miles	Total Life- Cycle Energy Use (million Btu per 100,000 miles)	Equivalent Miles per Gallon	Oil and Gas Shift-to- Investment Ratio	Miles to Investment Payback
Nickel-zinc	420.5	24.5	303.4	41.2	17.2	5,830
Lead-acid	416.1	11.3	302.6	41.3	36.8	2,720
Nickel-iron	411.4	22.6	331.4	37.7	18.2	5,490
Zinc-chlorine	402.4	15.0	353.6	35.4	26.8	3,730
Sodium sulfur (glass electrolyte)	430.3	19.6	266.2	47.0	22.0	4,550
Sodium sulfur (ceramic electrolyte)	417.4	36.1	325.3	38.4	11.6	8,650
Lithium-metal sulfide	427.3	34.6	291.4	42.9	12.3	8,100
Aluminum-air	132.7	31.3	954.9	13.1	4.2	23,6

Due to its special characteristics, the aluminum-air battery is not directly comparable with the other battery systems. The aluminum-air system is designed to have a quick recharge capability through the replacement of aluminum fuel. The battery contains several complex systems and any attempt to scale the battery to the small size analyzed (18.6 kWh) for the other batteries results in a highly unrealistic battery design. For this reason the baseline system used by the battery developers was used. This design has an energy storage capacity of 70 kWh instead of the 18.6 kWh capacity assumed for the other batteries. While this change affects the operational energy use very little, it does cause the investment energy to be overstated (because the investment energy is roughly proportional to a battery's storage capacity). This problem in comparing the batteries is an unavoidable consequence of the varying economies of scale of the various batteries. If, for example, all of the batteries had been compared on a 70 kWh storage capacity per vehicle, the lower performance batteries such as the lead-acid battery would have been sized to an unrealistically large battery weight for the reference vehicle.

Although the aluminum-air battery achieves a much lower equivalent miles per gallon (13.1 equivalent miles per gallon) than the other batteries, it is still able to effect a substantial shift of energy use from oil and gas to other fuels. In addition, this battery has long range and rapid refuel characteristics that have previously only been obtainable with internal combustion engines burning petroleum based fuels.

A factor that is not considered in Table I-9 is the effect of different operating lives for the various types of systems. All battery types have been assumed to last for the life of a vehicle (100,000 miles). A battery which would last only half as long as this would require a doubling of

the investment energy to account for two battery systems for 100,000 miles.

While the life-cycle analysis gives an indication of the overall energy use of various battery systems, the life-cycle results should be considered as one piece of information when comparing batteries. Other information such as specific energy, specific power, cost, state of technological development, and battery life are also important in comparing battery systems.

II. INTRODUCTION AND GENERAL ASSUMPTIONS

The use of energy, particularly the use of petroleum and natural gas, is one of the major problems confronting the United States today. Energy storage systems such as batteries, while not causing a reduced demand for energy, can be an important tool for shifting energy demand from scarce fuels such as gas and oil to abundant fuels such as coal. The effective use of many renewable energy sources such as solar or wind also requires energy storage to match the intermittent supply of energy to demand. For these reasons, research and development is occurring in all areas of energy storage, including batteries, thermal, mechanical, and other storage concepts. One of the the major uses for these devices will be to power electric vehicles.

The purpose of this study is to analyze the life-cycle energy use for several batteries being developed for use in electric vehicles. The life-cycle analysis considers energy use in all phases of battery life, including raw materials extraction, materials processing, battery manufacturing, operation, recycling, and disposal.

The following batteries have been analyzed in this report.

- Nickel-zinc
- Lead-acid
- Nickel-iron

- Zinc-chlorine
- Sodium-sulfur (glass electrolyte)
- Sodium-sulfur (ceramic electrolyte)
- Lithium-metal sulfide
- Aluminum-air.

The following limitations and assumptions were made to simplify the analysis:

- Only primary energy is considered in this analysis. Primary energy is the energy directly associated with the process of mining, refining, manufacturing, charging, discharging, etc. All the electrical, oil, natural gas, or coal energy consumed by equipment, materials handling, heating, ventilating, air conditioning, lighting, etc., is considered to be primary energy. Not included in this analysis is the secondary energy associated with the building of factories and the manufacturing of tools or equipment used in the process of mining, refining, etc. In line with this limitation, the manufacturing of the AC/DC conversion equipment and the building of the power plant are also excluded from this study. However, the energy consumption from operating the power plant to generate electricity for charging the battery is included. When a storage system is compared with heat engine vehicles, similar energies (i.e., energy to build oil refineries and auto manufacturing plants) are also not considered.

- The efficiency of electric power generation is incorporated in the energy study. There is electrical power consumption both in the initial investment phase and in the operational phase. A power plant efficiency of 32.5 percent was assumed for the initial investment phase and the disposal phase. This efficiency is the approximate national average efficiency of electric power generation.

In the operational phase, a power plant efficiency of 40 percent was assumed. This assumption represents nighttime and weekend coal base-load electric power generation for battery charging.

- The energy consumed during each stage of the life cycle is represented by the net balance of input energy and output energy of that stage. Credit is given for usable energy resulting from a process and for coproducts. For example, a manufacturing step may show a negative energy consumption because the chemical reaction involved is exothermic, and a large quantity of energy generated by the process in the form of steam is normally reused in the plant or exported to outside users.
- Energy effects resulting from differences in battery life were ignored. It was assumed that all batteries will last for the 100,000-mile lifetime of the vehicle. This may not actually be true for the early models of the batteries that first emerge.
- Operational energy was determined assuming installation in an advanced electric vehicle design which would be typical of the type of vehicle which could be mass produced in the mid-1980s. Details

of the procedures used to evaluate operational energy use in an electric vehicle appear in Chapter III.

- National averages for 1978 were used in computing the fuel mix for electric generation. These values are 44.3 percent coal, 16.5 percent oil, 13.8 percent natural gas, 12.7 percent hydroelectric, 12.5 percent nuclear, and 0.2 percent other (1). This mix has been used for both manufacture and operation.
- In comparing electric vehicle batteries, the energy stored on board the vehicle was fixed at 18.6 kWh. This results in lighter batteries (those with high specific energy) having a lower energy use per mile and it insures that all comparisons are for vehicles with equivalent ranges. Factors such as varying power characteristics between batteries were not considered.
- Battery power characteristics were assumed to be adequate for the mission and to have no effect on energy withdrawal.

III. EVALUATION METHODOLOGY FOR ELECTRIC VEHICLES

In order to translate battery parameters (efficiency, energy density, etc.) into vehicle performance characteristics, it is necessary to develop a methodology to perform this function. Since the parameter of interest in this study is energy efficiency (kWh/mile) as opposed to acceleration and power requirements, a relatively simple model of the vehicle can be used. The procedure used in this study consists of two parts, the vehicle and the driving cycle. Vehicle parameters are obtained from existing vehicle specifications and projections of battery performance, and standardized driving cycles are obtained from vehicle testing standards. The role of the vehicle evaluation methodology is to predict vehicle energy use per mile from physical vehicle specifications and driving cycle parameters.

A. Reference Vehicle Parameters

In order for the evaluation of the batteries to be realistic for 1985 and later, vehicle parameters should be typical of vehicles in production at that time. Because the performance of currently available production electric vehicles is considerably lower than that expected in the future, characteristics of present vehicles are unsuitable. The General Electric/Chrysler ETV-1 experimental electric vehicle was chosen to represent 1985 vehicle technology. It was designed under a Department of Energy contract to demonstrate the performance possible in an electric vehicle using the most advanced components and materials now available. Features

include advanced aerodynamic design, lightweight aluminum body components, improved lead-acid battery design, state-of-the-art motor and power conditioning components, and regenerative braking. Engineering specifications for this vehicle are shown in Table III-1 (2).

TABLE III-1. CHARACTERISTICS OF THE
GENERAL ELECTRIC/CHRYSLER EXPERIMENTAL ELECTRIC VEHICLE

Curb Weight	1503 kg (3315 lb)
Battery Weight	490 kg (1080 lb)
Normal Payload	150 kg (330 lb)
Total Road Weight	1653 kg (3645 lb)
Coefficient of Rolling Resistance	0.0111
Drag Coefficient	0.30
Frontal Area	1.82 m ² (19.6 ft ²)
Charger Efficiency	.90
Battery Efficiency	.75
Drivetrain Efficiency*	.73

B. Electric Vehicle Driving Cycles

Energy efficiency of vehicles is highly dependent on the speed and acceleration of the vehicle. For most vehicles, increased stopping, starting, and high-speed driving increase the amount of energy used per mile driven. In order to

**Includes power conditioning unit, motor, and transmission.*

compare vehicles in a consistent way, standardized driving cycles have been developed by various groups including the Environmental Protection Agency and the Society of Automotive Engineers. These cycles are intended to simulate actual traffic conditions and to provide a basis for the comparison of vehicles.

The most common driving cycle used for vehicle fuel economy measurement is the EPA Federal Driving Cycle. This cycle is used for fuel economy and emissions testing of internal combustion engine vehicles and consists of an 11-mile simulated urban drive which is completed in 31 minutes. The advantage of using this cycle is that all new car models sold in the United States are tested according to this procedure, providing a large amount of information on the performance of various vehicles on this cycle. Also, because EPA figures used to rate fuel economy of new cars are determined using this cycle, the procedure has official recognition. The primary disadvantage of this cycle is that it is a complex simulation of urban traffic characteristics and is difficult and cumbersome to use.

The most commonly used cycles for the evaluation of electric vehicles are the SAE J227a electric vehicle test procedures. These cycles were developed specifically for the evaluation of electric vehicles and are considerably simpler than the EPA driving cycle. The cycles consist basically of an acceleration period, travel at constant speed, a coast phase, and a braking phase which brings the vehicle back to rest. There are four different cycles (A, B, C, and D), each corresponding to different applications and having different maximum speeds, ranging from 10 to 45 miles per hour. Since a future general purpose vehicle would be expected to travel in typical suburban traffic, the D cycle, with a maximum speed of 45 miles per hour, is the most logical choice for this study.

Because electric vehicles are most commonly tested using the SAE J227a cycles instead of the EPA Federal Driving Cycle, and because the SAE cycles are considerably simpler to compute, the SAE J227a "D" cycle was chosen for the evaluation of the electric vehicles. In using the driving cycle selected, it was assumed that all accelerations and decelerations are constant over the acceleration/deceleration period. The coast portion of the cycle was simulated by a constant deceleration of 1 mph/sec ($.447 \text{ m/sec}^2$).

Figure III-1 shows the time velocity profile of this cycle. The cycle consists of a constant acceleration of $.719 \text{ m/sec}^2$ for 28 seconds, followed by 50 seconds of travel at 20.1 m/sec , a deceleration of $.447 \text{ m/sec}^2$ for 10 seconds, and a deceleration of 1.74 m/sec^2 for 9 seconds at which time the vehicle comes back to rest. The entire cycle lasts 97 seconds and the vehicle travels 1,465 meters during this period for an average speed of 15.1 m/sec .

C. Methodology to Determine Vehicle Energy Use

The method described here uses the vehicle parameters discussed earlier to compute the energy efficiency (kWh/mile) that could be expected from a vehicle.

1. Road Load Energy Required

The forces acting on a moving vehicle are the air drag force, the rolling resistance in the tires, and the motive force supplied by the engine. Using Newton's law, the equation of motion for the vehicle becomes

Figure III-1. SAE J227a "D" Cycle (Modified)

$$F - mgC_r - 1/2 C_d A v^2 = ma \quad (1)$$

where:

m = mass of vehicle
 a = acceleration of vehicle
 g = acceleration due to gravity
 C_r = coefficient of rolling friction
 C_d = air drag coefficient
 A = frontal area of vehicle
 F = force supplied by the engine
 v = velocity.

The power used in moving the vehicle is the force times the velocity (v).

$$P = Fv = mav + mgC_r v + 1/2 C_d A v^3. \quad (2)$$

Energy (E_1) is the time integral of the power

$$E_1 = \int_0^t P(t) dt$$

which can be determined if the acceleration and velocity are known for the duration of the driving cycle. This energy (E_1) represents the amount of energy that must be supplied to the wheels of a vehicle in order to follow the driving cycle.

2. Effects of Regenerative Braking and Power Train Efficiencies

Normally the change in kinetic energy from vehicle deceleration is converted into heat in the brakes. Most advanced electric vehicles use regenerative braking to recover some of this energy. Also, vehicle power trains, batteries,

and charges have inefficiencies which must be accounted for in the formulation of a methodology to predict vehicle energy use.

Figure III-2 shows a schematic structure of the power train, battery, and charger of an electric vehicle. The drivetrain is assumed to include the power conditioning unit, motor, and transmission. As can be seen from the diagram, energy for charging the battery comes from the wall plug through the charging system and from regenerative braking. Energy from the wall flows through the charger, battery, and drivetrain while energy recovered through regenerative braking passes through the drivetrain, battery, and back through the drivetrain. Each power system component has energy efficiency associated with it (N_1 , N_2 , and N_3 in Figure III-2).

Based on Figure III-2 the following equations can be written to relate the energy supplied to the charger (E_6), the road load energy (E_1), and the energy supplied by regenerative braking (E_2), other intermediate energy quantities, (E_5 , E_4 , E_3), and the efficiencies of each subsystem (N_1 , N_2 , N_3):

$$E_5 = E_6 N_1 \quad (3)$$

$$E_4 = (E_5 + E_3) N_2 \quad (4)$$

$$E_1 = E_4 N_3 \quad (5)$$

$$E_3 = E_2 N_3 \quad (6)$$

Solving these equations for E_1 , E_2 , and E_6 gives:

N_1 , N_2 , N_3 ARE ENERGY EFFICIENCIES OF THE CHARGER, BATTERY AND POWER

Figure III-2. Electric Vehicle Power System Schematic

$$E_6 = \frac{(E_1 - E_2 N_3^2 N_2)}{N_1 N_2 N_3} \quad (7)$$

where:

- E_1 = Energy required at the wheels to propel the vehicle
- E_2 = Energy available at the wheels for regenerative braking
- E_6 = Energy required at the wall outlet
- N_1 = Efficiency of the battery charger
- N_2 = Efficiency of the battery
- N_3 = Efficiency of the vehicle power train (including the power conditioning unit, engine and transmission).

Since the main difference in vehicles powered by different batteries is in the vehicle mass, the effect of vehicle mass changes on vehicle energy use has been computed (Figure III-3). This graph shows the expected performance of a vehicle having the same parameters as the GE/Chrysler vehicle discussed earlier except that the total gross weight has been varied between 1,000 and 2,200 kilograms. The energy needed per mile of travel (over a J227a "D" cycle) increases linearly with increased vehicle mass. The energy needed per mile by the GE/Chrysler vehicle is shown on this graph to be .36 kWh/mile which agrees with other simulations of this vehicle (3).

Figure III-3. Variation in Energy Efficiency of Electric Vehicles with Changes in Vehicle Mass

3. Method of Comparing Vehicles

There are many ways to compare the energy performance of vehicles. One possibility is to hold the gross weight of the vehicle constant by holding the total weight of the battery pack constant. In this case, the performance (range and acceleration) of the vehicle changes drastically with batteries of different energy density, causing a simple comparison of energy use per mile to reflect only differences in the efficiency of the battery.

The technique used in this study is to hold the amount of energy stored on board constant. With this assumption, ranges of all the vehicles would remain approximately constant and the variations in energy use due to differing energy densities and efficiencies can be determined. The GE/Chrysler vehicle used as the prototype for this study can store 18.6 kWh in the battery using lead-acid batteries with an energy density of 38 Wh/kg.

Energy densities for advanced near-term batteries are shown in Table III-2. Also shown in this table are the weights for each type of battery that would result in 18.6 kWh of battery storage, and the performance (kWh/mile) of an electric vehicle using a battery of this weight.

The aluminum-air battery is not included in the table due to several unique characteristics. This battery operates through a reaction between aluminum, water, and air. In the current design, the battery would carry enough water for a 400-km trip and enough aluminum for 1600 km (four water cycles). The fact that new reactants are added periodically makes the definition of specific energy incompatible with the definition used for the other batteries. In addition, recharging is performed by recycling spent aluminum fuel at a central

**TABLE III-2. COMPARISON OF ENERGY EFFICIENCY OF
ELECTRIC VEHICLE BATTERIES**

<u>Reference Vehicle:</u>	GE/Chrysler ETV-1
Road Weight without Battery: (including payload of 150 kg)	1,163 kg (2,564 lb)
Energy Stored in Battery:	18.6 kWh
Drag Coefficient:	.30
Frontal Area:	1.82 m ² (19.6 ft ²)
Rolling Resistance Coefficient:	.0111
Charger Efficiency:	.90
Drivetrain Efficiency:	.72
Regenerative Braking	

<u>Battery Type</u>	<u>Efficiency</u>	<u>Specific Energy</u>	<u>Battery Weight</u>	<u>Total Vehicle Road Weight</u>	<u>Energy Use for SAE J227a "D" Cycle</u>
Reference Lead-Acid	.75	38 Wh/kg	490 kg (1,080 lb)	1,653 kg (3,645 lb)	.357 kWh/mile
Advanced Lead-Acid	.75	50 Wh/kg	372 kg (820 lb)	1,535 kg (3,385 lb)	.344 kWh/mile
Nickel-Zinc	.75	70 Wh/kg	266 kg (587 lb)	1,429 kg (3,151 lb)	.327 kWh/mile
Nickel-Iron	.70	60 Wh/kg	310 kg (684 lb)	1,473 kg (3,248 lb)	.362 kWh/mile
Zinc-Chlorine	.61	101 Wh/kg	184 kg (406 lb)	1,347 kg (2,970 lb)	.397 kWh/mile
Sodium-Sulfur (Glass Electrolyte)	.80	108 Wh/kg	172 kg (379 lb)	1,335 kg (2,944 lb)	.289 kWh/mile
Sodium-Sulfur (Ceramic Electrolyte)	.70	104 Wh/kg	179 kg (395 lb)	1,342 kg (2,959 lb)	.339 kWh/mile
Lithium-Metal Sulfide	.70	98 Wh/kg	190 kg (419 lb)	1,353 kg (2,983 lb)	.301 kWh/mile
Aluminum-Air		Aluminum-Air battery is not directly comparable--see text.			

processing plant so the standard definition of battery efficiency also does not apply. Since the battery does not have a capability to be recharged in the vehicle, regenerative braking is not used with this battery. The battery configuration analyzed is a 70 kWh module, weighing 503 lb. To power a vehicle this battery would have to produce 0.252 kWh/mile. This figure is energy input to the drivetrain and is not the wall energy given for the other battery/vehicle combinations.

The assumption that a battery does not need to be replaced during the 100,000-mile life of the vehicle removes the effect of cycle life differences between batteries. Although projections have been made for the expected life of developmental batteries, they are considerably less accurate than projections of specific energy and power. For this reason, the variations in battery life are not considered in the energy calculation, although expected life of the various batteries will be noted.

IV. NICKEL-ZINC BATTERY

A. Battery Description

The nickel-zinc battery is in its developmental phase and must achieve several milestones before it will be commercialized. The two major problems are separator stability and zinc electrode shape change. As separators fail and the zinc electrode changes shape and loses capacity, the life of the battery quickly deteriorates. It is expected that these problems will be overcome and that nickel-zinc batteries will compete with lead-acid batteries in the near term. This is because both the energy and power densities of the nickel-zinc battery exceed the capabilities of the lead-acid battery.

The electrode reactions of the cell are:

The complete cell reaction is:

The nominal voltage for this reaction is 1.63 volts per cell. Higher voltages are achieved by connecting individual cells in series.

A nickel-zinc battery is composed of a case, plates, separators, and electrolyte. The active materials in the battery are the positive plate, made primarily from nickel hydroxide; the negative plate, made from zinc oxide; and the electrolyte, which is a potassium hydroxide solution.

The case is generally a plastic or rubber container. Polypropylene is the favored substance for cases because it is light, chemically inert, and strong, but any material that is nonporous and resistant to the electrolyte may be used.

The positive electrode (plate) is made from a nickel substrate with a nickel hydroxide hydrate pressed onto it. The substrate may be sintered to make it physically stronger, enable higher discharge rates, and give it a longer life expectancy.

The negative electrode (plate) is made from zinc. Additives or binders provide mechanical strength needed in the cycling of the battery. Trace materials are added to the zinc to stabilize the shape-change problem of the zinc electrode.

Separator materials that are used in existing commercial batteries consist of various materials such as cellulosic membranes and polypropylene films. None of these will stand up in the nickel-zinc cell environment. Separators which will hold up in the cell environment and withstand more than 500 operating cycles are being developed. These separators, which may be organic or inorganic, must have microporous membranes, and a low resistivity.

The electrolyte currently being used in nickel-zinc cells is potassium hydroxide. The electrolyte generally has a 30 to 45 percent concentration which varies with the charge state of the battery. The battery will require periodic addition of water to make up losses caused by electrolysis.

Current developments of the nickel-zinc battery are designed specifically for the electric vehicle market. This market requires both a high energy density and a high cycle life.

B. Battery Component Weights and Performance

Several firms are engaged in the development of nickel-zinc batteries for electric vehicle use. Each of these manufacturers is using a different approach to the design of an advanced nickel-zinc battery. The Gould nickel-zinc battery was selected for use in this analysis because data on the materials requirements were readily available and because the Gould system uses a sintered nickel electrode. Inclusion of the sintering process insures that the energy requirements estimates for battery assembly are the maximum that could be expected in the production of any nickel-zinc battery.

The Gould battery consists of 32 cells operating at 1.63 volts per cell. The battery system is designed around modules consisting of eight cells each. The module is the basic battery unit upon which the analysis was based. Items such as straps which hold cells together and intercell connectors were, therefore, assumed to be a part of the battery while such items as trays and power cables were not. Component weights in percent of total battery weight are shown in Table IV-1 (4, 5).

Battery energy density for this battery was assumed to be 70 Wh/kg (31.7 Wh/lb), which represents the developmental goals for the nickel-zinc battery. Efficiency of the battery was assumed to be 75 percent. The cycle life goal is 800 cycles (6).

TABLE IV-1. MATERIALS BREAKDOWN OF THE
NICKEL-ZINC BATTERY (DISCHARGED)

<u>Component</u>	<u>Percent of Total Battery Weight</u>
Positive Assembly	38.2
Nickel	15.3
Nickel Hydroxide (60% of electrode weight)	22.9
Negative Assembly (Zinc Oxide)	28.6
Electrolyte	
Potassium Hydroxide	5.6
Water	12.5
Plastic	7.6
Copper	3.7
Steel	3.4
Other	0.4
TOTAL	100

C. Energy Investment

Energy investment includes all the energy used in raw materials acquisition and battery assembly. Based on the materials and processes associated with the nickel-zinc battery, an analysis of the manufacturing of the following materials and processes has been performed:

- (1) Nickel
- (2) Zinc oxide
- (3) Nickel hydroxide
- (4) Potassium hydroxide

- (5) Plastic
- (6) Copper
- (7) Steel
- (8) Other materials
- (9) Battery assembly.

Each analysis contains a brief description of the process involved and a quantification of the energy it uses. For analytical purposes, all data have been normalized to energy units per pound of battery.

1. Nickel

Approximately 71 percent of the nickel used in the United States is imported. The process described below is used in producing nickel from domestic sources. It has been assumed that foreign processes are similar.

Nickel ores are mined from the earth and sent through a beneficiation process which produces a nickel, iron, and copper concentrate. The concentrate is roasted in a limited supply of air and then smelted, resulting in a raw matte containing about 15 percent nickel. The raw matte is sent through a converter, then crushed and separated into nickel and copper concentrates. The nickel concentrate is pelletized and roasted into a nickel oxide. It proceeds to a refinery where it is made into impure metal and then refined using the electrolytic process.

For every pound of electrolytic nickel produced, mining and ore beneficiation consume 27,445 Btu and refining consumes 44,400 Btu, resulting in a total of 71,855 Btu per pound of nickel (7). Figure IV-1 translates these figures into Btu of energy per pound of a nickel-zinc battery. For every pound

of nickel-zinc batteries produced, 10,994 Btu of energy are necessary in providing the nickel which enters the battery manufacturing process.

Figure IV-1. Energy Used in Nickel Production for Nickel-Zinc Batteries (Btu/lb of Battery)(7)

2. Nickel Hydroxide

Nickel hydroxide, the nickel active material that is deposited on the electrode, is manufactured at the battery plant. Because the processes used to produce nickel hydroxide are complex, this material is treated in depth in this section.

Nickel hydroxide can be produced in many ways, however most of the techniques require that nickel be dissolved in an acid solution to form a nickel salt after which it is converted to nickel hydroxide through the action of a strong base such as sodium hydroxide. While sulfuric acid has been used to make nickel hydroxide for nickel-iron batteries in the past, the advanced electrodes used in nickel-zinc, nickel-cadmium, and other batteries are made by impregnation of the electrode with nickel nitrate salts.

Nickel nitrate is made from the solution of nickel into nitric acid, which is in turn manufactured from ammonia. Figure IV-2 shows the materials flow associated with the production of nickel hydroxide. The procedures and energy requirements to produce the three major raw materials, ammonia, nickel, and sodium hydroxide, can be determined from previous research. These appear in Appendix A (7,8,9). Appendix A also contains information on the preparation of nitric acid from ammonia (9).

To determine the amount of energy needed to produce nickel nitrate and nickel hydroxide, an estimation technique developed by Sommerfield and White was used (10). This method estimates the process energy from the heat of reaction. The equation which relates the two parameters is:

$$E = A_0 + A_1h + A_2h^2$$

where

E = process energy (Btu/lb)

h = heat of reaction (Btu/lb)

A_0, A_1, A_2 = empirical constants

$A_0 = 5,088$ Btu/lb

$A_1 = 3.356$

$A_2 = 2.505 \times 10^{-4}$ lb/Btu.

The heat for the reaction:

Figure IV-2. Materials Flow for the Production of Nickel Hydroxide

is -22.7 kcal/mole of nickel nitrate hexahydrate or 142.2 Btu/lb of nickel nitrate hexahydrate. Using the equation, the energy use can be estimated to be 4,616 Btu/lb of product. Since hydrogen is produced, a credit equal to the energy needed to produce hydrogen using steam reformation has been included (1,838 Btu/lb of nickel nitrate hexahydrate).

The production of nickel hydroxide from nickel nitrate occurs at the same time as the material is applied to the nickel electrode. Sodium hydroxide is used to cause this chemical change. The energy for this process can be estimated using the same procedure that was used for nickel nitrate hexahydrate.

The heat for the reaction:

is 4.1 kcal/mole or 78.7 Btu/lb of nickel hydroxide. Using the Sommerfield and White equation, the energy for this process is 5,354 Btu/lb of nickel hydroxide.

Appendix A lists the total amount of energy needed to produce a pound of nickel hydroxide. It is based on the energy use per pound of each intermediate material in the process and the required amounts of each material as shown in Figure IV-2. Figure IV-3 shows the energy use per pound of battery assuming that nickel hydroxide is 60 percent of the nickel electrode by weight.

Figure IV-3. Energy Use in Producing Nickel Hydroxide for Nickel-Zinc Batteries (Btu/lb of Battery)

3. Zinc Oxide

Zinc, lead-zinc, and lead ores are mined from the earth and sent through a beneficiation process which produces a concentrate containing about 50 to 60 percent zinc. The concentrate is then dried, roasted, and sintered, after which it proceeds to a reduction-volatilization-condensation process and emerges as high-grade zinc. The zinc is vaporized and mixed with preheated air which oxidizes it.

Several different processes are used to produce zinc and zinc oxide. These include the electrothermic process (35 percent of all zinc produced), the vertical retort process (20 percent of all zinc produced), and the electrolytic process (45 percent of all zinc produced). Zinc oxide is commonly made concurrently with zinc metal using the American process, although superior quality oxides are made from zinc metal using the French process. Since it was assumed that high-quality oxide is necessary for battery use, the energy consumption for the French process was used to determine the energy requirements for zinc oxide.

For every pound of zinc oxide produced, mining and beneficiation consume 5,478 Btu, refining consumes 23,019 Btu, and oxidizing consumes 8,255 Btu, resulting in a total of 36,742 Btu per pound of zinc oxide (8,9). Figure IV-4 translates these figures into Btu of energy per pound of a nickel-zinc battery. For every pound of nickel-zinc batteries produced, 10,509 Btu of energy are necessary in providing the zinc oxide which enters the battery manufacturing process.

Figure IV-4. Energy Use in Zinc Oxide (ZnO) Production for Nickel-Zinc Batteries (Btu/lb of Battery)(8,9)

4. Potassium Hydroxide

The main constituent of the electrolyte is potassium hydroxide. There is 0.056 pound of potassium hydroxide in one pound of battery. Potassium is derived from ores of potassium chloride which are treated by flotation. The ores are crushed, then suspended in a saturated brine from which clay is floated off the top while potassium chloride is separated from the bottom. The potassium chloride goes through an electrolytic process to produce potassium hydroxide which is then filtered for purity.

For one pound of potassium hydroxide, mining of potassium chloride requires 1895 Btu (7), electrolysis of the potassium chloride requires 9,524 Btu, and drying of potassium hydroxide requires 11,424 Btu (9). Since chlorine and hydrogen are produced as coproducts, some of the energy has been allocated to chlorine and a credit has been given for hydrogen generation. Energy used in potassium chloride mining and electrolysis has been allocated to the products based on the weight of each produced (61% to potassium hydroxide, 39% to chlorine).

The steam used in the process is used primarily for drying of potassium hydroxide so all of this energy is allocated to potassium hydroxide. It has also been assumed that steam is generated equally from coal, gas, and oil.

Figure IV-5 translates these figures into Btu of energy per pound of a nickel-zinc battery. For every pound of nickel-zinc batteries produced, 919 Btu of energy are used in providing the electrolyte which enters the battery manufacturing process.

Figure IV-5. Energy Use in Potassium Hydroxide Production for Nickel-Zinc Batteries (Btu/lb of battery)(5,7)

5. Plastic-Ethylene and Polyethylene

Most battery containers and separators are made of plastic. Other materials such as paper, rubber, glass, and organic materials are also used. High-density polyethylene has been selected for study to represent the plastic materials for the containers and separators.

Natural gas is the primary feedstock for polyethylene production. It is first converted into ethylene and then polymerized to form polyethylene. For every net ton of plastic produced, ethylene production consumes 39,520 Btu and polyethylene production consumes 7,555 Btu, resulting in a total of 47,275 Btu per pound of plastic (11). Figure IV-6 translates these figures into Btu of energy per pound of a nickel-zinc battery. For every pound of nickel-zinc batteries produced, 3,593 Btu are necessary in providing the plastic which enters the battery manufacturing process.

6. Copper

Copper ores are mined from the earth and sent to concentrators. The concentrators crush and grind the ore and pass it through a flotation process which yields a copper concentrate containing about 25 percent copper. The concentrate is then smelted into a matte which is refined using the electrolytic process, yielding copper with a purity of more than 99 percent.

For every net ton of copper produced, mining consumes 10,805 Btu, the concentrator process consumes 21,165 Btu, smelting consumes 19,111 Btu, and refining consumes 5,066 Btu, resulting in a total of 56,146 Btu (see Appendix A) per pound of copper (8). Figure IV-7 translates these figures into Btu of energy per pound of a nickel-zinc battery. For every pound of nickel-zinc batteries produced, 2,077 Btu of energy are necessary in providing the copper which enters the battery manufacturing process.

Figure IV-6. Energy Use in Plastic Production for Nickel-Zinc Batteries (Btu/lb of Battery)(11)

Figure IV-7. Energy Use in Copper Production for Nickel-Zinc Batteries (Btu/lb of Battery)(8)

7. Steel

The production of raw steel involves the following principal operations:

- (1) Mining and beneficiation of iron ore
- (2) Mining and preparation of the feed raw materials such as coal, limestone, dolomite, fluorspar, etc.
- (3) Iron ore agglomeration
- (4) Coke, lime, and oxygen production
- (5) Smelting iron ore into pig iron
- (6) Refining pig iron and scrap into steel
- (7) Steel finishing.

About 94 percent of the iron ore mined in the United States in 1970 came from open pit mines; the balance was from underground mines. The commercially important iron ores are

magnetite, hematite, and limonite. The average iron content of crude ore mined in the United States in 1970 was about 34 percent (12). Most of the crude ore must be subjected to various concentrating or beneficiation techniques in order to reduce transportation and smelting costs. These beneficiation techniques include crushing, screening, and separation by gravity, flotation, or magnetic means.

The concentrated ores are then agglomerated with a limestone-dolomite flux into coarse particles or pellets. The pellets are fed to the blast furnace with coke and various fluxes and heated to a high temperature. The net result of the series of reactions in the blast furnace is the production of pig iron. The pig iron contains unacceptable levels of carbon, silicon, manganese, phosphorus, and sulfur. To produce steel, all these elements have to be substantially removed. Stainless steels are made by adding significant quantities of nickel or chromium or both and small amounts of other metals.

Three major types of furnaces are used to refine pig iron into steel:

- (1) The open hearth furnace
- (2) The basic oxygen furnace
- (3) The electric arc furnace.

In 1973, the open hearth furnace accounted for 26.4 percent of the steel produced in the United States while the basic oxygen furnace accounted for 55.2 percent and the electric arc furnace accounted for 18.4 percent (8). The basic oxygen furnace has been used in estimating the energy requirement for steel production.

Molten steel from the steel furnaces is either poured into ingots and milled into slabs, billets, and blooms, or continuously cast and cut to shape. In the former case, the ingots are first heated to a uniform temperature in "soaking pits," furnaces kept at a controlled temperature of around 2300°F, prior to milling.

It requires 13,616 Btu to produce one pound of steel which results in an energy requirement of 463 Btu/lb of battery. This is shown in detail in Figure IV-8.

8. Other Materials

Other materials are used in the nickel-zinc battery in very small amounts. These materials include cobalt, organics, and trace amounts of materials used to improve battery stability. The scope of this study did not allow for a detailed analysis of these trace materials. Since these materials form such a small portion of the battery's total weight, it has been assumed that their contribution to the life-cycle energy use is negligible.

9. Battery Assembly

a. Process Used. Manufacturing of the nickel-zinc battery can be broken down into 4 parts: nickel electrode fabrication, zinc electrode fabrication, container molding, and assembly.

The manufacture of the sintered nickel electrode is the most complex process in battery manufacture. The first step in this process is to prepare the substrate, on which the active material is deposited from nickel powder. An

Figure IV-8. Energy Use in Steel Production for Nickel-Zinc Batteries (Btu/lb of Battery)(8)

extremely fine nickel powder, manufactured from nickel carbonyl vapor, is used for this purpose because it results in a highly porous substrate. Energy data on the manufacturing of carbonyl nickel is not available so the energy requirement for electrolytic nickel has been used.

The nickel powder is molded around a nickel grid and sintered at high temperatures to form a porous, rigid base that can receive the active material. Sintering occurs at a temperature of 800° to 1000°C (1470° to 1830°F) in a time period of 5 to 20 minutes (13).

After sintering, the active material is applied as nickel hydroxide $[\text{Ni}(\text{OH})_2]$. Nickel hydroxide can be applied via a thermochemical process or an electrochemical process. In the thermochemical process, the sintered substrate is dipped into molten nickel nitrate salt. After the nickel nitrate has penetrated the substrate, the plates are roasted in an oven. This decomposes the nickel nitrate into an intermediate compound. The intermediate compound is then treated with a sodium hydroxide solution which results in pure nickel hydroxide on the plate. After this process, the plates are washed in water and dried.

Nickel hydroxide can also be formed on the plates by dipping them into an aqueous solution of nickel salt and electrically converting the nickel nitrate, which penetrates the plates, to nickel hydroxide. In either case, the net reaction transforms nickel nitrate into nickel hydroxide and sodium hydroxide into sodium nitrate. The energy used to both manufacture nickel hydroxide and impregnate it on the substrate has been included in nickel hydroxide manufacturing.

Fabrication of the zinc electrode begins with mixing of zinc oxide with binders. This mixture is then

pressed onto a nickel grid to form a solid plate. The battery case is molded from plastic into the required shape. After all of the components are formed, they are assembled into finished batteries and the electrolyte is added. Nickel-zinc batteries of this type are built and shipped in a discharged condition with the active materials in the form of nickel hydroxide and zinc oxide. After the battery is completed it is "formed" by subjecting it to several charge-discharge cycles.

b. Energy Used for Manufacturing. The following assumptions were used in evaluating the energy used in the battery manufacturing process:

- (1) The processes involved in battery assembly and zinc electrode manufacturing are essentially similar to those of producing a lead-acid battery. Energy data for these processes have been obtained from a plant visit to a lead-acid battery factory.
- (2) Although production of nickel hydroxide occurs at the battery plant during manufacturing, the energy for this process has been included in the nickel hydroxide section.
- (3) Sintering energy has been estimated to use the same amount of energy as the nickel hydroxide preparation process (1,226 Btu/lb of battery).
- (4) All of the manufacturing energy has been assumed to be electric (heating from resistance furnaces).

- (5) Formation consists of three charge-discharge cycles.
- (6) The nickel plate is estimated to have an active material content of 60 percent Ni(OH)_2 by weight.

Table IV-2 shows the energy used in nickel-zinc battery manufacturing.

TABLE IV-2. ENERGY USED IN NICKEL-ZINC BATTERY MANUFACTURING
(Btu/lb OF BATTERY)

	Electric	Coal	Gas	Petroleum	Other	Total
Case and Separator Molding	146	0	43	5	0	194
Zinc Electrode*	78	0	259	29	0	366
Formation	1,331	0	0	0	0	1,331
Sintering	1,226	0	0	0	0	1,226
TOTAL	2,781	0	302	34	0	3,117

**Energy for nickel electrode is included in nickel hydroxide production.*

D. Operation

Operational energy includes the energy used to charge the batteries as well as losses in the electric generator, the AC/DC converter, and in the battery itself. As has been shown in Chapter III, the energy use (at the wall outlet) of

the reference vehicle powered by nickel-zinc batteries is .327 kWh/mile over the SAE J227a "D" driving cycle. Over a lifetime of 100,000 miles, this vehicle would consume 32,700 kWh of electricity. If it is assumed that charging is done during off-peak periods from base-load fossil-fueled generating plants, the primary energy used for the operation of the vehicle is 279 million Btu. This assumes that the efficiency of generating and transmitting electricity from base-load plants is 40 percent.

E. Recycling

The amount of recycling possible in the nickel-zinc system has not been determined; however, reclamation of the nickel, zinc, and copper in these batteries could be feasible. In order to estimate the energy savings due to recycling of the battery components, the following assumptions have been made:

- (1) Half of the nickel, zinc, and copper is recovered from the battery.
- (2) The processes used in nickel and zinc recycling use half of the energy needed for production of these metals from virgin sources. Energy for the recycling of copper is based on Reference 14.

Under these assumptions, the recycling of nickel and zinc results in an energy credit of 25 percent of the energy originally used to produce them. This credit amounts to 5,389 Btu per pound of battery for nickel, 2,645 Btu per pound of battery for zinc, and 976 Btu per pound of battery for copper.

F. Total Life-Cycle Energy Use

As stated in Chapter III, Table III-2, the reference vehicle with nickel-zinc batteries installed contains 266 kg (587 lb) of batteries. Based on the information presented earlier in this chapter on energy per pound of battery, the amount of energy needed to produce 587 lb of battery is 29.7 million Btu. Vehicle operation uses 279 million Btu and recycling results in a credit of 5.6 million Btu. Details of the life cycle totals appear in the Executive Summary.

V. THE LEAD-ACID BATTERY

A. Battery Description

The lead-acid battery has existed for over 100 years and has been refined to the point that today it is one of the most inexpensive, most reliable, and most widely used storage batteries. It contains plates made of sponge lead (Pb), which is a porous form of lead, and lead peroxide (PbO₂). These plates are immersed in a solution of sulfuric acid (H₂SO₄), which acts as the electrolyte for the battery. During discharge, the positive plate is changed from lead peroxide into lead sulfate (PbSO₄). At the negative plate, the sponge lead is oxidized into lead sulfate. While charging, the processes are reversed and the lead sulfate at both plates is changed back into sponge lead and lead peroxide. Figure V-1 shows the charging-discharging process. The overall reaction for this process is (15):

The nominal voltage for this reaction is two volts per cell. Higher voltages are achieved by connecting individual cells in series.

A lead-acid battery is composed of a case, plates, separators, and sulfuric acid (Figure V-2). The active materials in a battery are the positive plate (made from lead peroxide), the negative plate (made from lead), and sulfuric acid. The lead materials are formed from a paste composed of lead oxides and water.

1 CHARGED CELL

MAXIMUM SULFURIC ACID—MINIMUM WATER

2 CELL DISCHARGING

3 CELL DISCHARGED

MINIMUM SULFURIC ACID - MAXIMUM WATER

4 CELL CHARGING

ELECTROLYTE BECOMING STRONGER

Figure V-1. Charging and Discharging Process
(Source: ESB, Inc.)

Figure V-2. Components of a Lead-Acid Battery.

Pastes are made from lead oxide and electrochemically converted into lead and lead peroxide after the pastes have been bonded to the grids. This process produces plates superior to those formed from lead peroxide and lead (16). The paste material is highly porous, giving the battery a large surface area. Since the reactions of the battery occur at the interface of the solid and liquid materials, a large surface area is essential for high capacity and power output.

The pastes used in battery manufacture are structurally very weak and are poor conductors of electricity. In order to provide an even distribution of electricity to the paste and support the paste structurally, a grid made from metallic lead is used. The grid consists of a lattice, cast from lead, which holds the paste in the spaces between the lattice-work. Antimonial lead has been the traditional material for lead grids, although recently other alloys, most notably calcium-lead alloys, have been used for grid material. These alloys have been developed primarily to reduce the decomposition of the water in the battery while charging. Electrolysis losses are a major reason why conventional batteries must have water added periodically (17). The major application of lead-calcium grids has been in "maintenance free" automotive batteries which do not require periodic water addition.

In order to keep the positive and negative plates from contacting each other and short circuiting the battery, thin insulators called separators are used. These separators, which may be made from glass, plastic, wood, asbestos, rubber, or fiberglass, are porous and allow the electrolyte to pass freely between the plates while preventing physical contact between the positive and negative plates. The separators also help to hold the active material onto the plates (loss of active material from positive plates is a common cause of battery failure).

Sulfuric acid forms the remaining portion of the active material. Sulfuric acid is usually diluted so that when the battery is fully charged, the specific gravity is 1.28 (37.5 percent sulfuric acid by weight). As the battery discharges, the sulfuric acid reacts with the lead materials to form lead sulfate, and the electrolyte becomes less acidic until, when the battery is fully discharged, the electrolyte is mostly water and the specific gravity approaches 1.12 (15).

The plates and the sulfuric acid are contained in a plastic or rubber case. Polypropylene is the favored substance for cases because it is light, chemically inert, and strong, but any material that is nonporous and resistant to sulfuric acid may be used.

Batteries must be used in conjunction with a battery charger, which supplies electrical energy at the proper voltage to charge the battery quickly without causing damage to the battery. Proper charging of a lead-acid battery must occur at rates comparable to the discharge rate of the battery; for most batteries, this means a charging period of over eight hours. Typically some energy is lost by the charger due to resistance and the conversion of electrical energy to a form that can be used to charge the battery. Charger efficiencies range from 80 to 90 percent (17).

B. Battery Component Weights and Performance

The most common use for lead-acid batteries is for starting, lighting, and ignition (SLI) use in automobiles. These batteries are not designed for extensive deep-cycle use and can only accept about 200 full charges before wearing

out. Considerably more expensive batteries are made for industrial use. These batteries, which have extended life (2000 charge-discharge cycles), are used primarily to power small forklifts and trucks used in warehouses and manufacturing plants. Other types of batteries are used for emergency power sources for buildings, marine use, electric vehicles, and powering of equipment in locations away from conventional electricity sources.

The electric vehicle lead-acid battery has a different material composition than a lead-acid battery designed for stationary or other industrial purposes. Table V-1 shows a comparison between the materials composition of an industrial lead-acid battery (C&D C75-15) and an advanced electric vehicle lead-acid battery. The electric vehicle battery component weights were obtained from Globe-Union projections of their advanced lead-acid battery design (18).

TABLE V-1. COMPARISON OF INDUSTRIAL AND ELECTRIC VEHICLE LEAD-ACID BATTERIES

	<u>Percent by Weight</u>	
	Industrial Battery	Electric Vehicle Battery
Lead	28	17
Lead Oxides	38	46
Electrolyte		
Sulfuric Acid	7	11
Water	11	18
Plastics	16	4
Other	0	4
TOTAL	100	100

The major differences in design are due to the fact that the electric vehicle battery is designed to be lighter and therefore has a higher percentage of active materials (lead

oxide and electrolyte). The battery has been assumed to have an energy storage density of 50 Wh/kg, an efficiency of 75 percent, and a cycle life of 750 cycles. These figures represent goals for the lead-acid development program (6).

C. Energy Investment

Energy use data for the major materials and processes associated with production of the lead-acid battery follow including sulfuric acid, lead, plastic and battery manufacturing. Recycling of used materials is included in the analysis of lead production.

1. Sulfuric Acid

Sulfuric acid comes from several different sources. Fifty-two percent of the sulfuric acid consumed is derived from mined sulfur, 29 percent comes from recovered elemental sulfur as a by-product of other industries, and the remainder comes from other sulfurous materials and smelter gas (sulfur dioxide) (8). The sulfur mining process consumes 953 Btu/lb of sulfuric acid (8). This energy is normally recovered by a waste heat boiler in the form of steam, of which approximately 40 percent is consumed outside the plant and 60 percent is consumed inside the plant. The net energy balance of sulfuric acid production from mined sulfur is 415 Btu/lb. The net energy consumption for the production of sulfuric acid is 18 Btu/lb (8). For the .107 lb of sulfuric acid needed for one pound of battery, 2 Btu are required to produce sulfuric acid (Figure V-3).

Figure V-3. Energy Used in the Production of Sulfuric Acid for Lead-Acid Batteries (Btu/lb of Battery)(8)

2. Lead

Lead and lead oxides account for 63 percent of the weight of a lead-acid battery. Lead production from ore requires 13,390 Btu/lb (7) and production from secondary sources requires 4,825 Btu/lb (14). The total energy requirement for lead in the lead-acid battery is 5,637 Btu per pound of battery (Figure V-4). In addition, 2,350 Btu/lb is required to produce lead oxides for the battery.

The electric vehicle lead-acid battery has been estimated to require 55 percent of its lead from primary sources and 45 percent from recycled sources. The basis for this estimate is that the lead used for grid material consists of 90 percent recycled lead while active materials use only 30 percent recycled lead. This is due to the fact that the active material must be made of a higher grade lead which is more easily obtained from primary sources.

3. Plastics

Most lead-acid battery containers and separators are made from plastic. While polypropylene is favored for these components, polyethylene has been used in this analysis because of its chemical similarity to polypropylene and the fact that more detailed data are available for the energy requirements of polyethylene production. Polyethylene requires 47,275 Btu/lb for its production (11). For 0.04 lb of polyethylene per lb of battery, this results in an energy use of 1,891 Btu/lb of battery (Figure V-5).

Figure V-4. Energy Used in the Production of Lead and Lead Oxide for a Lead-Acid Battery (Btu/lb of Battery)

Figure V-5. Energy Used to Produce Polyethylene for a Lead-Acid Battery (Btu/lb of Battery)(11)

4. Manufacturing

The energy used in lead-acid battery manufacturing can be divided into five major processes. These processes are grid manufacturing, paste manufacturing, plate manufacturing, plastic molding, and plate formation/battery assembly. The data for energy used in these processes were obtained from a lead-acid battery manufacturer and are shown in Table V-2. The formation process, in which the paste material is oxidized and reduced to lead dioxide and sponge lead, consumes almost half of the manufacturing energy. Grid manufacturing, which requires casting of the lead grid, uses the next largest portion of the manufacturing energy. A total of 3,790 Btu/lb is required to manufacture one pound of lead-acid battery.

TABLE V-2. ENERGY USED IN THE MANUFACTURE OF A LEAD-ACID BATTERY (Btu/lb OF BATTERY)

	Electric	Coal	Gas	Oil	Other	Total
Grid Manufacturing	78	0	948	107	0	1,133
Paste Manufacturing*	92	0	312	10	0	414
Plate Manufacturing	78	0	259	29	0	366
Plastic Molding	146	0	43	5	0	194
Assembly & Formation	1,251	0	388	44	0	1,683
TOTAL	1,645	0	1,950	195	0	3,790

**Includes lead oxide manufacturing.*

D. Operation

As has been shown in Chapter III, the energy use (at the wall outlet) of the reference vehicle powered by advanced lead-acid batteries is .344 kWh/mile over the SAE J227a "D" driving cycle. Over a lifetime of 100,000 miles, this vehicle would use 34,400 kWh of electricity. If it is assumed that charging is done during off-peak periods from baseload fossil-fueled generating plants, the primary energy used for the operation of the vehicle is 293.4 million Btu per 100,000 miles. This assumes that the efficiency of electric generation and transmission is 40 percent.

E. Recycling

A substantial lead recycling industry exists today and approximately 50 percent of all lead produced is from secondary sources. Much of this recovered lead comes from old batteries. Since a substantial recycling industry already exists, no explicit credits were allocated for recycling of lead-acid batteries. The credit has been included in the lead material analysis, however, by including secondary lead as a major source of battery material.

F. Total Life-Cycle Energy Use

The reference vehicle powered by advanced lead-acid batteries contains 372 kg (820 lb) of batteries, which results in a total energy investment of 9.2 million Btu per 100,000 miles. Operational energy for this battery is 293.4 million Btu per 100,000 miles.

VI. THE NICKEL-IRON BATTERY

A. Battery Description

The nickel-iron battery was originally developed by Thomas Alva Edison. Since that time it has been important for traction and standby applications. Recent emphasis on research and development of batteries suitable for electric vehicles has resulted in new design concepts for nickel-iron batteries which use different types of electrodes and manufacturing techniques than the Edison cells. These new nickel-iron cells are the subject of this study.

The nickel-iron battery uses an alkaline electrolyte and is similar in operation to nickel-zinc and nickel-cadmium storage batteries. In a fully charged nickel-iron cell the active anode material is nickel oxyhydrate (NiOOH), the active cathode material is metallic iron sponge (Fe), and the electrolyte is potassium hydroxide (KOH) and water (H_2O) with the addition of lithium hydroxide (LiOH) (13). The electrolyte does not take part in the chemical reaction, its composition being unchanged. However, it does function as a transferring agent by accepting hydroxide ions at the anode and depositing them at the cathode during the discharge cycle. During the charge cycle this action is reversed. The chemical reactions during discharge produce intermediate transitory compounds, the end result being the formation of nickel hydroxide, $\text{Ni}(\text{OH})_2$ on the anode and the formation of iron hydroxide, $\text{Fe}(\text{OH})_2$ on the cathode. The end formula for the chemical reaction in the cell, neglecting the intermediate reactions, is (13):

The nominal voltage for a battery under load is 1.2 V. The actual voltage at any time depends, however, on (1) whether the cell is open-circuited, discharging, or being charged, and (2) on the current rate and state of charge. The open circuit voltage varies between 1.25 and 1.35 V.

The nickel-iron battery is considered by DOE as one of the principal near-term alternatives to the lead-acid battery for electric vehicle applications. Its major advantage is its long cycle life. Westinghouse and Eagle-Picher are participating in the DOE program (managed through Argonne National Laboratory) to develop the nickel-iron battery. At the time of the preparation of this life-cycle energy analysis, the most detailed information on the components and manufacturing processes of the nickel-iron battery were those supplied by Westinghouse. Therefore, the energy analysis in this report applies to the nickel-iron battery as it is being developed for an electric vehicle by the Westinghouse Corporation.

The Westinghouse nickel-iron battery (19) is an 84-cell design, with a nominal voltage of 100.8 V and a rated capacity of 250 Ahr per cell. The battery consists of 14 modules, each of which is a 6-cell unit weighing 64 lbs. Figure VI-1 shows a diagram of the module design.

Each cell is rated at 250 Ahr at 1.2V DC and consists of a nickel electrode, an iron electrode, electrolyte, and hardware. The nickel electrode is a porous, nickel-plated

Figure VI-1. Module Design (19)

steel substrate of steel wool into which the active material (nickel oxyhydrate) is directly formed. The use of a steel substrate as the current collector provides a cost advantage over the use of nickel. Nickel active material is electrochemically deposited on this substrate.

The iron electrode is a porous form of iron that is made by the reduction of ferric oxide (Fe_2O_3) in the presence of hydrogen. The heat associated with the reduction process also binds the iron powder into a solid electrode.

The electrolyte is a solution of lithium hydroxide and potassium hydroxide with a density of 1.27 g/cm^3 at 25°C . The separator, made from polyethylene, is a combination of a barrier and an absorber material. The cell case is manufactured out of plastic. Polyphenylene oxide is currently used for the case, although other plastics, such as polyethylene, polypropylene, and polyvinyl chloride could be used.

B. Battery Component Weights and Performance

Because there is more information available on the Westinghouse battery than the Eagle-Picher battery with regard to the components in its manufacture, the life-cycle energy usage of the Westinghouse nickel-iron electric vehicle battery is developed in this report. The battery system is designed around six-cell modules. For the purposes of this life-cycle energy study, the module was considered to be the basic unit of analysis. Items which bind the cells together into modules, mechanically and electrically, are therefore assumed to be part of the battery. Items such as trays and power cables are not considered to be part of the battery.

Table VI-1 gives a breakdown of the weights of the module in terms of percent of total battery weight.

The Westinghouse cell uses a nickel electrode which consists of nickel oxyhydrate (NiOOH) which is electrochemically deposited on a substrate made from nickel-plated steel wool. The negative electrode is manufactured from iron oxide and consists of porous iron. The electrolyte consists of potassium hydroxide (KOH) and a small amount of lithium hydroxide (LiOH).

Although the nickel-iron battery is composed of the materials shown in Table VI-1, many of these materials are obtained by the manufacturer in different form. In addition, the battery manufacturing process requires the use of materials that do not become a part of the finished battery. Table VI-2 lists all of the materials that form a part of the nickel manufacturing process in pounds per pound of finished battery. This material list has been used in the calculation of the initial energy investment for the battery.

It has been assumed that the battery achieves a specific energy of 60 Wh/kg (132.3 Wh/lb) an efficiency of 70 percent and a cycle life of 2,000 cycles. These figures represent goals for the current research and development effort (6).

C. Energy Investment

Energy investment includes all of the energy used in raw materials acquisition and battery manufacturing. Analyses of the following materials and processes appear in this section:

TABLE VI-1. MATERIALS BREAKDOWN OF A NICKEL-IRON
ELECTRIC VEHICLE BATTERY

<u>Material</u>	<u>Percent by Weight</u>
Nickel	16.4
Hydrogen and oxygen in the nickel active material	8.0
Iron (active material)	13.1
Steel	29.2
Copper	3.5
Plastics	4.2
Electrolyte:	
Potassium Hydroxide	6.1
Lithium Hydroxide	1.2
Water	18.3
TOTAL	100.0

TABLE VI-2. MATERIALS USED IN PRODUCTION OF NICKEL-IRON
BATTERIES (ELECTRIC VEHICLE APPLICATION)

<u>Material</u>	<u>lb/lb of Battery</u>
Nickel	.164
Nickel Nitrate	.008
Nickel Sulfamate	.001
Steel	.292
Potassium Hydroxide	.061
Lithium Hydroxide	.012
Plastic	.042
Copper	.035
Ferric Oxide	.175
Process Materials	.064
Cobalt Nitrate	.007

- (1) Nickel
- (2) Steel
- (3) Potassium hydroxide
- (4) Lithium hydroxide
- (5) Plastics
- (6) Ferric oxide
- (7) Copper
- (8) Nickel nitrate and cobalt nitrate
- (9) Process materials
- (10) Battery manufacturing processes.

Energy use for each material in the investment and recycling/disposal phases are given in Btu per pound of battery.

1. Nickel

Approximately 71 percent of the nickel used in the United States is imported. The nickel production process described below is used for the production of nickel from domestic sources. In computing the energy requirement for nickel for the battery, all of the nickel in the battery has been assumed to have been produced by this process.

Nickel ores are mined from the earth and sent through a beneficiation process which produces a nickel, iron, and copper concentrate. The concentrate is roasted in a limited supply of air and then smelted, resulting in a raw matte containing about 15 percent nickel. The raw matte is sent through a converter, then crushed and separated into nickel and copper concentrates. The nickel concentrate is pelletized and roasted into a nickel oxide. It proceeds to a refinery where it is made into impure metal and then refined using the electrolytic process.

For every net ton of electrolytic nickel produced, mining ore beneficiation consumes 55×10^6 Btu and refining consumes 89×10^6 Btu, resulting in a total of 144×10^6 Btu/ton or 71,855 Btu per pound of nickel (7). The 0.164 lb of nickel needed to produce one pound of battery requires 11,784 Btu (Figure VI-2).

Figure VI-2. Energy Used in Nickel Production for Nickel-Iron Batteries for Electric Vehicles (Btu/lb of Battery) (7)

2. Steel

Steel is used primarily in the form of steel wool, which holds the active material and conducts current within the electrode. One pound of finished battery requires 0.292 lb of steel. Steel is produced from ore by first producing pig iron in a blast furnace and refining the pig iron into steel. A more detailed description of the steelmaking process appears in Chapter IV.

A total of 13,616 Btu is required for the production of one pound of steel (8). For the 0.292 pound of steel in one pound of nickel-iron battery, 3,976 Btu are required (Figure VI-3).

3. Potassium Hydroxide

Potassium hydroxide is the primary material used in the battery electrolyte. In addition, potassium hydroxide is used during formation of the nickel electrode, a battery manufacturing process. The standard concentration of potassium hydroxide used for these purposes is 25 percent (13), which results in a potassium hydroxide use of 0.061 lb per lb of battery.

Potassium is derived from ores of potassium chloride which are treated by flotation. The ores are crushed, then suspended in a saturated brine from which clay is floated off the top while potassium chloride is separated from the bottom. The potassium chloride goes through an electrolytic process to obtain potassium hydroxide and is then filtered for purity. Hydrogen and chlorine are produced as coproducts in this process.

Potassium hydroxide requires 16,405 Btu/lb for its production (8,9). Figure VI-4 shows the process used in producing potassium hydroxide and the energy for one pound of battery.

4. Lithium Hydroxide

Lithium hydroxide, which is used to improve the electrochemical properties of the electrolyte, is produced as lithium

Figure VI-3. Energy Used in Steel Production for Nickel-Iron Batteries (Btu/lb of Battery)(8)

**Figure VI-4. Energy Used to Produce Potassium Hydroxide
for a Nickel-Iron Electric Vehicle Battery
(Btu/lb of Battery)**

hydroxide monohydrate ($\text{LiOH} \cdot \text{H}_2\text{O}$) from brines and pegmatite ore. A total of 0.012 lb of lithium hydroxide monohydrate is needed for battery production.

The primary source of lithium is pegmatite, which contains spodumene, a lithium-bearing mineral. The production process is very complex, but it can be broken into the main steps of ore concentration, chemical production of lithium oxide, and production of lithium hydroxide. Ore concentration consists of mining, crushing, heavy media separation, grinding, flotation, dewatering, and drying. A credit is given to by-product spodumene which is used directly in ceramic applications.

Dry spodumene concentrate is sent to a chemical plant for conversion into lithium hydroxide. The major process is a calcining operation which results in soluble lithium oxide (Li_2O) being separated from the other insoluble minerals. Upon evaporation, crystals of lithium hydroxide monohydrate are formed. The production process consumes 70,625 Btu/lb of lithium hydroxide monohydrate. This figure is accurate to $\pm$ 20 percent. Figure VI-5 shows the process for producing lithium hydroxide and the energy required per pound of nickel-iron battery (20).

5. Plastics

For each pound of battery, 0.042 pounds of plastic are required. Plastic is used in the nickel-iron battery for the container and the separator. Currently, polypropylene is used for the separator and polyphenylene oxide is used for the case. Energy data for these two types of plastic are not readily available; however, a considerable amount of information exists for other types of plastic such as polyethylene and polyvinyl chloride (PVC).

Figure VI-5. Energy Used in Producing Lithium Hydroxide for Nickel-Iron Electric Vehicle Batteries (Btu/lb of Battery)(20)

Energy values for polyethylene have been used in this analysis. Polyethylene is produced from natural gas and petroleum feedstocks. Ethylene is produced first and this material is polymerized to produce polyethylene. Polyethylene production requires 47,275 Btu per pound of product (11). Figure VI-6 shows the steps in polyethylene production and the energy needed to produce 0.042 lb of polyethylene (5,011 Btu/lb of battery).

6. Ferric Oxide

Ferric oxide (Fe_2O_3) is the raw material used to produce the iron electrode in the battery. For each pound of finished battery, 0.175 lb of ferric oxide is required. Ferric oxide is produced from pig iron through the following steps (13):

- (1) Pig iron is dissolved in a 20 to 25 percent solution of sulfuric acid, producing ferrous sulfate (FeSO_4) and hydrogen gas.
- (2) The ferrous sulfate solution is filtered, recrystallized, and dried. The sulfuric acid recovered at this time is reused to dissolve more pig iron. The resulting material from this process is ferrous sulfate monohydrate ($\text{FeSO}_4 \cdot \text{H}_2\text{O}$).
- (3) The dried ferrous sulfate is roasted producing ferric oxide via the reaction:

The gaseous oxides of sulfur are absorbed and used to produce more sulfuric acid for use in dissolving pig iron.

Figure VI-6. Energy Used to Produce Plastic
(Polyethylene) for Nickel-Iron Batteries
(Btu/lb of Battery)(11)

Figure VI-7 is a process flow diagram showing the materials flow to each process. Note that although sulfur is usually recycled back to sulfuric acid in the plant, sulfuric acid has been shown as a raw material with no recycling. As will be shown, sulfuric acid uses very little energy in production so this assumption does not affect the final results.

Energy use for the entire process can be broken down into five parts:

- (1) Sulfuric acid production
- (2) Pig iron production
- (3) Ferrous sulfate production
- (4) Ferric oxide production
- (5) Credit for hydrogen generation.

The energies used to produce sulfuric acid and pig iron are 18 Btu/lb for sulfuric acid, 11,557 Btu/lb for pig iron (8). Details of these processes are shown in Appendix A. The credit for hydrogen is the amount of energy required to produce hydrogen by the steam reformation process (see Section C, 8 of this chapter). This value is 183,863 Btu/lb of hydrogen.

Energy use data for the production of ferrous sulfate and ferric oxide are not directly available. For this reason, an estimation technique developed by Sommerfield and White (10) has been used for these portions of the ferric oxide manufacturing process. This technique relies on an empirical correlation between actual energy use for chemical processes and the theoretical heat of reaction for the process. The correlation is in the form of a polynomial:

Figure VI-7.. Materials Flow for Production of Ferric Oxide

$$E = A_0 + A_1 h + A_2 h^2$$

where:

E = estimated energy use for the process (Btu/lb)

h = heat of reaction (Btu/lb of product)

A_0, A_1, A_2 = empirically determined constants

$$A_0 = 5,088 \text{ Btu/lb}$$

$$A_1 = 3.356$$

$$A_2 = 2.505 \times 10^{-4} \text{ lb/Btu.}$$

The chemical reaction for the production of ferrous sulfate is:

The heat of reaction for this process is -9.3 kcal/gmole of ferrous sulfate or -106 Btu/lb of ferrous sulfate. Using the Sommerfield and White procedure, the energy use for this process is 4,735 Btu/lb of ferrous sulfate.

The chemical reaction for the production of ferric oxide from ferrous sulfate is:

The heat of reaction for this process is 80.7 kcal/gmole or 908 Btu/lb of ferric oxide. Applying this figure to the Sommerfield and White equation gives an energy use for this process of 8,342 Btu/lb of ferric oxide.

The Sommerfield and White technique does not give any information concerning fuel type used in the process. Since the primary energy use in this process is heating, however, it has been assumed that the energy used for these two processes is derived equally from gas and oil.

Table VI-3 summarizes the energy use in producing ferric oxide from raw materials. A total of 20,878 Btu is needed to produce one pound of ferric oxide. Figure VI-8 shows the energy to produce the 0.175 lb needed for one pound of battery.

TABLE VI-3. ENERGY TO PRODUCE FERRIC OXIDE FROM RAW MATERIALS (Btu/lb OF FERRIC OXIDE)

Material	Amount (lb)	Btu/lb of Material	Btu/lb of Fe_2O_3
Sulfuric Acid	1.23	18	22
Pig Iron	0.70	11,557	8,090
FeSO_4	1.905	4,735	9,020
Fe_2O_3	1.00	8,342	8,342
Hydrogen Credit	0.025	(183,863)	(4,596)
TOTAL			20,878

7. Copper

Copper is used in the battery for electrical connectors between battery cells and modules. The copper requirement for a battery is 0.035 lb per pound of battery. The great majority of copper used in the United States is produced in the United States. Domestic copper is mined primarily from sulfide ores (8). The important ores of copper are sulfides of copper, copper-molybdenum, copper-zinc, and copper-lead zinc.

After being mined, the copper ores are sent to concentrators. The concentrators crush and grind the ore and

Figure VI-8. Energy to Produce Ferric Oxide for Use
in a Nickel-Iron Battery for Electric Vehicles
(Btu/lb of Battery)

pass it through a flotation process which yields a copper concentrate containing about 25 percent copper. The concentrate is then smelted into a matte which is refined using the electrolytic process, yielding copper with a purity of more than 99 percent.

For every net ton of copper produced, mining consumes 21.6×10^6 Btu, the concentrator process consumes 42.3×10^6 Btu, smelting consumes 38.2×10^6 Btu, and refining consumes 10.1×10^6 Btu, resulting in a total of 112.3×10^6 Btu per ton or 56,146 Btu per pound of copper (8). For the 0.035 lb needed for one pound of battery, the energy requirement is 1,965 Btu (Figure VI-9).

8. Nickel Nitrate and Cobalt Nitrate

Small amounts of nickel nitrate and cobalt nitrate are used during the electroprecipitation process which deposits active nickel material on the positive electrode. The amounts of these materials needed for one pound of battery are 0.007 lb (cobalt nitrate) and 0.008 lb (nickel nitrate). They are used in a hexahydrate form and the chemical formulas are $\text{Co}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ and $\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$. Nickel nitrate and cobalt nitrate are formed by dissolving the metals in solutions of nitric acid. The reactions which occur are:

The resulting aqueous solutions are dried to form the hexahydrate form of the compounds. Nitric acid is manufactured from ammonia.

Figure VI-9. Energy Used in Copper Production for Nickel-Iron Batteries (Btu/lb of Battery)(8)

The steps involved in the manufacture of cobalt nitrate or nickel nitrate are:

- (1) Production of nickel and cobalt
- (2) Production of ammonia
- (3) Production of nitric acid from ammonia
- (4) Production of nickel nitrate and cobalt nitrate.

The energies to produce nickel and cobalt are 71,855 Btu/lb and 62,115 Btu/lb (8,20). The energy to produce ammonia is 19,321 Btu/lb (8). Table VI-4 shows the materials and energy needed to produce nitric acid from ammonia (8).

TABLE VI-4. MATERIALS AND ENERGY REQUIRED TO PRODUCE NITRIC ACID

	Amount Needed per lb of NH_3	Energy Required per Unit	Energy Required per lb of HNO_3
Ammonia	0.287 lb	19,321 Btu/lb	5,545 Btu/lb
Electricity	0.0045 kWh	10,500 Btu/kWh (assumes genera- tion efficiency is 32.5%)	47 Btu/lb
Feedwater	0.40 lb	0	0
Steam (Steam is generated by the process for use)	0.875 lb	0	0
TOTAL			5,592 Btu/lb

In order to determine the energy to produce nickel nitrate and cobalt nitrate from the elemental metals and

nitric acid; the Sommerfield and White estimation technique, described in the section on ferric oxide (C, 6), was used.

The heat of reaction for the production of cobalt nitrate:

is -21.06 kcal/gmole or -132.2 Btu/lb of cobalt nitrate. Using the Sommerfield-White equation, the energy for this process is 4,648 Btu/lb of cobalt nitrate.

The heat of reaction for the production of nickel nitrate

is -22.7 kcal/gmole or -142.2 Btu/lb of nickel nitrate hexahydrate. Using the Sommerfield-White equation, the energy for this process is 4,616 Btu/lb of nickel nitrate hexahydrate.

The total energy to produce a pound of nickel nitrate and cobalt nitrate is shown in Tables VI-5 and VI-6. To produce the amounts of these materials needed for one pound of battery (0.007 lb of cobalt nitrate hexahydrate and 0.008 lb of nickel nitrate hexahydrate) the energy required is 124 Btu/lb of battery for cobalt nitrate hexahydrate and 157 Btu/lb of battery for nickel nitrate hexahydrate. Because of the small amount of energy needed to produce these materials and the lack of knowledge about some of the processes involved, a fuels breakdown was not performed for these materials. The energy for these materials is entered under "other" for the type of fuel.

TABLE VI-5. ENERGY USED TO MANUFACTURE NICKEL
NITRATE HEXAHYDRATE FROM RAW MATERIALS (Btu/lb)

Process	Amount lb/lb Nickel Nitrate Hexahydrate	Energy per Pound of Material	Energy per Pound of Nickel Nitrate Hexahydrate
Nitric Acid Production	.44	5,592	2,460
Nickel Production	.20	71,855	14,371
Nickel Nitrate Hexahydrate Production	1.0	4,616	4,616
Hydrogen Credit	.01	183,864	(1,838)
TOTAL			19,609

TABLE VI-6. ENERGY USED TO MANUFACTURE COBALT NITRATE
HEXAHYDRATE FROM RAW MATERIALS (Btu/lb)

Process	Amount lb/lb Cobalt Nitrate Hexahydrate	Energy per Pound of Material	Energy per Pound of Cobalt Hydrate Hexahydrate
Nitric Acid Production	.44	5,592	2,460
Cobalt Production	.20	61,978	12,396
Nickel Nitrate Hexahydrate Production	1.0	4,648	4,648
Hydrogen Credit	.01	183,864	(1,838)
TOTAL			17,666

In both reactions, .01 lb of hydrogen is generated per pound of product, resulting in an energy credit of 1,838 Btu/lb of product. Figures VI-10 and VI-11 show the energy used to produce nickel nitrate hexahydrate and cobalt nitrate hexahydrate for one pound of battery.

9. Process Materials

Small amounts of process materials are used in the battery manufacturing process including hydrogen and nitrogen. The energy required to produce these materials has been estimated to be 702 Btu per pound of battery.

10. Battery Manufacturing

The major processes in manufacturing of nickel-iron batteries are the fabrication and sintering of the steel wool grids, production of the nickel electrode, production of the iron electrode, molding of the plastic components, and assembly. Some of these operations involve chemical reactions and consume significant amounts of energy. Energy estimates for the manufacturing process have been made from data provided by the manufacturer and from estimates based on a plant visit to a lead-acid battery plant.

Manufacture of the nickel electrode requires more energy than any other process used to make nickel-iron batteries. Nickel is obtained in metallic form by the manufacturer; however, nickel oxyhydrate (NiOOH) is the material used as the active material in the battery. Nickel oxyhydrate is formed onto the steel wool grid by a three-step electrochemical process. The steel wool is first plated with nickel. The grid is then put into an electrolytic cell with a bar of

Figure VI-10. Energy Used to Produce Nickel Nitrate Hexahydrate for Nickel-Iron Electric Vehicle Batteries (Btu/lb of Battery)

Figure VI-11. Energy Used to Produce Cobalt Nitrate Hexahydrate for Nickel-Iron Electric Vehicle Batteries (Btu/lb of Battery)

nickel. This nickel is electrochemically deposited onto the grid as nickel hydroxide $[\text{Ni}(\text{OH})_2]$. The plate is then put into another electrolytic cell in which the nickel hydroxide $[\text{Ni}(\text{OH})_2]$ is converted into nickel oxyhydrate (NiOOH), the desired compound.

The energy used for these three processes has been estimated by the manufacturer to be 7.4 kWh of electricity per kilogram (3.36 kWh/lb) of nickel oxyhydrate that is deposited. There is 0.288 lb of nickel oxyhydrate in each pound of battery so the total energy used for this process is 0.766 kWh (electric) or 8,043 Btu/lb of battery (assuming a 32.5 percent efficiency of electric power generation).

The iron plate is produced from iron oxide by making a paste from the iron oxide, applying the paste to the steel wool grid, and heating the grid in the presence of hydrogen and nitrogen to reduce the iron oxide to elemental iron. Hydrogen acts as the reducing agent while nitrogen acts as an inert gas in this reaction. The process is carried out in an electric oven and requires 0.24 kWh of electricity for each plate manufactured (as estimated by the manufacturer). There are 66 iron plates in a battery module weighing 64 lb (19), so the energy used is 0.25 kWh (electricity) per pound of battery. Conversion to primary energy gives 2,625 Btu/lb of battery.

These two processes account for most of the energy used in the battery manufacturing process. Other manufacturing processes include molding of the battery case and miscellaneous assembly. Based on practices at one lead-acid battery plant, these operations have been assumed to require 194 Btu/lb of battery for molding, and 1,133 Btu/lb for miscellaneous assembly. Table VI-7 shows the energy use per pound of battery for the assembly processes.

TABLE VI-7. ENERGY USE IN NICKEL-IRON BATTERY ASSEMBLY
(Btu/lb of BATTERY)

	Electric	Coal	Gas	Petroleum	Other	Total
Molding of Plastic Parts	146	0	43	5	0	194
Nickel Electrode Manufacturing and Formation	8,043	0	0	0	0	8,043
Iron Electrode Manufacturing	2,625	0	0	0	0	2,625
Assembly and Other	78	0	948	107	0	1,133
Total	10,892	0	991	112	0	11,995

D. Operation

Operation of a vehicle using a nickel-iron battery is based on installing the battery in a reference vehicle. The General Electric/Chrysler vehicle is used again but the lead-acid batteries have been replaced by the advanced nickel-iron batteries with an energy storage density of 60 Wh/kg (27 Wh/lb). In order to compare the batteries on an equal basis, the amount of energy stored in vehicles is held constant at 18.6 kWh. For the nickel-iron battery, this results in a battery weight of 310 kg (684 lb).

The reference vehicle, with 684 lb of nickel-iron batteries (with a 70 percent efficiency) uses 0.362 kWh/mile of electricity. This amounts to 36,200 kWh per 100,000 miles or 308.8 million Btu/mile (allowing for a 40 percent efficiency of electricity generation).

E. Recycling

Materials that could potentially be recycled from a nickel-iron battery include nickel, ferrous materials, and copper. One pound of nickel-iron battery contains 0.164 lb nickel, 0.423 lb iron and steel, and 0.035 lb copper.

Nickel, as one of the most expensive and energy intensive parts of the nickel-iron battery is a prime candidate for recycling. Unfortunately, there is no nickel hydroxide recycling industry and data on the energy used for recycling of nickel hydroxide into nickel are not available. It has been assumed that nickel reprocessing would consume half of the energy required for nickel production from ore.

Iron and steel form a large portion of the battery and could be recycled if this were found to be economical. Production of steel from scrap metal uses 4,165 Btu/lb of steel (14). This results in a net credit (over the production of steel from ore) of 9,451 Btu/lb. The ferrous oxide has been assumed to be recycled as iron ore which is the reason for the low energy credit for the recycling of iron.

Recycling of scrap copper wire requires 1,905 Btu/lb. This results in a savings of 54,241 Btu/lb, when compared to the energy needed to produce copper from ore (14).

In computing the energy credits for materials recycling, it has been assumed that half of the total available material is actually recycled. Under these assumptions, the amount of energy credit due to recycling is shown in Table VI-8.

TABLE VI-8. ENERGY CREDITS DUE TO MATERIALS RECYCLING
IN THE NICKEL-IRON BATTERY (Btu/lb OF BATTERY)

Material	Amount in Battery (lb/lb Battery)	Amount Recycled (lb/lb Battery)	Energy Credit/ lb of Material	Energy Credit/ lb of Battery (Btu/lb)
Nickel	0.164	0.082	25,927	2,964
Iron	0.122	0.061	144	9
Steel	0.292	0.146	9,451	1,380
Copper	0.035	0.017	54,241	922
Total	0.622	0.311	--	5,257

F. Total Life-Cycle Energy Use

The investment energy to produce the 684 lb (310 kg) of nickel-iron batteries for the reference vehicle is 30.5 million Btu. Battery operation and vehicle power consume 308.8 million Btu, and recycling results in a credit of 3.7 million Btu.

VII. THE ZINC-CHLORINE BATTERY

A. Battery Description

The zinc-chlorine battery is presently being developed for utility load-leveling and electric vehicle applications. The two battery designs are essentially the same except for differences in materials requirements and electrical efficiency.

The zinc-chlorine battery concept is based on: (1) the electrochemical reaction between zinc, chlorine, and aqueous zinc chloride solution and (2) the chemical reaction between chlorine and water. These two reactions progressing simultaneously are expressed as follows:

Both reactions are highly reversible. The emf of a zinc-chlorine cell under standard conditions is 2.12 V corresponding to a free energy reaction of 97.9 kcal/mole. The value of X, which is dependent on experimental conditions, can be as low as 5.9. It must be emphasized that the active materials come from and are returned to the electrolyte during cycling. This is opposite to conventional battery systems where the active materials are localized at the electrode surface as insoluble materials.

The reactions of charging and discharging are represented in Figure VII-1. The battery cells are first built in a completely uncharged state equivalent to a fully discharged cell. Both the positive porous graphite electrode and the

Figure VII-1. Zinc-Chlorine Battery Operating Principle (21)

negative graphite substrate electrode are current collectors in a cell without separators. The electrodes are submerged in an aqueous zinc chloride solution. A tank of water connected to the zinc chloride solution by a pump is also part of the battery system. During the charging step, the zinc chloride electrolyte is electrolyzed producing a uniform deposit of zinc on an inert graphite electrode. The chlorine gas is removed from the cell and is passed to another chamber where it is mixed with water at about 10°C and chlorine hydrate is formed. The heat of formation (18 kcal/mole) must be removed from the hydrate as it forms (21).

To initiate discharge, the chlorine hydrate is heated by the exchange of heat between the warm stack electrolyte (40° to 50°C) and the chlorine hydrate-water mixture in the store. Chlorine is, thereby, evolved at the desired rate by decomposition of the hydrate. The chlorine is pumped back to the battery cell and mixed with the electrolyte. The chlorine-saturated electrolyte is then passed through the porous positive electrode and is consumed electrochemically, since zinc dissolves at the negative electrode. The voltage generated during discharge is approximately 2 volts (21).

B. Battery Component Weights and Performance

The battery module is divided into two sections separated by a chassis structure. The cover for each section is sealed to the edges of the divider. The battery stack is housed in the upper section and the pump, store compartments, and the auxiliaries are housed in the lower section. The battery stack consists of anodes and cathodes paired in a comb-type bipolar arrangement. One chlorine electrode is made up of two flat plates of graphite separated by a chamber. A single

flat plate of graphite is used for the zinc electrode. The basic cell unit consists of chlorine electrode faces paired with an equivalent number of zinc electrode faces. Ten such cell units are assembled in series to form a submodule. Six modules are arranged, two abreast, in three tiers to form a complete battery stack in one module. Figure VII-2 shows an exploded view of the proposed vehicle battery.

Table VII-1 shows that the major constituents of the zinc-chlorine battery are zinc chloride, graphite, and plastics. Lesser amounts of titanium, steel, and other trace materials are also used in the battery.

Storage density for the electric vehicle version of the zinc-chlorine battery is 100.9 Wh/kg (45 Wh/lb). Efficiencies range from 60 to 70 percent. An efficiency of 61 percent was assumed for the electric vehicle battery.

TABLE VII-1. ZINC-CHLORINE BATTERY COMPONENT WEIGHTS (ELECTRIC VEHICLE) (22)

Components	Percent of Total Battery Weight
Graphite	13.8
Plastics	21.7
Titanium	1.4
Steel	0.9
Zinc chloride	13.7
Water	48.5
TOTAL	100

Figure VII-2. Proposed Vehicle Battery

C. Energy Investment

Based on the materials and processes associated with the zinc-chlorine battery, an energy analysis of the following processes has been performed:

- (1) Graphite manufacturing
- (2) Plastic manufacturing
- (3) Steel manufacturing
- (4) Titanium manufacturing
- (5) Zinc chloride manufacturing
- (6) Other materials
- (7) Battery assembly.

Each analysis contains a brief description of the process involved and a quantification of the energy used for the entire process. Energy consumption data for battery materials are found in Appendix A.

1. Graphite

The graphite used for the electrode in the zinc-chlorine battery is produced synthetically from coke. Figure VII-3 shows this process which consists of coke production, calcination, crushing and mixing, forming, baking, graphitizing, and finishing (8).

Figure VII-3. Energy Used to Produce Graphite for the Zinc-Chlorine Battery (Electric Vehicle) Btu/lb of Battery (8)

The largest quantity of raw material used in graphite production is coke, which is made by coking coal or petroleum. Coke requires calcination in conventional rotary calciners. Volatiles may be burned and used to preheat the charge, which results in improved economy. The energy used in crushing and mixing, and molding is negligible compared to other processes. The calcined filler is reduced to the desired particle size by crushing. Following the necessary preparation and sizing of the raw materials, all the ingredients for a given formulation are weighed and transferred to the mixer. In certain formulations, it is advisable to preblend the dry ingredients. After mixing, the material is formed into the desired shape. A wide variety of forming methods have been used but extrusion, compression molding, and jar molding are most commonly used.

Baking is the next step in converting green carbon into a commercially usable product as graphite. In this process, pitch is used as a bonding bridge between filler particles resulting in a finished article of great strength. Because of the thermoplasticity of the green carbon, it must be supported in order to maintain its shape through the initial baking until sufficient binder has become coked and rigid enough to maintain the shape. The gas-fired ring furnace is the most efficient and economical way to bake carbon products. The baked carbon is a very hard and brittle material which cannot be easily machined by normal means. It has moderate electric and thermal conductivity.

The purpose of the graphitization process is to develop from the baked carbon the properties which are characteristic of carbon in the crystalline form of graphite. In this process the temperature of baked carbon is gradually raised from room temperature to 3,000°C. Most products which have been taken to 2,800°C or higher are considered fully "graphitized." The electric energy requirement, 2 to 3 kWh per

pound, is typical for large-electrode production. This energy figure depends on furnace size, degree of graphitization required, type of material being processed, and the manner of packing. Amorphous electrodes and baked carbon for structural uses require some machining. The energy consumption data are shown in Appendix A. Figure VII-3 shows the energy required to produce graphite per pound of battery (8).

2. Plastic

Plastic is used in the zinc-chlorine battery for containers. Polyvinyl chloride (PVC) is the primary plastic used in the zinc-chlorine battery.

Vinyl chloride is polymerized commercially by the following types of processes:

- (a) Suspension polymerization
- (b) Emulsion polymerization
- (c) Bulk polymerization
- (d) Solvent polymerization.

Suspension polymerization represents the major method used for making PVC in the United States. This type of polymerization is almost always performed in batches with 5 to 10 reactors per line, each line feeding a stripper, a set of blend tanks, and a finishing system. A reactor is prepared for a charge by the addition of an aqueous solution containing the suspending agent and other ingredients. The vinyl chloride monomer is then weighed in and the catalyst added.

The temperature is raised to the desired level and maintained by control of the jacket water temperature. At the end of the cycle, the batch is dropped to a shipper which consists of a heated agitated tank. The vaporized monomer is condensed, distilled, and recycled to the reactor. In this polymerization the monomer is vinyl chloride which is made from acetylene derived from calcium carbide and hydrochloric acid formed by burning hydrogen in chlorine (11). The energy consumption for the overall production sequence, including the energy used to produce the natural gas used as a feedstock, is shown in Appendix A. The energy used to produce PVC for the battery is shown in Figure VII-4.

3. Steel

Small amounts of steel are used as structural members in the battery and for some portions of the mechanical components. The processes involved in steel production have been discussed in detail in Chapter IV,7. Figure VII-5 shows the energy required to produce steel for one pound of battery (8).

4. Titanium

Titanium is used as an electrode material for the zinc-bromine battery. The ore used in the production of titanium is obtained by dredging beach sand in Australia. All titanium ore processed in the United States is imported. In addition, 28 percent of the refined titanium is also imported. Titanium is produced from ore using the Kroll process or the sodium process. Since the Kroll process accounts for 65 percent of domestic production, it was used in the study to analyze the energy requirements for titanium production.

Figure VII-4. Energy Used to Produce Plastic in Electric Vehicle Battery in Btu/lb of Battery (11)

Figure VII-5. Energy Used to Produce Steel for a Zinc-Chlorine Battery (Electric Vehicle) Btu/lb of Battery (8)

In the Kroll process, the concentrated ore is chlorinated to produce titanium tetrachloride and fed into a reactor with magnesium. In the reactor, the titanium is reduced to titanium sponge while the magnesium is oxidized to magnesium chloride. The magnesium chloride is separated into magnesium and chlorine by electrolysis for reuse. After reduction, the titanium is crushed and acid-leached to remove impurities.

Figure VII-6 shows the energy used to produce titanium for one pound of zinc-chloride battery (20).

5. Zinc Chloride

Zinc chloride used in the zinc-chlorine battery is produced through the reaction of zinc oxide with hydrochloric acid. The following section traces the raw materials flow necessary to produce zinc chloride.

a. Zinc Oxide. Zinc ores are mined from the earth and sent through a beneficiation process which produces a concentrate containing about 50 to 60 percent zinc. The concentrate is then dried, roasted, and sintered, after which it proceeds to a reduction-volatilization-condensation process and emerges as high-grade zinc.

Several different processes are used to produce zinc. These include the electrothermic process (35 percent of all zinc produced), the electrolytic process (45 percent of all zinc produced) and the vertical retort process (20 percent of all zinc produced). The electrolytic zinc process has the advantage of directly producing special high-grade zinc. To make special high-grade, the pyrolytic plants use a revolatilization refining step which requires more energy than the other processes. In order of energy consumption per pound of zinc, the electrolytic process uses the least energy

Figure VII-6. Energy Used to Produce Titanium for the Zinc-Chlorine Battery (Btu/lb of Battery)(20)

(26,863.30 Btu), followed by the vertical retort (29,046.47 Btu) and the electrothermic processes (32,399.36 Btu). The energy values for the various zinc production processes have been combined into one number based on the amount of zinc produced from each. It has been assumed that the French process, in which zinc oxide is manufactured from refined zinc, has been used. Figure VII-7 shows the energy used to produce zinc oxide (8,9).

b. Chlorine. Chlorine is produced from salt by electrolysis. Salt is mined from underground deposits by solution technique, purified, and electrolyzed in cells. Chlorine is one of the products resulting from the electrolysis of a number of minerals, salt, potash, or magnesium chloride. Depending on the mineral used and cell conditions, the other products are caustic soda, sodium metal, caustic potash, and potassium or magnesium metal. Electrolysis of an aqueous solution is performed in cells designed to separate the reaction products for subsequent treatment. Two basic types of aqueous cells constitute current design technology: (1) the diaphragm cell and (2) the mercury-amalgam cell. Diaphragm-cell electrolysis of salt produces 67 percent of the annual chlorine consumption. Traditionally, it requires 2,700 to 2,900 kWh of DC electrical energy per net ton of chlorine. Figure VII-8 shows the energy used to produce chlorine. The energy usage is allocated to all three product materials, chlorine, caustic soda, and hydrogen, on a proportional weight basis (8).

c. Hydrogen. Large quantities of hydrogen are manufactured by catalytically reacting hydrocarbons and steam to yield hydrogen and carbon oxides followed by the water-gas shift reaction. For the production of hydrogen from hydrocarbon and steam (steam reformer process), the material and utility requirements are as follows: for 1,000 standard cubic feet

Figure VII-7. Energy Used to Produce Zinc Oxide, Btu/lb of Zinc Oxide

Figure VII-8. Energy Used to Produce Chlorine
(Btu/lb of Chlorine)(8)

hydrogen (99.9 percent), natural gas - 10.4 l, steam - 163 kg, fuel oil - 88,200 kcal, and electricity - 0.9 kWh. These values result in an energy consumption for hydrogen of 183,863 Btu/lb (9).

d. Hydrochloric Acid. Hydrochloric acid is produced either as a by-product of organic chlorinations or by direct synthesis in the reaction of chlorine with hydrogen. In the latter process, hydrogen and chlorine gases are reacted in a vertical burner. The product hydrogen chloride is cooled and then absorbed in water. Exhaust gases are scrubbed and acid values are recycled. End products may include strong acid from the cooler, weak acid from the absorber column, a mixture of these, or anhydrous HCl. The anhydrous acid may be prepared by stripping gaseous HCl from strong acid. The condensate and column bottoms may then be recycled to the process. All wastes originate from wet scrubbing of tail gases to remove acidic gases and are waterborne. They consist of alkali metal or alkali earth chlorides. The reaction to produce hydrochloric acid is as follows:

At standard conditions, the heat of reaction is -22.1 kcal/gmole or -1,119 Btu/lb (23).

Using the procedure developed by Sommerfield and White (see Chapter IV, C, 2) (10), the energy required to produce one pound of hydrochloric acid from hydrogen and chlorine is 1,646 Btu.

e. Zinc Chloride. Zinc chloride is used as electrolyte in the zinc-chlorine battery. Two-Molar solution is used for this purpose. It is produced by reaction between zinc oxide and hydrochloric acid. The process flow diagram is shown in

Figure VII-9. The stoichiometric equation to produce zinc chloride is:

Under standard conditions, the heat of reaction is 78.33 kcal/gmole or 1,044.4 Btu/lb (23). Using the Sommerfield and White procedure (10) discussed in Chapter IV, the energy needed to produce zinc chloride is 8,800 Btu/lb of zinc chloride.

The sequence of reactions to produce zinc chloride and corresponding energy follow:

Natural gas + steam $\longrightarrow$ H_2	183,863 Btu/lb H_2 (.015 lb)
Cl_2 production	10,333 Btu/lb Cl_2 (.520 lb)
$\text{H}_2 + \text{Cl}_2 \longrightarrow 2\text{HCl}$	1,646 Btu/lb HCl (.535 lb)
ZnO from mine	36,742 Btu/lb ZnO (.597 lb)
$\text{ZnO} + 2\text{HCl} \longrightarrow \text{ZnCl}_2 + \text{H}_2\text{O}$	8,800 Btu/lb ZnCl_2

The total energy to produce zinc chloride is 39,747 Btu/lb. Figure VII-9 shows the energy required for one lb of battery.

Figure VII-9. Energy Used to Produce Zinc Chloride for Electric Vehicle Batteries (Btu/lb of Battery)

6. Other Materials

Other materials are used in zinc-chlorine batteries in very small amounts to improve the battery's stability. The scope of this study did not allow for a detailed analysis of these trace materials. Since these materials form such a small portion of the battery's total weight (less than 5 percent), it has been assumed that their contribution to the life-cycle energy use is negligible.

7. Battery Assembly

Assembly of the zinc-chlorine battery includes the shaping of the tanks, framework, and other components of the battery; manufacturing of pumps and compressors used in the battery; and the assembly of these components into a finished battery. The energy is used to operate process equipment and for heating and cooling of the building.

Since operating zinc-chlorine battery plants are not yet in full production, a detailed audit of the energy used in these plants is not available. For this reason, the energy used to fabricate the battery has been estimated to be one fourth of the total energy investment for this battery. This figure has also been used to estimate the assembly and fabrication energy for the other advanced batteries. This energy has been allocated equally among electric, gas, and oil sources.

D. Operation

As shown in Table III-2, the energy use of the reference vehicle powered by zinc-chlorine batteries is 0.397 kWh/mile over the SAE J227a "D" driving cycle. Over a life of 100,000 miles, this vehicle would consume 39,700 kWh of electricity. If it is assumed that charging is done during off-peak periods from base-load fossil-fueled generating plants, the primary energy used for the operation of the vehicle is 338.6 million Btu. This assumes that the efficiency of generating and transmitting electricity from base-load plants is 40 percent.

E. Recycling

Most of the zinc in a zinc-chlorine battery can be recycled easily in secondary smelters. In order to estimate the energy saving due to recycling of the battery components, the following assumptions have been made:

- (1) Fifty percent of the zinc chloride is recovered from the battery
- (2) The processes used in zinc recycling use half of the energy needed for production of that zinc chloride from ore.

Under these assumptions, the recycling of zinc results in an energy credit of 25 percent of the energy used in production. This credit results in a savings of 1,361 Btu/lb of battery.

F. Total Life-Cycle Energy Use

The investment energy to produce the 407 lb (184 kg) required to store 18.6 kWh per charge for a vehicle is 15.5 million Btu. Battery and vehicle operation consume 338.6 million Btu and recycling results in a credit of 0.6 million Btu.

VIII. THE SODIUM-SULFUR BATTERY (GLASS ELECTROLYTE)

A. Battery Description

The sodium-sulfur battery is an experimental storage battery which is presently being developed for use in electric load-leveling plants and electric vehicles. The active materials in this battery are sodium and sulfur, which are present in the battery in a liquid state. The need to use liquid sodium and liquid sulfur results in a battery operating temperature of approximately 300°C (570°F). The sodium-sulfur battery has the potential of providing high energy storage capacity in a very compact and lightweight unit.

A schematic description of the basic reaction of the sodium-sulfur battery is shown in Figure VIII-1. The battery consists of two reservoirs, one filled with liquid sodium and one with liquid sulfur, which are separated by a thin solid barrier. The barrier is made from a material that allows sodium ions to pass through it but is impervious to sulfur atoms. During discharge, positively charged sodium ions migrate through the solid electrolyte and form sodium polysulfide (Na_2S_x). This releases two electrons which generate current through the discharge circuit. During charging, the reverse process occurs: the Na_2S dissociates and the sodium ions migrate back across the electrolyte barrier. The voltage developed by this type of cell is 2.078 volts per cell. The cell reaction is:

Figure VIII-1. Sodium-Sulfur Battery Operating Principle

The sodium-sulfur battery consists of two liquid active ingredients separated by a solid electrolyte. More conventional batteries, such as the familiar lead-acid battery, use solids for the active materials and liquid electrolytes.

The solid electrolyte is one of the most crucial components of the sodium-sulfur battery and has been the subject of most of the research and development effort for this battery. Two different types of solid electrolyte are presently under development, one from β -alumina ceramic, and one from glass. While both electrolyte materials perform the same function in the battery, their physical appearance is drastically different. The β -alumina electrolyte consists of a large tube of ceramic material which protrudes into the sulfur reservoir and separates the sulfur from the sodium. The glass electrolyte is made up of very thin hollow glass fibers (50μ I.D. x 70μ O.D.), closed at one end, which are suspended in the molten sulfur so that the inside of the fiber contains sodium and the tube is surrounded by the sulfur. Thousands of these fibers are used per cell to make the glass electrolyte. Both types of electrolyte perform the same function, however; they allow sodium ions to pass while blocking the passage of sulfur and sodium sulfur compounds.

Other components of the sodium-sulfur cell include the case, current collectors for the liquid sulfur, and various insulators. Cases are made from metal (aluminum and stainless steel have been tested) in order to resist heat and conduct the electricity from the battery. Since molten sulfur is not a good conductor of electricity, the sulfur reservoir is filled with conductive material which distributes the electric current throughout the liquid. In the β -alumina type of cell, a felt made from carbon fibers is used for this purpose. In the glass fiber cell, strips of aluminum foil, coated with molybdenum or graphite, are used. The remainder of the cell

is composed of miscellaneous components such as insulators between the sodium and sulfur parts of the battery, electrical feed-throughs, and other hardware components such as filler plugs and structural components (24,25).

Since the sodium-sulfur battery operates at a high temperature, it requires a special insulated enclosure for use in an electric vehicle. This insulated enclosure must be adequate to prevent excessive thermal losses for the battery, as well as to provide cooling for periods of high power output and protection in case one of the battery cells ruptures.

A preliminary design for this battery enclosure has been developed by Ford Motor Company (26). It features a double-walled, vacuum-insulated aluminum and plastic container and is liquid cooled. Multiple layers of aluminum foil are inserted in the vacuum space to reduce radiation heat loss. It is assumed that an enclosure of this type is used in both types of sodium-sulfur battery. Table VIII-1 shows a breakdown of component weights for an entire battery using this design.

B. Battery Component Weights and Performance

Although there are two types of sodium-sulfur batteries being developed, only the glass electrolyte battery is being considered in this chapter. The ceramic electrolyte is discussed in detail in Chapter IX. Figure VIII-2 shows a cross section of a battery and Table VIII-2 shows the materials used for a battery designed for electric vehicle use, including the battery container. Individual cell materials data were obtained from the battery developers (27).

Figure VIII-2. Sodium-Sulfur Battery Using Glass Fiber Electrolyte (25)

TABLE VIII-1. SODIUM-SULFUR BATTERY COMPONENTS (26)

Component	Percent of Battery Weight
Battery Cells	74.1
Electrical Connections (copper)	2.9
Insulated Container (60% plastic, 40% aluminum)	12.8
Battery Tie Down and Support (aluminum)	7.5
Filler Material (glass microspheres)	1.4
Bus Bars and Lead-Throughs (Copper)	1.3
TOTAL	100

TABLE VIII-2. MATERIALS USED IN THE SODIUM-SULFUR
(GLASS ELECTROLYTE) ELECTRIC VEHICLE BATTERY

Material	Percent of Battery Weight
Sodium	12.1
Sulfur	26.2
Glass:	
Fibers	1.7
Tube Sheet	3.4
Insulating Filler (microspheres)	1.4
Aluminum	32.5
Steel	10.8
Plastic	7.7
Copper	4.2
TOTAL	100

Battery efficiencies for the glass electrolyte battery are very high, with an expected efficiency of 90 percent. This efficiency has been demonstrated in the prototype batteries; however, for this study, a slightly more conservative figure has been assumed. The efficiency of the electric vehicle battery has been assumed to be 80 percent. The storage density of the battery has been assumed to be 140 Wh/kg (63 Wh/lb) for a cell which translates to 108 Wh/kg (49 Wh/lb) for the total battery.

C. Energy Investment

Based on the materials and processes associated with the sodium-sulfur battery, an analysis of the following materials and processes has been performed:

- (1) Sodium
- (2) Sulfur
- (3) Glass
- (4) Aluminum
- (5) Steel
- (6) Copper
- (7) Plastic
- (8) Other materials
- (9) Battery assembly.

1. Sodium

The principal operations required for the production of metallic sodium are:

- (a) Underground mining of rock salt
- (b) Salt purification
- (c) Salt crystallizing
- (d) Salt drying
- (e) Electrolysis.

The rock salt mining process is very similar to that of underground coal mining involving conventional techniques such as undercutting, drilling, blasting, loading, transporting, and housing. The mined rock salt is then dissolved in water, treated with soda ash and caustic soda to precipitate metallic impurities, filtered to remove the resulting sludge, and crystalized by evaporation of water. The salt crystals are next dried with moderate heat, cooled, and transported to the electrolysis cell-feed storage area. The electrolysis process uses a Downs cell which is essentially a steel shell lined with firebrick, containing cylindrical graphite anodes surrounded by an iron-gauze diaphragm and a cylindrical iron cathode. Heat is supplied to the cell to maintain the NaCl (sodium chloride) in a molten state for the electrolysis process. The products of this process are commercially pure sodium metal and gaseous chlorine (7).

Energy is required in all the five principal operations required for the production of metallic sodium. For every pound of sodium produced, 1.5 lb of chlorine are recovered. The total energy required for the production of one ton of sodium metal and the resulting 1.5 lb of by-product chlorine gas is 59,500 Btu (7). Strictly on a product weight basis, the total energy input could be allocated as: sodium (Na) -- 23,800 Btu/lb; and chlorine (Cl₂) -- 35,700 Btu/1.5 lb. However, this electrolysis process is used only when metallic sodium is the primary product desired. The chlorine-caustic soda process is utilized when chlorine is the desired primary product. This process requires only 9,000 Btu/lb of Cl₂.

Therefore, by assigning an energy credit of 9,000 Btu/lb of Cl_2 produced we can arrive at a value of 46,000 Btu/lb of sodium metal produced. The energy use for the production of the required sodium for the electric vehicle battery is shown in Figure VIII-3.

2. Sulfur

Sulfur is obtained either from mines or from chemical processes used to remove sulfur from fuels and chemical plant effluents. For the purposes of this study, we have assumed that all of the sulfur used in the battery is freshly mined sulfur. Sulfur from other sources is essentially "free" on an energy basis since it is a by-product of an environmental control process. It is not possible, within the scope of this study, to determine how much sulfur used in the battery would come from these sources, so we have assumed that all sulfur is obtained from sulfur mines.

Sulfur is mined using the Frasch process by pumping hot water into an underground sulfur deposit. The hot water melts the sulfur and carries it to the surface where it is purified and dried. Sulfur mining by the Frasch process consumes 985 Btu/lb of sulfur including transportation of the finished sulfur. Nearly all of this energy (930 Btu/lb) is from natural gas (8). Figure VIII-4 shows the energy used for producing sulfur for electric vehicle batteries.

Figure VIII-3. Energy Used to Produce Sodium for Sodium-Sulfur, Glass Electrolyte, Electric Vehicle Batteries (Btu/lb Battery)(7)

Figure VIII-4. Energy Used to Produce Sulfur for Sodium-Sulfur Batteries for Electric Vehicle Use (Btu/lb Battery)(8)

3. Glass

Glass is used for three purposes in the sodium-sulfur battery system. Tube sheet glass is used to separate the sodium and sulfur chambers and glass fibers are used as the electrolyte in the battery. The sodium-sulfur battery uses fine hollow fibers of specialized glasses made from borax, sodium chloride, sodium carbonate, and sand. Except for the raw materials, this glass is manufactured in the same way as conventional glass. For the glass fibers, the materials breakdown by weight is 91 percent borax, 4 percent sodium chloride, and 5 percent sand (27). For tube sheet glass, the proportions are 94 percent borax and 6 percent sodium carbonate (27). Glass fibers account for approximately 33 percent of the glass in the battery cell and tube sheet glass accounts for the remainder. Small glass microspheres are also used in the battery for thermal insulation of the battery package. This glass is assumed to be produced by conventional glass-making techniques.

The processes required for the production of glass can be generally categorized as:

- (a) Raw material mining and preparation
- (b) Raw material transportation
- (c) Batch handling and cullet crushing
- (d) Melting
- (e) Fining and conditioning
- (f) Forming
- (g) Post forming
- (h) Product handling.

The several varieties and categories of glass are all made by essentially the same processing steps with some variations and additions for different end products. The basic process flow diagrams for tube sheet glass, glass fibers, and microspheres are presented in Figures VIII-5, VIII-6, and VIII-7.

Basically, the glass production process starts with batch mixing of the raw materials to minimize segregation in the batch. The mixture is melted in a glass furnace at temperatures of around 1,500°C. It is then fined (removal of trapped gases) and melt cooled for handling in the forming step. The molten glass is then fed to forming machines and transformed into end products by various processes.

Exclusive of raw materials, 20,125 Btu are required to produce one pound of glass. This energy has been allocated as follows: batch handling and cullet crushing, 1 percent; melting, fining, and conditioning, 65 percent; forming, 14 percent; post forming, 15 percent; product handling, 2 percent; and space heating, 3 percent (7). Different raw materials are used for the different types of glass in the battery. These are shown in Figures VIII-5 through VIII-7.

Figure VIII-5. Energy Used to Produce Tube Sheet Glass for the Electric Vehicle Sodium-Sulfur Battery (Btu/lb of Battery)

Figure VIII-6. Energy Used to Produce Glass Fibers for the
Electric Vehicle Sodium-Sulfur Battery
(Btu/lb of Battery)

Figure VIII-7. Energy Used to Produce Glass Microspheres for Sodium-Sulfur Batteries for Electric Vehicles (Btu/lb of Battery)(7)

4. Aluminum

Aluminum is used in the sodium-sulfur battery for anodes, cathodes, and for the foil which distributes current throughout the molten sulfur. Aluminum is produced from bauxite using a complex process which consists of ore preparation, conversion of bauxite to alumina using the Bayer Process, and reduction of the alumina to aluminum using an electrochemical smelting process. Aluminum is unique among the major industrial metals in that it is smelted in an electrolytic cell instead of a furnace. This procedure makes aluminum production highly energy intensive, with much of the energy in the form of electricity.

The primary ore used for aluminum production is bauxite. Most of this ore (85 percent) is imported. Secondary aluminum production accounts for 21 percent of all aluminum consumed, 80 percent of this secondary production is from new scrap, the rest comes from recycled old scrap. The following analysis gives energy consumption for primary production of aluminum only.

Bauxite is mined from surface mines, crushed, ground and dried. At this point it is shipped to an aluminum processing plant for conversion into aluminum. Since 85 percent of all aluminum ore is imported, transportation uses a significant amount of energy.

Production of aluminum occurs in two steps, the production of alumina from bauxite, and the electrical conversion of alumina to aluminum. The Bayer process is used to extract alumina from bauxite. In this process, bauxite is mixed with caustic soda under heat and pressure, which separates the alumina in the bauxite, leaving behind the impurities in the ore.

Smelting of alumina to aluminum occurs in an electrolytic reduction cell. Alumina is dissolved in a molten cryolite (sodium-aluminum fluoride) electrolyte. When an electric current is passed through this solution, aluminum is deposited on the cathode and oxygen is deposited on the anode. The aluminum is then collected and molded into ingots for transportation and later use.

The processes used in manufacturing aluminum are shown in Figure VIII-8 (8). The energy figures include the energy needed to manufacture the cathodes and anodes (made from carbon) used in the electrolytic reduction process. These figures also show the energy needed (in Btu/lb battery) to produce aluminum for the electric vehicle battery.

Figure VIII-8. Energy Used to Produce Aluminum for Sodium-Sulfur Batteries for Electric Vehicles (Btu/lb of Battery)(8)

5. Steel

Steel is used for the outer casing of the battery. A complete description of the steel manufacturing process is found in Chapter IV, C,7. Figure VIII-9 shows the energy to produce steel for the battery.

6. Copper

Copper ores are mined from the earth and sent to concentrators. The concentrators crush and grind the ore and pass it through a flotation process which yields a copper concentrate containing about 25 percent copper. The concentrate is then smelted into a matte which is refined using the electrolytic process, yielding copper with a purity of more than 99 percent.

For every net ton of copper produced, mining consumes 10,805 Btu, the concentrator process consumes 21,165 Btu, smelting consumes 19,111 Btu, and refining consumes 5,066 Btu, resulting in a total of 56,146 Btu (see Appendix A) per pound of copper (8). Figure VIII-10 translates these figures into Btu of energy per pound of a sodium-sulfur battery.

7. Plastic

Plastic is used as the outer casing for the battery module for a vehicle. The plastic envisioned for this purpose is a polyamide material (nylon or a related polymer). Due to the lack of data concerning the energy needed to produce polyamide polymers, the energy analysis here has been based on an equivalent amount of polyethylene plastic.

Figure VIII-9. Energy Used to Produce Steel for Sodium-Sulfur Batteries for Electric Vehicles (Btu/lb of Battery)(8)

Polyethlyene is produced from natural gas. As a first step, ethylene is produced from natural gas, the ethylene is then introduced into a high pressure reactor in the presence of a catalyst, where it forms the polyethylene polymer. Figure VIII-11 shows the energy used to make plastic for the sodium-sulfur battery case in Btu/lb of battery (11).

8. Other Materials

Other materials are used in the sodium-sulfur battery in very small amounts. These materials include ceramics for seals and insulators, and trace amounts of materials used in the glass, tube sheet, and cathode foil to improve electrical properties and reduce corrosion. The scope of this study did not allow for a detailed analysis of these trace materials. Since these materials form such a small portion of the battery's total weight, it has been assumed that their contribution to the life-cycle energy use is negligible.

9. Battery Assembly

Although the battery assembly process has been defined and broken into specific operations, it is difficult to use this information to estimate the energy costs of producing the battery. For this reason, the battery assembly energy has been assumed to be one-fourth of the total investment energy for the battery. This assumption has been made for all of the advanced battery designs.

Figure VIII-10. Energy Use in Copper Production for Sodium-Sulfur Batteries (Btu/lb of Battery)(8)

Figure VIII-11. Energy Required to Produce Polyethylene for a Sodium-Sulfur, Glass Electrolyte, Electric Vehicle Battery (Btu/lb of Battery)(11)

D. Operation

Table III-2 shows the vehicle specifications used in the analysis. The net energy efficiency of the vehicle powered by the sodium-sulfur battery is .289 kWh/mi. Allowing for a 40 percent efficiency of electric generation, this results in a net energy use of 2,465 Btu/mi or 246.5 million Btu per 100,000 miles.

E. Recycling

Several elements of the sodium-sulfur battery are potentially recyclable. These elements include the steel case, sodium, sulfur, aluminum parts, and possibly the glass fibers. Because the economics and processes that would be used for recycling have not been fully developed, only recycling of the steel case, copper wiring, and aluminum is being considered at this time. It has been assumed that these materials would be recycled at a rate of 50 percent. Energy for the production of these materials from secondary sources has been obtained from Reference 14. Recycling at these rates results in an energy credit of 510 Btu/lb battery for steel, 19,165 Btu/lb battery for aluminum, and 1,134 Btu/lb battery for copper.

Many of the other battery components have a potential for recycling, but because the technology for recycling has not yet been developed, a detailed assessment is beyond the scope of this study. A prime recycling candidate is the sodium, which is expensive and very energy intensive in primary production. Sodium is present in the worn out battery in the form of sodium sulfide. Sodium could be separated from the sulfur through electrolysis or conversely the battery

could be filled directly with sodium sulfide and the sodium and sulfur would be separated through the normal battery charging process. Recovery of sodium also entails recovery of sulfur. Sulfur is relatively inexpensive and consumes little energy in production; the rationale for recycling of sulfur would be based less on economic or energy factors and more on the fact that sulfur recovery occurs as a by-product of sodium recovery and that sulfur is a harmful pollutant which cannot be discharged into the environment.

F. Total Life-Cycle Energy Use

The total life-cycle energy use for the sodium-sulfur glass electrolyte battery is 270.6 million Btu/100,000 miles. This includes 27.5 million Btu/100,000 miles for energy investment, 246.5 million Btu/100,000 miles for operation, and 3.4 million Btu/100,000 miles credit for recycling. These numbers are based on a battery weight of 379 lb/vehicle.

IX. SODIUM-SULFUR (CERAMIC ELECTROLYTE) BATTERY

A. Battery Description

The sodium-sulfur ceramic electrolyte battery is similar to the glass electrolyte battery discussed in Chapter VIII. The major differences are that a single tube of β -alumina ceramic is used instead of the multiple glass tubes for the electrolyte and a carbon felt is used instead of aluminum foil for current collection in the sulfur reservoir. As in the sodium-sulfur glass electrolyte battery, the basic cell reaction is:

The operating temperature of the battery is 300°C (570°F) in order to keep the sodium and sulfur in a liquid state. The β -alumina ceramic separates the sodium reservoir from the sulfur reservoir. By allowing only sodium ions to pass through it, this material makes the battery operation possible. A more complete description of the operating principles of the sodium-sulfur battery and of the differences between the glass and ceramic electrolyte designs appears in Chapter VIII, Section A.

B. Battery Component Weights and Performance

Figure IX-1 shows a cross section of a sodium-sulfur electrolyte cell. This figure shows the sodium and sulfur reservoirs, the β -alumina ceramic tube, and other major

Figure IX-1. Sodium-Sulfur Battery Using Beta-Alumina Electrolyte (24)

battery components. A summary of the weights of the various components is shown in Table IX-1. The battery is expected to have a specific energy of 104 Wh/lb (47 Wh/kg), including the weight of the insulated enclosure. Battery efficiency is projected to be between 70 and 80 percent. The efficiency for the electric vehicle battery considered here has been assumed to be 70 percent.

TABLE IX-1. MATERIALS REQUIREMENTS FOR A SODIUM-SULFUR (CERAMIC ELECTROLYTE) BATTERY

Material	Percent of Battery Weight
Sulfur	29.4
Sodium	17.8
β -alumina	7.7
α -alumina	1.0
Steel	13.0
Aluminum	15.3
Graphite felt	2.5
Copper	4.2
Plastic	7.7
Glass	<u>1.4</u>
TOTAL	100.0

C. Energy Investment

Based on the materials and processes associated with the sodium-sulfur ceramic battery, an analysis of the following manufacturing processes has been performed:

- (1) Sodium
- (2) Sulfur
- (3) Aluminum
- (4) α -alumina
- (5) β -alumina
- (6) Graphite
- (7) Steel
- (8) Copper
- (9) Plastic
- (10) Glass
- (11) Other materials
- (12) Battery assembly.

1. Sodium

The principal operations required for the production of metallic sodium are:

- (a) Underground mining of rock salt
- (b) Salt purification
- (c) Salt crystallizing
- (d) Salt drying
- (e) Electrolysis.

The processes involved in sodium production have been described in Chapter VIII and are not repeated here. Figure IX-2 shows the energy to produce sodium for one pound of battery (7).

Figure IX-2. Energy Used to Produce Sodium
For Sodium-Sulfur Ceramic Batteries (lb of Battery)(7)

2. Sulfur

Sulfur is obtained either from mines or from chemical processes used to remove sulfur from fuels and chemical plant effluents. For the purposes of this study, we have assumed that all of the sulfur used in the battery is freshly mined. Sulfur from other sources is essentially "free" on an energy basis since it is a by-product of an environmental control process. All sulfur for use in the battery was assumed to be obtained from sulfur mines. The results of this study show little sensitivity to this assumption because sulfur contributes only about 0.5 percent to the material energy requirement and only 0.01 percent to the total energy investment.

Sulfur is mined using the Frasch process, by pumping hot water into an underground sulfur deposit. The hot water melts the sulfur and carries it to the surface where it is purified and dried. Sulfur mining by the Frasch process consumes 985 Btu/lb of sulfur including transportation of the finished sulfur. Nearly all of this energy (930 Btu/lb) is from natural gas (8). Figure IX-3 shows the energy required to produce sulfur for the sodium-sulfur battery.

Figure IX-3. Energy Used to Produce Sulfur for Sodium-Sulfur Ceramic Batteries (Btu/lb of Battery)

3. Aluminum

Aluminum is used in the sodium-sulfur ceramic battery for the anodic container. A detailed process description for aluminum manufacturing appears in Chapter VIII, C,4, and this information is not repeated here.

Figure IX-4 shows the processes and energy required to produce aluminum for the sodium-sulfur battery (8).

Figure IX-4. Energy Used to Produce Aluminum for Sodium-Sulfur Ceramic Batteries (Btu/lb of Battery)(8)

4. α -Alumina

Alpha-alumina is used for the insulating ring which supports the electrolyte tube, separates the anodic and cathodic compartments from the electrochemical reaction viewpoint, and also acts as a sealing surface. The primary ore used for alumina production is bauxite. Bauxite is mined from surface mines, crushed, ground, and dried. The Bayer process is used to extract alumina from bauxite. In this process, bauxite is mixed with caustic soda under heat and pressure, separating the alumina in the bauxite and leaving

behind the impurities in the ore. The energy to produce α -alumina is 16,161 Btu/lb or 162 Btu/lb of battery for a requirement of .01 lb. α -alumina per pound of battery (8).

5. β -Alumina

The sequential procedure for laboratory preparation of β -alumina powder is shown in Figure IX-5. "Raw materials used are α -alumina and sodium carbonate. The α -alumina is precalcined. The components are dry-blended in a polyethylene container, and the β -alumina is synthesized by fusion of the α - Al_2O_3 - Na_2O_3 mixture in a crucible of skull type using an induction furnace. The block of material thus obtained is crushed and ball-milled in a metal jar. Any iron resulting from the grinding operation is leached out using HCL. After washing with distilled water and drying, the β -alumina powder is stored in air" (28).

The β -alumina electrolyte contains 8.7 to 8.8 percent Na_2O and 0.7 percent Li_2O ; the remainder is Al_2O_3 . An estimate has been made of the energy required to manufacture electrolyte tubes from β -alumina by the manufacturer. This estimate is that 7.7 kWh is required for one tube for a 215 Whr cell (29). Since on the average 25 percent of the cells are rejected, the energy requirement for usable tubes is 10.2 kWh per tube. Assuming that the tube size and energy use can be scaled directly to the 0.4 kWh cell, this results in 19 kWh per cell or 47.5 kWh per pound of electrolyte. Allowance for the efficiency of electric generation and transmission results in a figure of 498,750 Btu/lb. In addition, since β -alumina is produced from alumina, the energy to produce alumina from ore must be added to the energy of producing the tubes. The energy to produce alumina is 16,161 Btu/lb, making the total energy to produce β -alumina 514,911 Btu/lb. The energy to

Figure IX-5. Laboratory β -Alumina Powder Preparation

produce Na_2O and Li_2O has been ignored due to the small amounts required. Figure IX-6 shows the energy required to produce β -alumina for the sodium-sulfur battery.

Figure IX-6. Energy Used to Produce β -Alumina for Sodium-Sulfur Ceramic Batteries (Btu/lb of Battery)

6. Graphite

The space between the β -alumina tube and the cathodic container is filled with an electrically conductive graphite felt. These fibers conduct electric current to the molten sodium active material. Graphite felt is made using a process similar to that used to produce carbon electrodes. The major difference is that a fiber is used as the raw material instead of petroleum coke. The fiber is subjected to a high heat in an inert atmosphere which turns it into graphite. Since the original structure of the fibers is retained, the graphite produced is also a fibrous material. We have assumed, since the processes are similar, that the energy to produce graphite felt is the same as the energy to produce graphite electrodes.

The process used in producing graphite has been described in detail in Chapter VII. Figure IX-7 shows the energy required to produce graphite for the sodium-sulfur battery (8).

7. Steel

Steel is used for the casing of the sodium-sulfur cell. A detailed description of the steel manufacturing process appears in Chapter IV, C, 7, and it is not repeated here. Figure IX-8 shows the energy required to produce steel for the sodium-sulfur glass electrolyte electric vehicle battery.

8. Copper

Copper ores are mined from the earth and sent to concentrators. The concentrators crush and grind the ore and pass it through a flotation process which yields a copper concentrate containing about 25 percent copper. The concentrate is then smelted into a matte which is refined using the electrolytic process, yielding copper with a purity of more than 99 percent.

For every net ton of copper produced, mining consumes 10,805 Btu, the concentrator process consumes 21,165 Btu, smelting consumes 19,111 Btu, and refining consumes 5,066 Btu, resulting in a total of 56,146 Btu (See Appendix A) per pound of copper (8). Figure IX-9 translates these figures into Btu of energy per pound of a sodium-sulfur battery.

Figure IX-7. Energy Used to Produce Graphite for a Sodium-Sulfur Battery (Btu/lb of Battery)(8)

Figure IX-8. Energy Used to Produce Steel for a Sodium-Sulfur, Ceramic Electrolyte, Electric Vehicle Battery (Btu/lb of Battery)(8)

Figure IX-9. Energy Use in Copper Production for Sodium-Sulfur Batteries (Btu/lb of Battery)(8)

9. Plastic

Plastic is used as the outer casing for the battery module. The plastic envisioned for this purpose is a polyamide material (nylon or a related polymer). Due to the lack of data concerning the energy needed to produce polyamide polymers, the energy analysis here has been based on an equivalent amount of polyethylene plastic.

Polyethylene is produced from natural gas. As a first step, ethylene is produced from natural gas. The ethylene is then introduced into a high pressure reactor in the presence of a catalyst, where it forms the polyethylene polymer. Figure IX-10 shows the energy used to make plastic for the sodium-sulfur battery case in Btu/lb of battery (11).

Figure IX-10. Energy Used to Produce Plastic for
a Sodium-Sulfur Electric Vehicle Battery
(Btu/lb of Battery) (11)

10. Glass

Very small hollow glass spheres (microspheres) are used as insulating filler material inside the battery module. The glass has been assumed to come from conventional raw materials and be processed similarly to conventional glass materials. Figure IX-11 shows the energy use for glass production (7). A more detailed description of the glassmaking process appears in Chapter VIII, C, 3.

11. Other Materials

Other materials are used in the sodium-sulfur battery in very small amounts. These materials include Na_2O and Li_2O for ceramics, and trace amounts of materials used in ceramic

Figure IX-11. Energy to Produce Glass for a Sodium-Sulfur Battery (Btu/lb of Battery)(7)

tubes, and cathode foil to improve electrical properties and reduce corrosion. The scope of this study did not allow for a detailed analysis of these trace materials. Since they form less than 2 to 5 percent of the battery's total weight, it has been assumed that their contribution to the life-cycle energy use is negligible.

12. Battery Assembly

Although battery assembly has been defined and broken down into specific operations, it is difficult to use this information to estimate the energy costs of producing the battery. In order to estimate energy use, it has been assumed that battery assembly requires one-fourth the amount of energy required for the entire battery manufacturing process. Based on this assumption, the assembly energy value is 24,200 Btu/lb of battery.

D. Operation

The operational energy requirement for a vehicle powered by the sodium-sulfur battery is .339 kWh/mi as shown in Table III-2. For a battery life of 100,000 miles, this results in an energy use of 289.2 million Btu.

E. Recycling

Several parts of the sodium-sulfur battery could be recycled. The portions include the sodium, sulfur, aluminum, steel, and copper components. Because the processes that

would be used to reclaim materials such as sodium and sulfur have not yet been developed or tested, only recycling of aluminum, steel, and copper are being considered. It has been assumed that half of the amount of these materials present in the battery are recycled. Energy for the production of these materials from secondary sources has been obtained from Reference 14. Recycling at these rates results in an energy credit of 614 Btu/lb of battery for steel, 1,139 Btu/lb of battery for copper, and 9,053 Btu/lb of battery for aluminum.

F. Life-Cycle Energy Use

The total life-cycle energy use for the sodium-sulfur ceramic electrolyte battery is 298.4 million Btu, including 10.3 million Btu energy investment, 289.2 million Btu operational energy and 1.1 million Btu recycling credit.

X. THE LITHIUM-METAL SULFIDE BATTERY

A. Battery Description

The lithium-metal sulfide battery is an experimental storage battery which is presently being developed for use in electric load-leveling plants and electric vehicles. The lithium-metal sulfide cell employs solid electrodes and a molten salt electrolyte. The active material in the negative electrode is lithium in the form of a lithium-aluminum alloy. The active material in the positive electrode is sulfur, in the form of an iron sulfide. The electrolyte is a mixture of LiCl and KCl eutectic salts with a melting point of about 350°C (660°F) which necessitates a battery operating temperature of over 400°C (750°F).

Lithium-metal sulfide batteries used for load-leveling applications use an FeS positive electrode while batteries for electric vehicle applications use cathodes of either FeS or FeS₂. Although cells having FeS₂ positive electrodes can achieve higher specific energy and power than FeS cells, the high sulfur activity associated with FeS₂ requires the use of molybdenum or an as yet undeveloped protective coating in the current collector (30). The overall reactions for FeS and FeS₂ cells are:

The open circuit voltage plateau for the first reaction is 1.33 V, for the second reaction there are open circuit voltage plateaus of equal capacity at 1.76 V and 1.33 V.

B. Battery Component Weights and Performance

The cell design is the same for both EV and LL applications, and does not change with choice of FeS or FeS₂ cathodes. Lithium aluminum/iron sulfide bicell and multiple cell designs are shown in Figures X-1 and X-2. These cells contain vertically oriented electrodes in a sandwich configuration, such that there is a central positive electrode between two negative electrodes, which are half as thick as the positive electrode. The electrodes are porous, sponge-like structures filled with the molten electrolyte. Separators are used between the electrodes to provide electrical insulation between the electrodes and permit the migration of lithium ions through the electrolyte. In electric vehicle applications, the separator takes the form of a boron nitride felt, and for load-leveling applications, the separator is a magnesium oxide powder suspended in the electrolyte.

Other components of the lithium-metal sulfide cells include the housing, negative and positive current collectors, and the feedthrough. These components are made from low-carbon steel, with molybdenum coatings added to the positive current collectors of FeS₂ cells. The feedthroughs are copper cores clad in steel. The remainder of the cell is composed of miscellaneous structural components such as the picture frame electrode holders and perforated plates adjacent to the electrodes. These components are also made of low-carbon steel.

Lithium-metal sulfide cells can be assembled at any state of charge by varying the lithium content of the LiAl electrode and the relative amounts of FeS, FeS₂, LiS, and iron in the positive electrode. Since the state of charge at the time of assembly does not affect the performance of the

Figure X-1. Lithium-Aluminum/Iron Sulfide Cell (31)

Figure X-2. Multiplate Li-Al/FeS Cell (31)

cell, the choice is based mainly on the ease of fabrication and the cost of the materials (30). Fabrication in the discharged state appears to be the most economical method, and will be the method analyzed for energy requirements. Due to unsolved problems with using FeS_2 cathodes, most of the prototype electric vehicle cells that have been built use FeS positive electrodes. For this reason, only the LiAl/FeS cell is being considered here.

The lithium-metal sulfide cells will be assembled into the form of a long rectangular battery. This configuration would provide an economical installation in a vehicle, using the battery housing as an integral frame member. The battery components consist of 120 cells aligned in two rows on a cell tray, each cell separated by an asbestos-like electrical insulation called Raybestos®. Between the two rows of cells is an electrical resistance heater. Above the cells is a cooling tube through which air is circulated. These latter two components are part of the thermal management system required to maintain a relatively constant operating temperature. During steady-state operation, the heater will not be required and cooling is anticipated to be minimal. Electrical connections are attached above the cells. The cell tray is wrapped with a Raybestos® liner and inserted in an insulated containment vessel along with cell tray end plates at each end. The containment vessel is insulated with a microporous ceramic material called "Min-K." An insulation block of Min-K material is inserted in the open end of the vessel. Feedthrough connections are attached to the electrical connector through the insulation block and a heater plate installed at the same end. All battery components and hardware are made of stainless steel except copper for the electrical connectors and the Min-K and Raybestos® materials. It is anticipated that in another year or so, an evacuated containment vessel

will be available to replace the insulated one. This new vessel, currently under development, will provide thermal resistance through the use of a vacuum to provide a more volume-efficient container. A new type of material will take the place of steel to reduce the weight while improving the structural stability required of evacuated containers. However, this type of containment vessel has not been fully developed, and will not be considered in this study.

Table X-1 shows the components of the battery systems and their weights per kWh for use in electric vehicle and load-leveling applications. The electric vehicle battery is designed for a high specific energy, achieved by using less steel in the cell can and miscellaneous structural components, resulting in a lower total weight.

Battery efficiencies in the range of 75 to 85 percent have been achieved by prototype multicell units, and an efficiency of 78 percent has been assumed for this study for the electric vehicle urban driving cycle application (32). Battery specific energy has been taken to 44.5 Wh/lb (98 Wh/kg) (33).

C. Energy Investment

Based on the materials used in the lithium-metal sulfide battery, an analysis of the following materials and processes has been performed:

- (1) Lithium chloride and lithium sulfide
- (2) Aluminum
- (3) Iron and steel

TABLE X-1. MATERIALS USED IN THE LITHIUM-METAL SULFIDE BATTERY

Material	Amount (Percent)
Steel	34.3
Lithium Sulfide (Li_2S)	9.5
Aluminum	10.8
Iron	9.5
Lithium Chloride (LiCl)	9.4
Potassium Chloride (KCl)	12.0
Boron Nitride (BN)	1.4
Molybdenum	0.2
Copper	3.5
Asbestos	2.1
Thermal Insulation	7.3
Total	100

- (4) Potassium chloride
- (5) Molybdenum
- (6) Boron nitride
- (7) Thermal insulation
- (8) Asbestos
- (9) Copper
- (10) Battery assembly.

Detailed tables showing energy use by type to produce each of the materials appear in Appendix A.

1. Lithium Products

Two lithium compounds are used in the lithium-metal sulfide battery: lithium sulfide and lithium chloride. Lithium sulfide is used in the manufacturing process since the battery is assembled in the discharged state. Since lithium sulfide is not being made commercially, its only producer for use in the prototype batteries considers the process to be proprietary. The energy estimates supplied by this producer are for bench-scale laboratory production processes, and no estimates were given for commercial production on a plant scale. Based on the information provided on the manufacturing process and energy usage for lithium sulfide production, an estimate of 321,799 Btu/lb LiS_2 was used.

Lithium chloride is used as part of the molten salt electrolyte for the lithium-metal sulfide battery. It is manufactured primarily from lithium carbonate, which in turn comes principally from domestically mined pegmatites. The primary pegmatite mineral containing lithium compounds is spodumene ore, which is obtained from open-pit mines and concentrated by crushing, separation, grinding, flotation, dewatering, and drying. The concentrated ore is then shipped

to lithium chemicals plants. In producing lithium carbonate, the concentrated ore is calcined in a kiln to convert the a-spodumene to more reactive b-spodumene. It is then ground, mixed with sulfuric acid, and roasted for a short period of time. Ground limestone is added to neutralize excess acid, and the acid-roasted ore is leached, washed, and filtered. Lithium carbonate is precipitated out by the addition of sodium carbonate, centrifuged, and dried. Hydrochloric acid is then added to form a lithium chloride solution, which is evaporated and dried to crystal form. The production processes and energy requirements for lithium chloride used in electric vehicle batteries are shown in Figure X-3 (20).

2. Aluminum

Aluminum is alloyed with lithium to form the anode in the lithium-metal sulfide battery. Aluminum is produced from bauxite using a complex process which consists of ore preparation, conversion of bauxite to alumina using the Bayer process, and reduction of the alumina to aluminum using an electrochemical smelting process. Aluminum production processes have been described in detail in Chapter VIII. The processes used in manufacturing aluminum and the energy use per pound of battery are shown in Figure X-4 (8).

3. Iron and Steel

Iron and steel are used for mechanical components of the battery and as the active material in the battery. Iron and steel production processes are described in detail in Chapter IV.

Figure X-3. Energy Used to Produce Lithium Chloride for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb Battery)(20)

Figure X-4. Energy Used to Produce Aluminum for Lithium-Metal Sulfide Batteries for Electric Vehicle Use (Btu/lb Battery)(8)

Energy used for iron production in lithium-metal sulfide batteries is shown in Figure X-5 and energy used to produce steel is shown in Figure X-6 (8).

4. Potassium Chloride

Potassium chloride, used with lithium chloride as the electrolyte for the lithium-metal sulfide battery, is obtained principally by the flotation process. About 91 percent of the potassium salts produced in the United States come from underground ore mines in New Mexico and Utah (20). The flotation process begins with suspending crushed ore in brine, removing clay, and separating potassium chloride in the flotation froth. Sodium chloride is centrifuged and recycled as the brine. The froth containing the potassium chloride is also centrifuged. The clay that has been removed is subjected to hot leaching and thickening to recover fine particles of potassium chloride, and then cooled in crystallizers. The crystals are then centrifuged with the froth. The potassium chloride is dyed, screened, granulated, and packaged. The potassium chloride production processes and their energy requirements for use in electric vehicle batteries are shown in Figure X-7 (20).

5. Molybdenum

Molybdenum is obtained primarily from ores containing approximately .34 percent molybdenite, and is produced in the form of molybdic oxide (MoO_3). The major end use for molybdenum in the United States is as an alloying element in the production of various types of steels, and it is usually added in the form of molybdic oxide (20). The use of molybdenum in the lithium-metal sulfide battery is as an alloying element

Figure X-5. Energy Used to Produce Iron for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb of Battery)(8)

Figure X-6. Energy Used to Produce Steel for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb of Battery)(8)

Figure X-7. Energy Used to Produce Potassium Chloride for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb of Battery)(20)

for steel in the positive current collector. In the molybdenic oxide production process, the ore is mined, crushed, ground, and concentrated. This is then transported and roasted in a multiple hearth furnace at an average temperature of 1,100°F to convert the concentrate to molybdenic oxide. Since large quantities of the fine concentrate are carried off in the flue gas, two multiclones in series with an electrostatic precipitator achieve a dust collection efficiency of about 98.5 percent. These recovered particulates are recycled to the roaster feed (20). The production processes, containing energy requirements for use of molybdenum in electric vehicle batteries are shown in Figure X-8.

6. Boron Nitride Felt

Boron nitride (BN) felt is used as the separator material in the electric vehicle batteries. The boron nitride felt manufacturing process is relatively new, developed principally for producing the material for lithium-metal sulfide batteries. Although the process is considered proprietary and a detailed flow diagram is not given, energy requirements were provided (34). The major constituents necessary for producing BN felt are boric oxide, ammonia, and nitrogen. These are combined to form boron nitride fibers which are then bonded to form a felt, like an unwoven cloth. A simplified flow diagram containing energy requirements for boron nitride felt for electric vehicle applications is shown in Figure X-9.

Figure X-8. Energy Used to Produce Molybdenum for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb of Battery)(20)

TOTAL: 10,109

BORON NITRIDE FELT

Figure X-9. Energy Used to Produce Boron Nitride Felt for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb Battery)(34)

7. Thermal Insulation

The thermal insulation currently envisioned for the lithium-metal sulfide battery is a special high-temperature, low-thermal conductivity material known as "Min-K." The material composition and processes used to produce this material are proprietary and could not be obtained in enough detail to estimate the energy required for its manufacture.

All that is known about the material is that it consists of a silica material with fiber reinforcement and a passifier which blocks radiation through the material. The material is produced by mixing the component materials, cold pressing them to shape, and curing by baking the material in an oven. The resulting material is brittle and has excellent thermal insulation properties.

Since the processes involved in the manufacture of this material are proprietary, we have analyzed the battery based on the assumption that a lower-performance insulation such as fiberglass could be used. The energy analysis for the insula-

tion is based on the energy requirements for the production of glass fibers. Glass production processes have been discussed in depth in Chapter VIII; Figure X-10 shows the energy to produce glass insulation for the lithium-metal sulfide battery in Btu/lb of battery (8).

8. Asbestos

A type of asbestos is used for electrical insulation material in both the electric vehicle and load-leveling batteries. The majority of North American asbestos fiber production consists of open-pit mining of chrysotile asbestos. The ore is crushed, dried, recrushed, and screened. Undersized pieces go to waste rock, and oversized pieces are milled, cleaned, and graded. The asbestos fiber production processes, containing energy requirements in Btu per pound of battery, are shown in Figure X-11 for use in electric vehicle batteries (7). Energy requirements for bag filters and cyclone systems needed for health and environmental controls are included in the figure (7).

9. Copper

Copper ores are mined from the earth and sent to concentrators. The concentrators crush and grind the ore and pass it through a flotation process which yields a copper concentrate containing about 25 percent copper. The concentrate is then smelted into a matte which is refined using the electrolytic process, yielding copper with a purity of more than 99 percent.

For every net ton of copper produced, mining consumes 10,805 Btu, the concentrator process consumes 21,165 Btu,

Figure X-10. Energy Used to Produce Glass Insulation
Used in a Lithium-Metal Sulfide Battery
(Btu/lb Battery)(8)

Figure X-11. Energy Used to Produce Asbestos Fibers for Lithium-Metal Sulfide Batteries for Electric Vehicles (Btu/lb of Battery)(7)

smelting consumes 19,111 Btu, and refining consumes 5,066 Btu, resulting in a total of 56,146 Btu (see Appendix A) per pound of copper (8). Figure X-12 translates these figures into Btu of energy per pound of a lithium-metal sulfide battery.

Figure X-12. Energy Used in Copper Production for Lithium-Metal Sulfide Batteries (Btu/lb of Battery)(8)

10. Battery Assembly

The assembly of a 50 kWh lithium-metal sulfide battery has been conceptualized and flow charted for a fully automated system capable of manufacturing up to 45 batteries per day, each battery containing 120 cells and weighing about 1,153 pounds (33). Each cell weighs 7.85 lb, adding up to about 942 lbs for 120 cells, which is about 82 percent of the total battery weight (33). It is anticipated that two of these batteries would be used for electric vehicle applications. These batteries will also be used as modules for load-leveling applications. The basic cell assembly process is expected to occur in dry room conditions, and begins with an automatic shaker filler press for the positive plate construction, and an automatic cutter press for the separator material. These are then hand assembled with the negative plate in a cell

can, and are automatically welded in place. The terminal assemblies and insulator blocks are then hand welded into place. The header plate and feedthrough assembly are automatically welded and crimped in place, and the cell is heated and filled with the molten electrolyte in an automatic conveyor belt oven. Completed cells proceed to the battery manufacturing line where they are automatically assembled in cell trays, along with front and rear plates, and welded. Cell interconnections are automatically welded on, and the miscellaneous hardware such as the thermocouple harness, cooling tube, header plate, and seal are hand welded in place. The cell tray assembly is then inserted in the insulated containment vessel and bolted together by hand.

Energy requirements for each step are difficult to estimate since the process is only in the conceptual stage. Based on similar battery manufacturing and industrial operations, an estimate of the energy requirements as a function of component production energy requirements was made. It was assumed that 33 percent of the energy required for producing each component of the battery would be required to manufacture the lithium-metal sulfide battery. This energy requirement has been assumed to be evenly distributed between electric, gas, and oil sources.

D. Operation

The methodology described in Chapter III was used to calculate the operational energy for a vehicle powered by a lithium-metal sulfide battery. The net energy efficiency of the vehicle powered by the lithium-metal sulfide battery is .301 kWh/mile (see Table III-2.) Allowing for a 40 percent efficiency of electric generation, this results in a net

energy use of 2,568 Btu/mile or 256.8 million Btu per 100,000 miles.

E. Recycling

Several components of the lithium-metal sulfide battery have potential for recycling. Since reuse of materials results in a lowered energy requirement for raw materials production, recycling, in effect, results in an energy credit that can be applied to the manufacturing processes.

The potentially recyclable elements in this battery are steel, lithium sulfide, iron, aluminum, the lithium chloride component of the eutectic salt, and boron nitride felt. The steel, aluminum, and iron components can be recycled through existing channels of scrap recovery. Special processing stations would have to be established for recovery of the lithium products and the boron nitride felt, both of which require a dry environment. The boron nitride felt would have to be recovered intact to be worth reclaiming (35). Because the economics and processes that would be used for recycling have not been fully developed, only recycling of the aluminum, steel, and iron is being considered at this time. A 50 percent recovery rate has been assumed for all three of the materials, which means that the recycling credits are applied to half of the weight of the respective battery components. In calculating the energy credits, the recovered iron is assumed to replace iron ore in the iron and steel production process because of the sulfide content assumed to remain in the iron upon battery recycling. The recycling energy consumption and credits are given in Table X-2. Information on energy requirements for secondary production of these metals is from Reference 14.

TABLE X-2. RECYCLING CREDITS FOR LITHIUM-METAL SULFIDE
ELECTRIC VEHICLE BATTERY

Material	lb Recycled/lb Battery	Credit (Btu/lb Recycled)	Credit (Btu/lb Battery)
Aluminum	.054	117,575	6,349
Steel	.171	9,451	1,616
Iron	.048	144	7
Copper	.017	54,242	922
TOTAL	.288		8,894

XI. THE ALUMINUM-AIR BATTERY

A. Battery Description

The aluminum-air battery uses the reaction of aluminum with air to produce electric power. The aluminum-air battery differs from other electric vehicle batteries in that it is mechanically rechargeable through replacement of the aluminum fuel plates. The recharging of the battery actually occurs when spent aluminum fuel (in the form of alumina) is processed back into new fuel plates. This characteristic, coupled with its high specific energy, gives the aluminum-air battery a range and convenience approaching those for conventional vehicles.

Under DOE contracts, the Lawrence Livermore Laboratory and Lockheed Missiles and Space Company have explored lithium-, aluminum-, and calcium-air systems. Only aluminum appears to present real possibilities for use in the intermediate term (1985-1990), because of its relative abundance and its large expected domestic production capacity in the 1980s (36). The fuel cycle associated with the aluminum-air battery involves the transportation of aluminum fuel plates and cell reaction products between industrial production plants and highway service stations. The vehicle would be stocked periodically with metal sufficient for a nominal range of 1600 km. At more frequent intervals (500 or 750 km), the vehicle would stop to take on demineralized water and to discharge the reaction product. The latter would be in the form of an air-dried powder of trihydrated alumina (hydrargillite). This product would then be returned to aluminum production plants, calcined, and used as feedstock for the Hall-Heroult process. Figure XI-1 shows the flow of materials and energy for the battery system.

Figure XI-1. One Possible Refueling Schedule for an Electric Vehicle Powered by Aluminum-Air Battery

The essential structure of an aluminum-air power cell is shown in schematic form in Figure XI-2. In the current design concept, the cell consists of an aluminum anode plate (roughly 30 cm square and 0.2 cm thick) and an air-cathode module with grooves for electrolyte flow. Other components are provided for settling, washing, and drying hydrargillite precipitate $[\text{Al}(\text{OH})_3]$, for condensing water from the air-cathode exhaust vapor, for removing carbon dioxide and road dirt from the incoming airstream, and for storing water and reaction product.

During discharge, aluminum anode plates and water react with atmospheric oxygen to produce electric energy and a reaction product. As the aluminum anode dissolves, it forms an unstable, soluble reaction product -- sodium aluminate.

This is allowed to precipitate slowly to form hydrargillite:

The reaction product, a trihydrated alumina called hydrargillite or gibbsite, is further processed within the battery to form a purified, alkali-free, air-dried powder consisting of granules about 20 to 40 μm in diameter (37). These processes are part of the Bayer process used in the aluminum industry today to produce alumina feedstock for metal production. Thus, the battery output matches an intermediate feedstock in the production of aluminum. The net chemical reaction is:

Figure XI-2. Schematic of a Unit Cell in an Aluminum-Air Battery

The aluminum-air cell requires auxiliary equipment to process the fuel for recycling, purify the air, and recirculate the electrolyte. The five subsystems that support the operation of the aluminum-air cell are shown in Figure XI-3. They are air, electrolyte, hydrargillite, water, and coolant.

Air enters the system, where it is first heated and then used to dry the $\text{Al}(\text{OH})_3$ product. Air is then scrubbed to remove carbon dioxide, saturated with water, and finally reacted in the cell stack. Water is condensed from the exiting air, which is then vented to the atmosphere.

Electrolyte is circulated between the cell stack and the crystallizer, where $\text{Al}(\text{OH})_3$ is allowed to crystallize under controlled conditions. Heat of reaction and $\text{Al}(\text{OH})_3$ crystallization is removed by heat exchange with a coolant. Crystallized $\text{Al}(\text{OH})_3$ crystals are removed from the crystallizer as a paste, washed with reactant water, drained, partially dried, and stored.

Tap water enters the system, is heated and evaporated in the air stream. Condensed water from air is used both to wash the product and as reactant in the cell. In the event more water is condensed than is required for the chemical reaction, the excess is recycled into the tap water. Alternatively, if not enough water is condensed, distilled water must be supplied. Coolant is used to transfer heat from the electrolyte to the atmosphere and to heat the incoming air and the $\text{Al}(\text{OH})_3$ paste (38).

Estimation of the total energy cost of propulsion requires forecasting of aluminum and electricity production efficiencies for future years. Due to rapid increases in electricity costs, it is likely that future aluminum smelting plants will be more energy efficient than present plants. The types of

Figure XI-3. Aluminum-Air Power Cell System (39)

plants used will depend on a number of factors including the availability of energy in other countries, the costs of shipping bauxite and aluminum, and perhaps the effect of introducing the aluminum-air battery. If the aluminum-air battery comes into general use, reprocessing plants dedicated to battery material processing will be required. Current aluminum reduction plants, using technology developed over 20 years ago, require approximately 8 kWh/lb of aluminum (17.6 kWh/kg) for the reduction step (8). Plants designed for higher energy prices using state-of-the-art technology are able to achieve an energy use of 6 kWh/lb (13.2 kWh/kg). This range of future aluminum smelting energy efficiencies makes the overall efficiency sensitive to assumptions concerning the technology that will be in place when the battery is used.

For the purposes of this study, an optimistic number representing the best available aluminum smelting technology was used (6 kWh/lb). This value reflects the technology that will be used if the aluminum-air battery becomes a major power source for vehicles.

In addition to the energy used in the reprocessing plant, an energy penalty must be paid for transportation of the fuel back and forth from the recharging station to the plant. To account for this value, it has been assumed that the fuel is transported 50 miles by truck and 500 miles by rail both to and from the processing plant.

It has also been assumed that aluminum reduction would utilize base-load power with an efficiency of generation (from fossil or nuclear sources) of 40 percent. This assumption is consistent with the recharging assumptions made for other types of batteries.

Metallic aluminum is produced by the electrolytic reduction of pure alumina in a bath of fused cryolite. The carbon for the reaction comes from the anode, for which 0.5 to 0.6 lb of carbon is required per pound of metal (8).

Carbon anodes are manufactured from coke and used in the cell. The cryolite bath is prepared and its composition controlled. Alumina is dissolved in the molten cryolite bath. The solution of alumina in molten cryolite is electrolyzed to form metallic aluminum. It serves as the cathode. The carbon electrode is oxidized by the liberated oxygen. The molten aluminum is tapped from the cells, alloyed, cast into ingots, and cooled.

Total efficiency of this storage system depends on electrical generating efficiency, aluminum refining efficiency, energy required in distribution, conversion efficiency of the power cells, and efficiency in the vehicle's power train. With today's best aluminum anode alloy, the net discharge energy conversion efficiency of the power cell under urban driving conditions is about 53 percent of standard free energy of $\text{Al-H}_2\text{O-O}_2$ reaction. The energy that can be obtained from the aluminum fuel at this efficiency is 4.2 kWh/lb or 1.9 kWh/kg.

B. Battery Component Weights and Performance

Table XI-1 shows the weights for the various materials in the battery. Since the aluminum-air battery absorbs and rejects water to the atmosphere and also absorbs oxygen from the air, its weight changes during its discharge cycle. The

TABLE XI-1. MATERIALS USED FOR THE ALUMINUM-AIR BATTERY (39)

Material	Weight in Battery (lb)*	Percent
Aluminum	140.7	28.0
Polyethylene and Other Plastics	88.2	17.5
Steel	39.5	7.8
Electrolyte:		
Water	70.1	14.0
Sodium Hydroxide	12.3	2.4
Al(OH) ₃ Seed Crystal	33.1	6.6
Copper Electrical Connections	33.1	6.6
Water	77.6	15.4
Other	<u>8.4</u>	<u>1.7</u>
TOTAL	503.0	100.0

**Based on a 70 kWh battery (per water cycle) with a power output of 40 kw.*

weights given in Table XI-1 are for a recharged battery [Al(OH)₃ has been removed and the battery has been refilled with water]. The amount of aluminum fuel (which is only replaced every four water cycles) is an average over the aluminum fill-refill cycle. During a normal discharge cycle, the water and oxygen absorbed from the air are approximately balanced by water lost in the condenser, so the battery only increases in weight by 5 percent; for this reason the battery weight has been assumed to be constant.

The weights in Table XI-1 are for a 70 kWh battery (per water cycle) designed to be filled with water four times before replacing the aluminum. This means that the energy storage density of the battery is 139 Wh/lb (63 Wh/kg). The energy efficiency of the battery is not directly comparable with that of a conventional battery since the fuel reprocessing occurs off-site. The battery does, however, produce 4.2 kWh/kg of aluminum fuel (1.9 kWh/lb).

C. Energy Investment

Based on materials and processes associated with the aluminum-air battery, an analysis of the following materials and processes has been performed.

- (1) Aluminum
- (2) Sodium hydroxide (electrolyte)
- (3) Plastic
- (4) Steel
- (5) Copper
- (6) Alumina
- (8) Battery assembly.

Each analysis contains a brief description of the process involved and a quantification of energy used for the entire process.

1. Aluminum

Aluminum is used in the aluminum-air battery for the anode. Aluminum is produced from bauxite using a complex process which consists of ore preparation, conversion of bauxite to alumina using the Bayer process, and reduction of the alumina to aluminum using an electrochemical smelting process. The aluminum production process has been discussed in detail in Chapter VIII and is not repeated here. The processes used in manufacturing aluminum are shown in Figure XI-4 (8).

2. Sodium Hydroxide

Sodium hydroxide, used as the electrolyte for the aluminum-air cell, is made by the electrolysis of salt. In this process, direct current is passed through a sodium chloride (salt) solution in specially designed cells. The salt brine is decomposed by the current to form 10 to 12 percent sodium hydroxide solution, with hydrogen gas forming at the cathode and chlorine gas at the anode as coproducts (9). Two types of cells, the mercury cathode and the diaphragm, are used; new installations use the diaphragm because of the danger of mercury pollution in effluent.

The electrolyte is a saturated (about 25 percent) salt solution, which is heated and passed into purification tanks, where it is treated with sodium carbonate and caustic soda to remove calcium and magnesium compounds. The purified brine

Figure XI-4. Energy Used to Produce Aluminum
for Aluminum-Air Batteries
(Btu/lb of Battery)(8)

is neutralized with hydrochloric acid, reheated, and fed to the cells for electrolysis. The cell contains a diaphragm of asbestos to separate the graphite or metallic anode from the steel screen or wire cathode. Brine flows into the anode compartment, where chlorine is evolved, and then through the porous diaphragm which allows the ions to pass but reduces diffusions of the products from the cathode compartment where sodium hydroxide and hydrogen are formed. Several purification processes may be used, depending on the concentration of product which is obtained. To produce one pound of sodium hydroxide, 1.65 lb of salt is required. The energy requirement per pound of sodium hydroxide is shown in Appendix A. Figure XI-5 shows the energy used to produce sodium hydroxide.

3. Plastic

It is anticipated that many of the battery components, such as pipes for the electrolyte and storage tanks for the fluids, will be made of plastic. Polyethylene is used in this analysis to represent these plastics since most of the plastic parts are expected to be made of polyethylene.

Polyethylene is produced by the polymerization of ethylene, which is produced from natural gas. For every net ton of plastic produced, ethylene production consumes 79×10^6 Btu and polyethylene production consumes 15.5×10^6 Btu, resulting in a total of 94.55×10^6 Btu per ton (see Appendix A), or 47,275 Btu per pound of plastic. Figure XI-6 translates these figures into Btu of energy per pound of an aluminum-air battery (11).

Figure XI-5. Energy Used to Produce Sodium Hydroxide for Aluminum-Air Batteries (Btu/lb of Battery)(9)

Figure XI-6. Energy Used to Produce Plastic for Aluminum-Air Batteries (Btu/lb of Battery) (11)

4. Steel

Steel is used in the aluminum-air battery for structural parts, motors and pumps, and for current collectors. The processes involved in steel production are described in Chapter V and are not repeated here. Figure XI-7 shows the processes involved in steel production and the energy required to produce steel for the aluminum-air battery (8).

5. Copper

Copper ores are mined from the earth and sent to concentrators. The concentrators crush and grind the ore and pass it through a flotation process which yields a copper concentrate containing about 25 percent copper. The concentrate is then smelted into a matte which is refined using the electrolytic process, yielding copper with a purity of more than 99 percent.

For every net ton of copper produced, mining consumes 10,805 Btu, the concentrator process consumes 21,165 Btu, smelting consumes 19,111 Btu, and refining consumes 5,066 Btu, resulting in a total of 56,146 Btu (see Appendix A) per pound of copper (8). Figure XI-8 translates these figures into Btu of energy per pound of an aluminum-air battery.

6. Alumina

A small amount of aluminum hydroxide $[\text{Al}(\text{OH})_3]$ is used as seed crystals in the aluminum hydroxide precipitation tank in the battery. This material is essentially a hydrate of aluminum oxide and the processes have been assumed for the production of this material.

Figure XI-7. Energy Used to Produce Steel for an Aluminum-Air Battery
(Btu/lb of Battery)(8)

Figure XI-8. Energy Use in Copper Production for Aluminum-Air Batteries (Btu/lb of Battery)(8)

Alumina is the result of processing of bauxite ore. The major steps include the ore purification processes, where bauxite is separated from other rock, and Bayer processing, in which bauxite ore is mixed with caustic soda under a high temperature and pressure.

Bayer processing results in a pure grade of alumina which can then be processed into aluminum or other materials. Figure XI-9 shows the energy required to produce alumina for battery seed crystals (8).

Figure XI-9. Energy Used to Produce Alumina for the Aluminum-Air Battery (8)

7. Other Materials

The only other material present in quantity in the aluminum-air battery is water, which is used for cooling, as a reactant, and as part of the electrolyte. Other materials, such as paper for the air intake duct, miscellaneous electric motor parts, and other materials account for less than 2 percent of the battery and their investment energy is not included.

8. Battery Assembly

Although the battery assembly process has been defined and broken down into specific operations, it is difficult to use this information to estimate the energy used in producing the battery. In order to provide some estimate of the amount of energy used in the battery assembly, it has been assumed that the aluminum-air battery manufacturing process consumes roughly one-third of the energy required for the materials used in the battery. Using this figure, the energy cost for manufacturing is 16,248 Btu/lb of battery.

D. Operation

Because of its special characteristics, the aluminum-air battery has been analyzed using slightly different assumptions from the other vehicle batteries. The assumptions used to evaluate the aluminum-air battery are as follows:

- (1) The General Electric/Chrysler experimental electric vehicle was used as the reference vehicle for the analysis.

- (2) The energy on board the vehicle was set at 70 kWh per water refill cycle. This energy is considerably greater than the 18.6 kWh assumed for the other batteries discussed in this report. The reason 70 kWh was used is that this number is the size of the reference battery used by Lawrence Livermore Laboratory in analyzing the battery. The aluminum-air battery, with its rapid refueling capability and high energy storage capacity does not compare directly with more conventional storage batteries which are charged and discharged in the vehicle. It is unlikely that the aluminum-air cell will ever be used in a low range vehicle since its major advantage is long range and rapid refueling. An attempt to scale the aluminum-air battery down to a size of 18.6 kWh is unrealistic since it would not be practical to build a system with a capacity that small.
- (3) The SAE J227"D" driving cycle was used as the reference for energy efficiency calculations (see Chapter III).
- (4) Since the aluminum-air battery cannot be recharged on board, no regenerative braking was assumed.

The major effect of assumption (2) is to increase the investment energy for the aluminum-air battery. If equal performance (storage capacity) batteries were compared, the aluminum-air battery's investment energy would be about one-third of the value calculated.

Assumption (4) increases the energy use per mile on the SAE J227"D" cycle by approximately 20 percent, increasing the operational energy by this amount.

A major factor in the operational energy is the amount of energy required to reprocess alumina back into aluminum fuel. The reprocessing step is a portion of the normal aluminum production process and consists largely of electrolytically reducing the alumina using an electric current. Past performance of aluminum smelters as described in reference (8) requires an electricity use of 8 kWh per pound (17.6 kWh/kg). This technology was developed and used during a time when electricity was inexpensive and does not reflect the most efficient technology available. Modern plants with new technology have the potential of achieving a lower energy use of 6 kWh/lb (13.2 kWh/kg), which may result in a reduction in the recharge energy. Since any significant use of the aluminum-air battery will require new dedicated plants, it is likely that the most energy-efficient processes will be used. Therefore, the best available technology (6 kWh/lb) was assumed for alumina reprocessing.

The projected energy use of the aluminum air-powered vehicle is .252 kWh/mile input to the vehicle drivetrain from the battery. Since aluminum provides 1.9 kWh/lb (4.2 kWh/kg), the aluminum fuel use will be .132 lb Al/mile or 13,200 lb per 100,000 miles. Using advanced processing technology, this aluminum would require 924 million Btu.

E. Recycling

When the battery no longer operates, the aluminum fuel can still be recycled for use in other vehicles. The alumina from the battery can be used directly in aluminum production and the energy credit is equal to the amount of energy that would be required to produce the alumina from ore. The difference between the energy to produce calcined alumina

from ore and a similar product from the battery product is 19,375 Btu/lb Al. Since all of the fuel is recycled, the credit is for 0.280 lb Al per pound of battery or 5,425 Btu/lb of battery.

It has also been assumed that 50 percent of the copper and steel are recycled, resulting in an energy credit of 369 Btu and 1,790 Btu.

F. Life-Cycle Energy Use

The total life-cycle energy use for the aluminum-air battery (100,000 miles) is 952.5 million Btu. This includes an energy investment of 32.7 million Btu, an operational energy of 923.6 million Btu, and a recycling credit of 3.8 million Btu.

XII. CONCLUSIONS

Several conclusions can be made on the basis of the life-cycle analyses of electric vehicle batteries:

- Life-cycle energy use is dominated by operational energy use. Small changes in energy efficiency have a larger effect on total energy use than relatively large changes in investment energy
- The life-cycle assumption (100,000 miles) assumes that batteries will last between 1,500 and 2,000 cycles. If batteries cannot achieve this performance level, investment energy becomes a correspondingly greater portion of the total life-cycle energy use
- The use of batteries to power vehicles causes a fuel shift from gas and oil many times the energy investment to build the batteries
- The largest single factor in determining the life-cycle energy use of a battery is the battery efficiency
- Advanced batteries, although they require less raw material, have a higher energy investment because they use materials which are more energy intensive.

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APPENDIX A
ENERGY REQUIREMENTS FOR
BATTERY MATERIALS

TABLE A-1. ENERGY USE IN PRODUCTION OF
SULFURIC ACID (Btu/lb) (1)

	Electric	Coal	Gas	Petroleum	Other	Total
Frasch Mined Sulfur	70	0	485	18	(356)	217
Recovered Sulfur	37	0	0	0	(200)	(163)
Other Sulfur	15	0	0	0	(84)	(69)
Smelter Gas	0	0	0	0	33	33
TOTAL	122	0	485	18	(607)	18

TABLE A-2. ENERGY USE IN PRODUCTION OF
LEAD (Btu/lb) (1)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining and Ore Preparation	3,425	0	0	415	555	4,395
Smelting	485	3,825	415	0	265	4,990
Refining	245	65	2,280	0	695	3,285
Other	625		375	30	(305)	725
TOTAL	4,780	3,890	3,070	445	1,210	13,395

TABLE A-3. ENERGY USE IN PRODUCTION OF
POLYETHYLENE (Btu/lb) (2)

	Electric	Coal	Gas	Petroleum	Other	Total
Ethylene Production	120	55	32,535	11,080	(4,270)	39,520
Polyethylene Production	3,600	0	1,630	2,525	0	7,755
TOTAL	3,720	55	34,165	13,605	(4,270)	47,275

TABLE A-4. ENERGY USE IN PRODUCTION OF
NICKEL (Btu/lb) (3)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining and Beneficiation	20,020	0	0	2,385	5,050	27,455
Refining	14,720	0	21,205	695	7,780	44,400
TOTAL	34,740	0	21,205	3,080	12,830	71,855

TABLE A-5. ENERGY USE IN PRODUCTION OF
NICKEL HYDROXIDE

	Electric	Coal	Gas	Petroleum	Other	Total
Ammonia Production (3)	56	0	7,432	0	2	7,490
Nickel Production (3)	21,330	0	13,020	1,891	7,878	44,119
Nitric Acid Production (4)	63	0	0	0	0	63
Nickel Nitrate Production	0	0	0	0	8,528	8,528
Sodium Hydroxide Production	5,981	4,543	4,543	4,543	(2,083)	17,527
Nickel Hydroxide Production	5,354	0	0	0	0	5,354
TOTAL	32,784	4,543	24,995	6,434	14,325	83,081

TABLE A-6. ENERGY USE IN PRODUCTION OF
AMMONIA (Btu/lb) (3)

	Electric	Coal	Gas	Petroleum	Other	Total
Reforming	0	0	15,365	0	1	15,366
Shift, Carbon Dioxide Removal and Methanation	105	0	0	0	4	109
Compressing Synthesis Gas	0	0	3,595	0	0	3,595
Synthesis	40	0	210	0	1	251
TOTAL	145	0	19,170	0	6	19,321

TABLE A-7. ENERGY USE IN PRODUCTION OF
NITRIC ACID (Btu/lb) (4)

	Electric	Coal	Gas	Petroleum	Other	Total
Ammonia Production (3)	42	0	5,501	0	2	5,545
Nitric Acid Production	47	0	0	0	0	47
TOTAL	89	0	5,501	0	2	5,592

TABLE A-8. ENERGY USE IN PRODUCTION
OF SODIUM HYDROXIDE

	Electric	Coal	Gas	Petroleum	Other	Total
Salt Mining (1)*	99	0	0	0	0	99
Electrolysis of Salt (4)*	13,095	0	0	0	0	13,095
Hydrogen Credit*	0	0	0	0	(4,596)	(4,596)
Steam (4)**	0	5,345	5,345	5,345	0	16,035
Subtotal	13,194	5,345	5,345	5,345	(4,596)	24,633
Allocated to Chlorine	6,157	0	0	0	(2,145)	4,012
Allocated to Sodium Hydroxide	7,037	5,345	5,345	5,345	(2,451)	20,621

* Allocated 53 percent to sodium hydroxide, 47 percent to chlorine.

**Allocated to sodium hydroxide production. Steam energy is equally divided among coal, gas, and petroleum.

TABLE A-9. ENERGY USE IN PRODUCTION OF
NICKEL NITRATE HEXAHYDRATE (Btu/lb)

	Electric	Coal	Gas	Petroleum	Other	Total
Nitric Acid Production	39	0	2,420	0	1	2,460
Nickel Production	6,948	0	4,241	616	2,566	14,371
Nickel Nitrate Hexahydrate Production	0	0	0	0	4,616	4,616
TOTAL	6,987	0	6,661	616	5,345	19,609

TABLE A-10. ENERGY USE IN PRODUCTION OF
ZINC OXIDE (Btu/lb) (1,4)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining and Beneficiation	3,769	0	0	460	1,249	5,478
Drying, Roasting, Pelletizing, Sintering, and Filtering	1,652	546	718	109	264	3,289
Reduction/Electrolysis	12,339	2,098	0	0	3,403	17,840
Zinc Oxide Manufacturing (French Process)	0	8,255	1,880	0	0	10,135
TOTAL	17,760	10,899	2,598	569	4,916	36,742

TABLE A-11. ENERGY USE IN PRODUCTION OF
POTASSIUM HYDROXIDE (Btu/lb) (3,4)

	Electric	Coal	Gas	Petroleum	Other	Total
Potassium Chloride Mining*	819	0	45	13	1,018	1,895
Electrolysis*	9,524	0	0	0	0	9,524
Steam**	0	3,808	3,808	3,808	0	11,424
Hydrogen Credit*	0	0	0	0	(3,310)	(3,310)
Subtotal	10,343	3,808	3,853	3,821	(2,292)	19,533
Allocated to Chlorine Production	3,978	0	27	5	(882)	3,128
Allocated to Potassium Hydroxide Production	6,365	3,808	3,826	3,816	(1,410)	16,405

* Allocated 61% to potassium hydroxide, 39% to chlorine.

**Allocated 100% to potassium hydroxide. Steam is generated equally from coal, oil, and gas.

TABLE A-12. ENERGY USE IN PRODUCTION OF
COPPER (Btu/lb) (1)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining	4,141	17	110	2,684	3,852	10,804
Concentrating	15,525	0	1,233	122	4,286	21,166
Smelting	2,340	63	9,848	5,742	1,118	19,111
Refining	1,653	88	1,518	1,494	313	5,066
TOTAL	23,659	168	12,709	10,042	9,568	56,146

TABLE A-13. ENERGY USED TO PRODUCE PIG IRON
(Btu/lb) (1)

	Electric	Coal	Gas	Petroleum	Other	Total
Iron Ore Production	54	0	0	87	4	145
Iron Ore Pellet Production	476	0	142	200	176	994
Iron Ore Sinter	73	356	35	0	103	567
Coal for Coking	0	11,253	0	0	0	11,253
Coke Production	212	0	0	60	(2,122)	(1,850)
Scrap Mill Scale	0	0	0	0	0	0
Limestone Production	4	1	1	18	3	27
Refractories	0	0	0	0	20	20
Oxygen	0	0	0	0	30	30
Tar and Pitch	0	0	0	0	80	80
Blast Furnace	130	30	165	290	1,955	2,570
By-Product Credit from Blast Furnace	0	0	0	0	(2,280)	(2,280)
TOTAL	949	11,640	343	655	(2,031)	11,556

TABLE A-14. ENERGY USED TO PRODUCE STEEL
(Basic Oxygen Furnace - Btu/lb) (1)

	Electric	Coal	Gas	Petroleum	Other	Total
Pig Iron	895	10,980	324	618	(1,915)	10,902
Scrap	0	0	0	0	0	0
Scrap Transportation	0	0	0	18	0	18
Ferro Manganese	0	0	0	0	333	333
Ferro Silicon	0	0	0	0	73	73
Aluminum	0	0	0	0	79	79
Limestone Mining and Preparation	0	0	0	1	0	1
Lime Production	17	107	108	13	2	247
Fluorspar	0	0	0	5	2	7
Pellets	2	0	1	1	1	5
Mill Scale	0	0	0	0	0	0
Refractories	0	0	0	0	97	97
Oxygen	0	0	0	0	212	212
Basic Oxygen Furnace	194	0	121	0	0	315
Casting	12	71	0	0	288	371
Slabbing	160	755	30	0	11	956
TOTAL	1,280	11,913	584	656	(817)	13,616

TABLE A-15. ENERGY USE IN PRODUCTION OF
FERRIC OXIDE (Btu/lb)

	Electric	Coal	Gas	Petroleum	Other	Total
Sulfuric Acid (1)	150	0	597	22	(747)	22
Pig Iron (1)	655	8,148	240	459	(1,422)	8,090
Iron Sulfate Production	0	0	4,510	4,510	0	9,020
Ferric Oxide Production	0	0	4,171	4,171	0	8,342
Hydrogen Credit	0	0	0	0	(4,596)	(4,596)
TOTAL	815	8,148	9,518	9,162	(6,765)	20,878

TABLE A-16. ENERGY USE IN PRODUCTION OF
LITHIUM HYDROXIDE MONOHYDRATE (Btu/lb) (5)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining	0	0	0	2,659	1,423	4,082
Ore Concentration	4,386	0	0	2,514	3,916	10,816
Credit for By-Product Spodumene	0	0	0	0	(3,502)	(3,502)
Calcining	3,489	50,000	0	0	975	54,464
Production of Lithium Hydroxide	357	0	0	0	4,412	4,769
TOTAL	8,232	50,000	0	5,173	7,224	70,629

TABLE A-17. ENERGY USE IN PRODUCTION OF
HYDROGEN (Btu/lb) (4)

	Electric	Coal	Gas	Petroleum	Other	Total
Gas Feedstock	0	0	45,710	0	0	45,710
Steam*	0	24,618	24,618	24,518	0	73,854
Process Energy**	1,691	0	31,304	31,304	0	64,299
TOTAL	1,691	24,618	101,632	55,922	0	183,863

* Steam has been allocated equally among coal, gas, and petroleum.

**Process energy has been allocated equally between gas and petroleum.

TABLE A-18. ENERGY USE IN PRODUCTION OF
COBALT (5)

	Electric	Coal	Gas	Petroleum	Other	Total
Precipitation	820	0	0	0	20,865	21,685
Thickening, Filtration, and Electrolysis	40,355	0	0	0	75	40,430
TOTAL	41,175	0	0	0	20,940	62,115

TABLE A-19. ENERGY USE IN PRODUCTION OF
STEEL FROM SCRAP (ELECTRIC ARC PROCESS) (Btu/lb) (5)

	Electric	Coal	Gas	Petroleum	Other	Total
Raw Materials and Scrap Preparation	0	0	0	0	845	845
Steelmaking	2,625	0	50	0	0	2,675
Continuous Casting	130	0	305	0	90	525
Other	120	0	0	0	0	120
TOTAL	2,875	0	355	0	935	4,165

TABLE A-20. ENERGY USE IN PRODUCTION OF
COPPER FROM HIGH GRADE SCRAP WIRE (Btu/lb) (5)

	Electric	Coal	Gas	Petroleum	Other	Total
Scrap Preparation and Transportation	0	0	0	240	265	505
Melting and Casting	105	0	1,700	0	(505)	1,300
Other	25	0	75	0	0	100
TOTAL	130	0	1,775	240	240	1,905

TABLE A-21. ENERGY USE IN PRODUCTION OF
LEAD FROM SECONDARY SOURCES (Btu/lb) (5)

	Electric	Coal	Gas	Petroleum	Other	Total
Blast Furnace	160	1,435	0	70	1,365	3,080
Kettles	25	10	550	0	95	680
Casting	35	0	0	0	0	35
Other	340	0	685	5	0	1,030
TOTAL	560	1,435	1,235	75	1,460	4,825

TABLE A-22. ENERGY CONSUMPTION FOR POLYVINYL CHLORIDE
MANUFACTURING (Btu/lb OF PVC)(2)

	Electricity	Coal	Petroleum	Natural Gas	Other	Total
Gas	---	5.0	10.0	160.0	---	175.0
Natural Gas Processing	---	---	---	3,100.0	---	3,100.0
Oxygen	584.7	---	---	---	---	584.7
Ethylene	54.5	---	4,350.0	10,205	(1,840.0)	12,769.5
Acetylene	363.8	---	---	4,840.0	(1,300.0)	3,903.8
Chlorine/Caustic	5,272.7	1,430.0	70.0	835.0	---	7,607.7
Vinyl Chloride	1,214.3	---	2,455.0	1,640.0	---	5,309.3
Polyvinyl Chloride	2,425.1	2,340.0	1,185.0	2,440.0	---	8,390.1
TOTAL	9,915.1	3,775.0	8,070.0	23,220.0	(3,140.0)	41,840.1

TABLE A-23. ENERGY USED TO PRODUCE LITHIUM CHLORIDE (Btu/lb)*

	Electric	Coal	Gas	Petroleum	Other	Total
Mining and Concentrating	4,359	0	0	4,826	1,826	11,011
Ore Transportation	0	0	0	316	0	316
Calcining	2,650	49,693	0	0	621	52,964
Grinding	185	0	0	0	105	290
Sulfuric Acid	0	0	0	0	35	35
Acid Roaster	0	10,080	0	0	0	10,080
Limestone	0	0	0	0	969	969
Blending and Thickening	197	0	0	0	0	197
Leaching, Washing, and Filtering	55	0	0	0	454	509
Sodium Carbonate	0	0	0	0	12,880	12,880
Precipitator	0	0	0	0	0	0
Evaporating and Centrifuging	115	0	0	0	3,826	3,941
Hydrochloric Acid	0	0	0	0	0	0
Drying and Crystallizing	0	0	0	2,642	0	2,642
Total	7,561	59,773	0	7,784	20,716	95,834

*Much of this data is from Reference 5; it has been supplemented with discussions with lithium chloride manufacturers.

TABLE A-24. ENERGY USED TO PRODUCE POTASSIUM CHLORIDE (Btu/lb)(3)

	Electricity	Coal	Gas	Oil	Other	Total
Mining	247	0	0	9	45	301
Crushing	29	0	0	0	0	29
Scrubbing and Classifying	39	0	0	0	0	39
Leaching Clay	13	0	31	0	122	166
Thickening	14	0	0	0	4	18
Conditioning and Flotation	43	0	0	0	56	99
Thickening, NaCl	3	0	0	0	0	3
Centrifuging, NaCl	32	0	0	0	0	32
Crystallizing	28	0	0	0	70	98
Centrifuging, KCl	22	0	0	0	1	23
Drying and Screening	25	0	0	0	271	296
Granulating	28	0	0	0	128	156
Warehousing and Loading	38	0	0	0	0	38
Total	561	0	31	9	697	1,298

TABLE A-25. ENERGY USED TO PRODUCE MOLYBDIC OXIDE (Btu/lb)(3)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining	9,265	0	1,550	3,515	1,425	24,755
Crushing	2,535	0	0	0	0	2,535
Grinding	15,915	0	0	0	0	15,915
Beneficiation	14,495	0	0	0	8,095	22,590
Concentrate Transportation	0	0	0	680	0	680
Roasting	0	0	2,250	0	0	1,250
Grizzly-Mill-Cooler	80	0	0	0	0	80
Multiclone	115	0	0	0	0	115
Precipitator	145	0	0	0	0	145
General Plant	4,260	0	0	0	0	4,260
Total	46,810	0	11,800	4,195	9,520	72,325

TABLE A-26. ENERGY USED TO PRODUCE BORON NITRIDE FELT
(Btu/lb)(3,6)

	Electric	Coal	Gas	Petroleum	Other	Total
Boric Oxide	412	0	823	444	5,735	7,414
Ammonia	3,944	0	521,483	0	163	525,590
Nitrogen	3,584	0	0	0	0	3,584
Process Energy	182,744	0	2,757	0	0	185,501
Total	190,684	0	525,063	444	5,898	722,089

TABLE A-27. ENERGY COST OF ALUMINUM PRODUCTION FROM ALUMINA
(OLD TECHNOLOGY) (Btu/lb ALUMINUM) (1)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Hydrargillite Transportation				445		445
Calcining of Alumina			3,860			3,860
Cathode and Anode Preparation	380*	260	1,045	7,000	2,335	11,020
Alumina Reduction	68,250**	--	--	5	3,230	71,485
Aluminum Transportation				230		230
TOTAL	68,630	260	4,905	7,680	5,565	87,040

*Assumes 32.5 percent efficiency for electricity generation and transmission.

**Assumes 40.0 percent efficiency for electricity generation and transmission,
and 8 kWh/lb of aluminum produced.

TABLE A-28. ENERGY COST OF ALUMINUM PRODUCTION FROM ALUMINA
(NEW TECHNOLOGY) (Btu/lb ALUMINUM) (1)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Hydrargillite Transportation				445		445
Calcining of Alumina			3,860			3,860
Cathode and Anode Preparation	380*	260	1,045	7,000	2,335	11,020
Alumina Reduction	51,180**	--	--	5	3,230	54,415
Aluminum Transportation				230		230
TOTAL	51,560	260	4,905	7,680	5,565	69,970

*Assumes 32.5 percent efficiency for electricity generation and transmission.

**Assumes 40.0 percent efficiency for electricity generation and transmission,
and 6 kWh/lb. of aluminum produced.

TABLE A-29. ENERGY USED TO PRODUCE TITANIUM (Btu/lb)(3)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining, Concentrating, and Transportation of Rutile	1,533	0	0	3,502	0	5,135
Chlorination	9,130	0	0	9,905	20	19,055
Make-Up Chlorine	0	0	0	0	10,350	10,350
Purification and Batch Reactor	165	0	5,285	170	185	5,805
Make-Up Magnesium	0	0	0	0	55,490	55,490
Electrolytic Recovery of Magnesium and Chlorine	112,875	0	0	0	0	112,875
Chipping, Leaching and Drying	1,230	0	1,385	0	196	2,811
TOTAL	124,933	0	6,670	13,677	66,221	211,521

TABLE A-30. ENERGY USED TO PRODUCE ZINC CHLORIDE (Btu/lb)

	Electric	Coal	Gas	Petroleum	Other	Total
Hydrogen (4)	25	369	1,525	839	0	2,758
Chlorine (1)	4,863	0	0	48	462	5,373
Hydrochloric Acid Production	0	0	440	441	0	881
Zinc Oxide Produc- tion (1,4)	10,503	6,506	1,551	340	2,935	21,935
Zinc Chloride Pro- duction	0	0	4,400	4,400	0	8,800
TOTAL	15,491	6,875	7,916	6,068	3,397	39,747

TABLE A-31. ENERGY USED IN CHLORINE PRODUCTION (Btu/lb)(1)

	Electric	Coal	Gas	Petroleum	Other	Total
Salt Mining	99	0	0	0	0	99
Brine Purification and Filtration	24	0	0	200	633	857
Brine Heating	0	0	0	0	1,022	1,022
Brine Electrolysis	15,275	0	0	0	243	16,518
Coproduct Credit (H ₂ and NaOH)	(3,766)	0	0	(107)	(1,015)	(9,888)
Chlorine Cooling and Drying	12	0	0	0	6	18
Compressing and Liquifying	1,707	0	0	0	0	1,707
TOTAL	9,351	0	0	93	889	10,333

TABLE A-32. ENERGY USED TO PRODUCE GRAPHITE (Btu/lb)(1)

	Electric	Coal	Gas	Petroleum	Other	Total
Petroleum Coke	0	0	0	22,500	0	22,500
Calcination	315	0	1,500	1,000	0	1,815
Crushing & Grinding	79	0	0	0	0	79
Mixing	394	0	200	5,600	0	6,194
Extrusion	158	0	100	0	0	258
Baking	473	0	8,300	0	0	8,773
Impregnation	184	0	200	2,550	0	2,934
Graphitizing	32,025	0	0	0	0	32,025
Machining	132	0	0	0	0	132
Other	3,150	0	2,500	0	0	5,650
TOTAL	36,910	0	12,800	30,650	0	80,360

TABLE A-33. ENERGY USED TO PRODUCE SODIUM (Btu/lb)(3)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining	127	0	0	23	26	176
Salt Purification	37	198	198	198	692	1,323
Salt Crystallizing	10	1,608	1,608	1,608	0	4,834
Salt Drying	69	86	86	86	0	327
Electrolysis	52,500	0	0	0	360	52,860
Credit for Chlorine	0	0	0	0	(13,500)	(13,500)
TOTAL	52,743	1,892	1,892	1,915	(12,422)	46,020

TABLE A-34. ENERGY USED TO PRODUCE SULFUR (Btu/lb) (1)

	Electric	Coal	Gas	Petroleum	Other	Total
Mining	5	0	932	0	16	953
Transportation	0	0	0	34	0	34
TOTAL	5	0	932	34	16	987

TABLE A-35. ENERGY USED TO PRODUCE ALUMINUM (Btu/lb) (1)

	Electricity	Coal	Natural Gas*	Petroleum*	Other	Total
Mining, Ore Preparation and Ore Transportation	160	--	475	1,725	35	2,395
Bayer Processing	1,070	---	10,710	6,850	2,655	21,285
Cathode and Anode Preparation	380	260	1,045	7,000	2,335	11,020
Reduction	84,000	--	---	5	3,230	87,235
TOTAL	85,610	260	12,230	15,580	8,255	121,935

**Energy used in the form of process steam has been distributed equally to gas and petroleum energy sources.*

TABLE A-36. ENERGY TO PRODUCE GLASS (Btu/lb)(1)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Sand	0	0	0	0	214	214
Limestone	0	0	0	6	9	15
Feldspar	0	0	0	28	55	83
Soda Ash	0	0	0	66	128	194
Batch Handling	201	0	0	0	0	201
Melting and Fining	972	0	10,100	1,966	44	13,082
Forming	2,340	0	475	0	2	2,817
Post Forming	628	0	2,353	0	37	3,018
Product Handling	172	0	205	14	12	403
Space Heating	91	0	375	135	2	603
TOTAL	4,404	0	13,508	2,215	503	20,630

TABLE A-37. ENERGY USED TO PRODUCE GLASS TUBES
FOR THE SODIUM-SULFUR BATTERY
(Btu/lb of GLASS)(1)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Borax	215	0	430	384	2,997	4,026
Sodium Chloride	6	0	0	7	86	99
Sand	0	0	0	9	19	28
Batch Handling	201	0	0	0	0	201
Melting and Fining	972	0	10,100	1,966	44	13,082
Forming	2,340	0	475	0	2	2,817
Post Forming	628	0	2,353	0	37	3,018
Product Handling	172	0	205	14	12	403
Space Heating	91	0	375	135	97	603
TOTAL	4,625	0	13,938	2,515	3,199	24,277

TABLE A-38. ENERGY USED TO PRODUCE TUBE SHEET GLASS FOR
THE SODIUM-SULFUR BATTERY (Btu/lb OF GLASS)(1)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Borax	224	0	447	400	3,116	4,187
Soda Ash	0	0	0	10	549	559
Batch Handling	201	0	0	0	0	201
Melting and Firing	972	0	10,100	1,966	44	13,082
Forming	2,340	0	475	0	2	2,817
Post Forming	628	0	2,353	0	37	3,018
Product Handling	172	0	205	14	12	403
Space Heating	91	0	375	135	97	603
TOTAL	4,628	0	13,955	2,525	3,762	24,870

TABLE A-39. ENERGY USED TO PRODUCE ALUMINA (Btu/lb)(1)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Mining and Pre- paration of Ore	85	0	251	913	19	1,268
Bayer Processing	566	0	5,670	3,626	1,406	11,268
Total for α -Alumina	651	0	5,921	4,539	1,425	12,536
Energy to Produce β -Alumina from α -Alumina	498,750	0	0	0	0	498,750
Total for β -Alumina	499,401	0	5,921	4,539	1,425	511,286

TABLE A-40. ENERGY USED TO PRODUCE ALUMINUM FROM SECONDARY SOURCES
(Btu/lb)(5)

	Electricity	Coal	Natural Gas	Petroleum	Other	Total
Reverberatory Furnace	80	0	5,000	0	2,285	7,365
Ingot Casting	15	0	0	0	0	15
Air Pollution Control	125	0	0	0	0	125
Space Heating	0	0	25	0	0	25
TOTAL	220	0	5,025	0	2,285	7,530

REFERENCES FOR APPENDIX A

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APPENDIX B

SAMPLE CALCULATION OF
MEASURES OF PERFORMANCE

APPENDIX B

SAMPLE CALCULATION OF MEASURES OF PERFORMANCE

This appendix illustrates a sample calculation of the measures of performance which are shown in Table I-9. The example uses data for the nickel-zinc battery, but the numbers are computed similarly for all of the other batteries.

1. Operational Oil and Gas Shift

This figure is obtained from Figure I-1. The oil and gas shift is the amount of fuel saved by replacing a vehicle powered by an internal combustion engine with an electric vehicle (505 million Btu) minus the oil and gas used to generate electricity for charging the battery. The nickel-zinc battery requires 46 million Btu of oil and 38.5 million Btu of gas for charging. The total oil and gas shift is, therefore, 505 million Btu minus 46 million Btu, minus 38.5 million Btu, or 420.5 million Btu shifted per 100,000 miles.

2. Net Investment Energy

This value can be obtained from Figure I-1 or Table I-1. It is the investment energy minus the recycling credit. For the nickel-zinc battery we have 29.8 million Btu (investment) minus 5.3 million Btu (recycling credit), equals 24.5 million Btu per 100,000 miles.

3. Total Life-Cycle Energy Use

This figure comes directly from the bottom of Table I-1, 303.4 million Btu per 100,000 miles.

4. Equivalent Miles per Gallon

This number is computed from the total life-cycle energy use as follows:

$$\text{MPG} = \frac{1}{\frac{\text{life-cycle energy use}}{\text{Btu}/100,000 \text{ miles}}} \times 125,000 \text{ Btu/gallon.}$$

For the nickel-zinc battery we have:

$$\text{MPG} = 125,000 \text{ Btu/gallon} \times \frac{100,000 \text{ miles}}{303.4 \times 10^6 \text{ Btu}} = 41.2 \text{ MPG.}$$

5. Oil and Gas Shift-to-Energy-Investment Ratio

This number is the oil and gas shift calculated in Section 1 divided by the net energy investment, calculated in Section 2. For the nickel zinc battery, this number becomes:

$$\frac{420.5 \text{ million Btu}}{24.5 \text{ million Btu}} = 17.2$$

6. Miles to Payback the Investment with an Oil and Gas Shift

This number is computed as the net energy investment divided by the oil and gas shift per mile or:

$$24.5 \text{ million Btu (investment)} \times \frac{100,000 \text{ miles}}{420.5 \text{ million Btu}}$$

$$= 5,826 \text{ miles which is rounded to } 5,830.$$