Cost and Energy Consumption Estimates for the Aluminum-Air Battery Anode Fuel Cycle

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Richland, Washington 99352

SUMMARY

At the request of DOE's Office of Energy Storage and Distribution (OESD), Pacific Northwest Laboratory (PNL) conducted a study to generate estimates of the energy use and costs associated with the aluminum anode fuel cycle of the aluminum-air (Al-air) battery. The results of this analysis indicate that the cost and energy consumption characteristics of the mechanically rechargeable Al-air battery system are not as attractive as some other electrically rechargeable electric vehicle battery systems being developed by OESD. However, there are distinct advantages to mechanically rechargeable batteries, which may make the Al-air battery (or other mechanically rechargeable batteries) attractive for other uses, such as stand-alone applications. Fuel cells, such as the proton exchange membrane (PEM), and advanced secondary batteries may be better suited to electric vehicle applications. The overall conclusion that Al-air may not be the best technology for providing electric vehicle power is based on a number of findings:

- The expected utility grid-to-shaft efficiency of the Al-air battery is 24%, while grid-to-shaft efficiencies of typical secondary battery systems are approximately 50%.
- A significant breakthrough in Al-air battery technology and improvements in aluminum production processes must occur for the grid-to-shaft efficiency of the Al-air battery to exceed 35 percent.
- Using the Al-air battery in a hybrid vehicle dramatically increases net vehicle efficiency; however, this is due to use of a more efficient secondary battery for most of the supplied power.
- The cost associated with the use of 99.99% pure aluminum-alloy anodes in the aluminum-air battery is estimated to be \$2.11 to \$3.05 per kilogram of anode consumed. Currently, 99.999% pure aluminum base metal is required. If this higher purity metal must be used in a mature battery system, costs would likely be even higher.
- The efficiency-adjusted fuel cost of the Al-air battery is \$0.55-0.80 per kWh of shaft output, while secondary battery systems have efficiency-adjusted fuel costs of approximately \$0.073 per kWh of shaft output.

Other findings of this study include the following:

- In a commercialized market, the recycling of hydrargillite, a precipitate of the battery reaction, into new anodes would almost certainly need to be pursued to maintain stable aluminum and alumina markets and to keep the consumer cost of anodes down.
- The size of hydrargillite particles at discharge from the battery system is not a limiting factor for their use as feedstock in the aluminum production process if the hydrargillite calcining process during recycling is closely controlled.
- During repeated processing of hydrargillite through the fuel cycle, the hydrargillite should not pick up significant amounts of impurities.
- The electrolyte solution entrained with the hydrargillite upon discharge from the battery system could be washed away during hydrargillite reprocessing at negligible additional cost and energy consumption, if the aluminum production process used can tolerate low levels of electrolyte in the recycled hydrargillite. If the aluminum production process is not tolerant, washing could be complex and costly.
- The cost of common alloying agents currently being used in the battery development program is not a prime cost driver in the overall operating cost of the Al-air battery.

Considering all these findings, it was concluded that Al-air battery development and integration should be preceded by the evaluation of these fundamental issues:

- the value of special characteristics, such as rapid refuelability, high specific energy, and long-range capability relative to efficiency and the efficiency-adjusted fuel cost
- the likelihood of major efficiency breakthroughs in the battery system and fuel cycle
- specific applications in which the Al-air battery would be more attractive and justify its development.

If evaluation of these issues indicates poor future viability of the Al-air battery system, major research efforts should be directed toward other battery or fuel cell systems, such as the PEM fuel cell, which have higher potential for beneficial applications. Also, the transfer of information learned in Al-air battery development to other technological applications should be strongly pursued. A technology that would be likely to benefit from such transfer is the zinc-air battery system.

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1.0 INTRODUCTION

The mechanically rechargeable aluminum-air (Al-air) battery operates as a fuel cell, consuming aluminum alloy plates (anodes) to produce electricity. In addition to electricity, the battery produces hydrated alumina (hydrargillite) as a reaction product. The hydrargillite ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$) is similar to an intermediate product in aluminum production. For this reason, it is believed that the hydrargillite could be recycled into aluminum for reuse as fuel for the battery.

The Al-air battery is seen as potentially viable as a power source for an electric vehicle from a technical standpoint. However, the practicality and economic viability have yet to be proven. The battery is mechanically rechargeable; therefore, an electric vehicle powered by such a battery would be limited in range only by the amount of aluminum fuel the vehicle could carry. This is a significant advantage over secondary-battery-powered electric vehicles, which are range limited by the battery's electrical storage capacity and cannot be rapidly recharged. An alternative scenario would be to couple a secondary battery with an Al-air battery, utilizing the Al-air portion of the system for meeting peak power requirements and as a range extender.

The net energy consumption and cost of fuel (aluminum plates) of the Al-air battery were determined for the process of refining the hydrargillite byproduct into alumina, using the alumina in an aluminum production process to manufacture new aluminum plates and using the plates as battery fuel to produce electricity and hydrargillite. This complete processing loop, from aluminum plate to hydrargillite to alumina and back to aluminum plate, is called the "fuel cycle" in this study. Because of the relative complexity of the fuel cycle for the Al-air battery-powered vehicle as compared to those powered by secondary batteries, a detailed analysis is required to determine the total cost and direct energy consumption of this fuel cycle. Direct energy is defined as the total energy consumed in all manufacturing and reprocessing steps, excluding transportation and embodied energy associated with raw materials. With this information, an informed decision can be made with respect to the cost competitiveness of operating an Al-air battery-

powered vehicle and the net electrical efficiency of the battery itself, from both a national energy perspective and from a consumer standpoint.

DOE's aluminum-air battery development effort began in the late 1970s; since that time, there have been several studies examining the operating economics and/or energy use of the battery. The first of these efforts was performed in the early 1980s (Hudson and Putnam 1980) and, although it provided a good examination of energy use and operating economics, the preliminary nature of the battery design and operating requirements made it impossible to examine every aspect of the system to the levels of detail currently possible. During the mid-1980s, a number of projects were able to improve the quality of cost and energy-use information. In particular, work performed by McMinn and Branscomb (1981) and Cooper (1984) added significantly to the information available on aspects of this system. However, as the development of the aluminum-air battery continues and future funding priorities must be established, better-defined, long-term cost estimates and energy use-projections are required to help evaluate the economic feasibility of the battery.

The major objective of this study was to generate estimates of the energy use and costs associated with the aluminum anode fuel cycle of the aluminum-air battery. While this study uses much of the previous work as a foundation, there are three fundamental differences between this work and earlier studies: 1) the energy consumption associated with the aluminum-air battery-powered vehicle fuel cycle is examined in greater detail than previously, 2) the reprocessing cost of the hydrargillite has been examined to a greater extent than in the past, and 3) the most current baseline operating scenario, which includes the addition of 50 kg of aluminum plates for every three discharges of hydrargillite, additions of water, and possibly the addition of electrolyte, has been incorporated into the estimates. Additional uncertainty issues have also been identified.

The efficiency analysis methodology used in this study suggests several important questions that have a critical bearing on the results. First, "Why evaluate electrical efficiency from both national energy and consumer perspectives?" Efficiencies must be evaluated from a national energy

perspective, because it is DOE's responsibility to promote the development of technologies which will not only succeed in the consumer market place but will also utilize our national energy supplies in the most efficient manner. Efficiency must also be evaluated from a consumer perspective, because this efficiency directly relates to the cost of operations and, consequently, viable commercialization.

Second, "Why use the complex concept of the aluminum anode fuel cycle rather than the simple efficiency measure of roundtrip efficiency (i.e., electrical energy out of the battery divided by electrical energy into the battery)?" For a typical secondary battery (e.g., lead-acid, sodium-sulfur), energy-out divided by energy-in coupled with other system losses is efficiency calculated from a consumer perspective. For an aluminum-air battery which consumes fuel (i.e., aluminum anodes), the consumer only cares about the efficiency with which aluminum is converted to electricity. This parallels the roundtrip efficiency concept of a secondary battery. However from a national energy perspective, a fair evaluation must consider all energy required to make an aluminum-air battery discharge electricity. Because the anodes consumed in the battery require intensive energy input to manufacture them, this energy input, which is a portion of the fuel cycle, must be included in the efficiency analysis.

A final critical question then arises: "If we are going to include the energy required to manufacture the anodes for an aluminum-air battery, shouldn't the energy required to manufacture lead in lead-acid or sulfur in sodium-sulfur batteries be included during comparison analysis with the aluminum-air battery?" The answer is no, because every time the aluminum-air battery discharges a kWh of electricity, aluminum is consumed. Thus, the aluminum is a consumable commodity. In a conventional secondary battery such as lead-acid, the lead is merely a media for storing energy, and a single pound of lead may last thousands of charges and discharges. Thus, it is not consumed and should not be included in efficiency calculations.

2.0 CONCLUSIONS AND RECOMMENDATIONS

Two measures of efficiency and fuel cost for the Al-air battery system were developed in this study. These include grid-to-shaft efficiency and the efficiency-adjusted fuel cost. The grid-to-shaft efficiency is a measure of the energy efficiency of a battery system from a national energy perspective. The efficiency-adjusted fuel cost is the cost of fuel per unit of energy output from the electric vehicle system. These two measurement factors were determined by analyzing the Al-air battery fuel cycle. Many efficiencies could have been cited, each of which is correct in its own context; however, grid-to-shaft efficiency represents a measure that is comparable for electrically and mechanically recharged batteries. Having a comparable efficiency is significantly more important than the specific type of efficiency measure used.

For estimation purposes, the fuel cycle was divided into three major parts: service cycle aspects, hydrargillite reprocessing, and anode manufacture. Each of these major parts was evaluated with respect to the cost and energy consumption impacts it has on the overall fuel cycle.

The service aspects include four basic operations: installation of the anodes, removal of hydrargillite, addition of water and electrolyte, and shipment of the hydrargillite to a reprocessing facility. By assessing a number of possible electric vehicle servicing, fuel taxing, and service center profit scenarios, a cost contribution toward the fuel cycle of \$0.36 - 1.30 per kilogram of aluminum is estimated. The only direct energy consumption associated with service aspects of the fuel cycle is shipping the hydrargillite to a reprocessing facility, which requires 529 kJ per kilogram of aluminum.

Two types of hydrargillite reprocessing operations were evaluated: 1) calcining, and 2) washing and calcining. A significant cost or energy consumption difference between these two alternatives could not be determined. However, aluminum industry experts indicated that washing could be a complex task if the residual electrolyte associated with the hydrargillite is not tolerable by the aluminum production process utilizing the recycled

hydrargillite. During the evaluation of reprocessing methods, three technical issues were identified and evaluated for their energy consumption and cost implications: 1) how the entrained solution associated with the hydrargillite affects reprocessing; 2) how the particle size of the hydrargillite crystals would affect the use of calcined hydrargillite for producing aluminum; and 3) how repeated cycling of hydrargillite through the fuel cycle affects the amount of impurities, particularly iron, in the aluminum anodes.

It was optimistically concluded that the solution entrained with the hydrargillite could be washed away at the hydrargillite reprocessing facilities at minimal cost and with minimal energy consumption. The particle size problems can also easily be solved. The only requirement of the battery regarding particle size is that the particles must be large enough for the battery separator to collect them. Although the developer's goal of 40 microns for particle size is not large enough for direct use in the Hall process for aluminum production, by carefully controlling calcining temperatures during reprocessing, the particles would agglomerate to the appropriate size. Finally, it was concluded that iron concentrations in the aluminum anodes would remain minimal through repeated fuel cycles. Although some iron would be picked up during the Hall process, an approximately equal amount would volatilize from the cell in the form of iron oxides. The estimated cost and energy consumption associated with hydrargillite reprocessing are \$0.084/kg·Al and 3550 kJ/kg·Al, respectively. The cost reflects credit for the value of recycled hydrargillite.

In a study by Reynolds Aluminum (McMinn and Branscomb 1981), it was concluded that the lowest-cost anodes could be made by going directly from molten Hall cell metal to a continuous anode casting operation. Therefore, this manufacturing approach was used to calculate the energy consumption and cost of anode manufacture. By evaluating the anode manufacturing process at the unit operation level, energy consumption was estimated as 14.51 kWh and 5950 kJ/kg·Al.

The total of all attributed energy consumption for the use of aluminum anodes as fuel for the aluminum-air battery is 10×10^3 kJ/kg·Al plus 14.5 kWh/kg·Al. Using a conversion factor of 10,550 kJ/kWh, this is equivalent to

15.5 kWh/kg·Al. The aluminum-to-electricity battery efficiency using a BDW-series alloy^(a) and calculated over a standard drive cycle was 3.8 kWh/kg·Al. Based on this efficiency and energy input of 15.5 kWh/kg·Al, the net fuel cycle efficiency is 25%.

There is potential for near-term improvement of the fuel cycle efficiency to 32%, if developing improvements in aluminum processing (i.e., Hall process improvements or development of carbothermic aluminum production processes) are implemented. An increase in the battery discharge efficiency to 4.5 kWh/kg·Al would increase fuel cycle efficiency to 29% percent. An increase to a discharge efficiency greater than 4.5 kWh/kg·Al is not very likely. Technology-based research on the Al-air battery strongly indicates that there exists a barrier to achieving a higher specific energy (ELTECH 1987). If both increased discharge efficiency to 4.5 kWh/kg·Al and improvements in aluminum production come to fruition, the net fuel cycle efficiency would be approximately 38%.

The only difference between the net fuel cycle efficiency and a utility grid-to-vehicle shaft efficiency is that the grid-to-shaft efficiency includes efficiency losses associated with the vehicle motor, which turns electricity into usable power. Table 2.1 compares the grid-to-shaft efficiencies of several vehicles.

Use of the Al-air battery coupled with a secondary battery in a hybrid vehicle would allow for the discharge of both battery systems in a manner that capitalizes on the Al-air battery's ability to provide high power levels during acceleration or ascent of steep grades, while the secondary battery provides steady-state energy. Consequently, the net vehicle efficiency would be improved over that of an electric vehicle powered solely by an Al-air battery. The problem with such a configuration is the cost and engineering design implications of containing two battery systems in one vehicle.

(a) The BDW-series alloys were the preferred aluminum alloys (ELTECH 1987) during the preparation of this study. Prior to publication of this work, alloy preference shifted. Reviews of the new alloy indicate that the results of this study were not affected by the change.

TABLE 2.1. Comparison of Grid-to-Shaft Efficiencies

<u>Technology</u>	<u>Transmission and Distribution</u>	<u>Fuel Cycle</u>	<u>Charger</u>	<u>Battery</u>	<u>Motor</u>	<u>Grid- to-Shaft</u>
Al-air	NA	0.25	NA	NA	0.95	0.24
Al-air Hybrid(a)	NA/0.825	0.25/NA	NA/0.90	NA/0.70	0.95	0.45
Generic Secondary Battery	0.825	NA	0.90	0.70	0.95	0.49

(a) Assumes 20% use of the Al-air battery and 80% use of the secondary battery.

The cost associated with the fuel cycle is partially dependent on the actual vehicle aluminum-to-road mile efficiency (i.e., the kg·Al required per road mile) because of the selected alternative methodologies used in this study for estimating service station markup and taxes. Since the aluminum-to-road efficiency is dependent on final vehicle design, a range of efficiencies was evaluated. This range covered 12.3 to 19 miles/kg·Al (19.8 to 30.6 km/kg·Al). Using these efficiencies and applying the results described above, the cost estimates presented in Table 2.2 were prepared. The range of anode costs presented in Table 2.2 results from the four different service-cycle estimating methodologies considered. From this information, it was concluded that alloying using typical agents and base-metal purity levels of up to 99.99% aluminum was not significantly more costly than using unalloyed 99.5% aluminum.

TABLE 2.2. Range of Anode Cost Estimates

<u>Miles/kg(km/kg)</u>		<u>Alloyed 99.99%</u>	<u>Unalloyed 99.5%</u>
19	(30.6)	\$2.21 - \$3.05/kg	\$2.03 - \$2.77/kg
14.6	(23.5)	\$2.14 - \$3.05/kg	\$1.96 - \$2.77/kg
12.3	(19.8)	\$2.11 - \$3.05/kg	\$1.93 - \$2.77/kg

Table 2.3 compares the efficiency-adjusted fuel costs for the Al-air battery to an electric vehicle using a secondary battery and an internal combustion engine (ICE)-powered vehicle. Fuel costs are presented as a function of cost per kJ and cost per kWh of shaft output. These estimates are based on a gasoline cost of \$7.77 per MBtu (EIA 1987a), an off-peak electricity cost of 4.05 cents per kWh, and an electrical motor efficiency of 95%. As shown, the Al-air battery has the highest unit fuel cost. Even significant cost reductions in the aluminum industry would not eliminate this wide margin.

The efficiency-adjusted fuel costs are shown for comparison. Equitable comparisons must be made on a life-cycle cost basis, because a life-cycle cost analysis considers all the lifetime expenses of purchasing and operating a technology, not the fuel cost alone. A complete life-cycle cost analysis was not included in the scope of this study. However, a Jet Propulsion Laboratory study (Hardy 1985) estimated the life-cycle cost of an Al-air battery-powered five-passenger vehicle to be twice as high as that of a comparable ICE-powered vehicle and 50% higher than that of a conventional secondary battery.

In summary, the following conclusions were reached:

- The expected grid-to-shaft efficiency of the Al-air battery fuel cycle is 24%, while typical secondary battery systems have efficiencies of approximately 50%.
- A significant breakthrough in Al-air battery technology and improvements in aluminum production processes must occur for the efficiency of the Al-air battery fuel cycle to exceed 35%.

TABLE 2.3. Comparison of Efficiency-Adjusted Fuel Cost

Technology	Charger	Battery/Motor Combination	Engine	\$/kWh	\$/kJ
Al-air	NA	(0.47)(0.95)	NA	0.56 - 0.80 ^(b)	150 - 220 x 10 ⁻⁶
Al-air Hybrid ^(a)	NA/.90	(0.47)(0.95)/(0.70)(0.95)	NA/NA	0.19	52 x 10 ⁻⁶
Generic Secondary Battery	.90	(0.70)(0.95)	NA	0.068	19 x 10 ⁻⁶
ICE	NA	NA	.18	0.15	41 x 10 ⁻⁶

(a) Assumes 20% utilization of the Al-air battery and 80% utilization of the secondary battery. Other utilizations could be approximated using linear interpolation.

(b) Based on an anode cost of \$2.11 to \$3.05/kg and 3.8 kWh/kg generated using the anode.

- Using the Al-air battery in a hybrid vehicle dramatically increases net vehicle efficiency; however, this is due to use of a more efficient secondary battery for most of the supplied power.
- In a commercialized market, hydrargillite reprocessing would almost certainly need to be pursued to maintain stable aluminum and alumina markets and to keep the consumer cost of anodes down.
- The size of hydrargillite particles at discharge from the battery system is not a limiting factor for their use for feedstock in the aluminum production process, if the hydrargillite calcining process is closely controlled.
- During repeated processing of hydrargillite through the fuel cycle, the hydrargillite should not pick up significant amounts of impurities.
- The electrolyte solution entrained with the hydrargillite upon discharge from the battery system could be washed away during hydrargillite reprocessing at negligible additional cost and energy consumption, if the aluminum production process used can tolerate low levels of electrolyte in the recycled hydrargillite. If such a tolerant aluminum process is not used, washing could be complex.
- The cost of common alloying agents is not a prime cost driver in the overall operating cost of the aluminum-air battery.
- The cost associated with the use of aluminum-alloy anodes in the aluminum-air battery is estimated to be \$2.11 to \$3.05 per kilogram anode consumed, based on current best-practice Hall process aluminum production.

The results of this analysis indicate that the cost and energy consumption characteristics of the Al-air battery system in both Al-air and Al-air hybrid electric vehicles are relatively unattractive compared to other electric- and ICE-powered vehicles. If future R&D funds are to be spent on the Al-air battery, the following issues should be addressed:

- the value of special characteristics, such as rapid refuelability, high specific energy, and long-range capability relative to efficiency and the efficiency-adjusted fuel cost
- the likelihood of major efficiency breakthroughs in the battery system and fuel cycle
- specific applications that would make the Al-air battery be most attractive and whether these applications justify its development.

If evaluation of these issues indicates poor future viability of the Al-air battery system, major research efforts should be directed toward other battery systems that have higher potential for beneficial applications. Also, the transfer of information learned in Al-air battery development to other technological applications should be strongly pursued.

3.0 GENERAL COST AND ENERGY CONSUMPTION ASSESSMENT METHODOLOGY

The Al-air battery consumes water, oxygen, and aluminum (anodes) in a chemical reaction involving an alkaline electrolyte to generate electricity and produce a reaction byproduct called hydrargillite. Theoretically, the hydrargillite, which is composed mainly of hydrated alumina ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$), could be recycled into alumina and used as raw material for production of new aluminum plates through the use of the Hall process.

The battery is fundamentally different from secondary batteries in that electricity is stored in the form of the aluminum anode plates, whereas secondary batteries store electricity chemically within their electrodes. This difference in storage mechanisms necessitates careful definition of efficiencies in order to develop comparable values for the different technologies. This evaluation considers two efficiencies for the Al-air and comparison technologies: the utility grid-to-shaft efficiency and consumer purchase point of energy-to-shaft efficiency.

The utility grid-to-shaft efficiency is a measure of the battery system's efficiency from a national energy perspective and is useful for making comparisons for prioritizing research and development (R&D). The end points of the grid-to-shaft efficiency, the utility grid and electric vehicle motor shaft, were selected, because at both of these points the form of energy is the same for the Al-air and conventional secondary batteries. In the case of the Al-air battery; the electricity is used in aluminum plates to produce anodes for the battery; in the case of a secondary battery, the electricity travels over transmission and distribution lines to the end-user, where it is used to directly charge the battery. To calculate the grid-to-shaft efficiency for the Al-air battery, all the direct energy consumed during the production of the aluminum anodes from alumina and recycling of hydrargillite (i.e., the complete fuel cycle), plus motor and auxiliaries inefficiencies, must be considered.

The consumer, however, is interested only in the electric vehicle efficiency that affects the cost to operate the vehicle; thus, a second efficiency, the consumer purchase point of energy-to-shaft efficiency, is

needed. This efficiency, coupled with the cost of fuel, represents the efficiency-adjusted fuel cost to the consumer. The consumer efficiency for an Al-air electric vehicle is represented by the total amount of energy received from the vehicle shaft divided by the theoretical energy yield of the aluminum anode. In the case of a secondary battery, the consumer efficiency is represented by the total amount of energy out of the vehicle shaft divided by the amount of energy input into the battery system as measured at the purchase meter. Thus, the consumer efficiency of a secondary battery accounts for charger losses and motor inefficiencies. The efficiency-adjusted fuel cost is represented by the purchase cost per unit of energy, whether it be in the form of electrical energy or an aluminum anode, divided by the consumer efficiency. The efficiency-adjusted fuel cost is the cost per unit of energy (e.g., dollars-per-kWh) the consumer receives from the electric vehicle system.

An integral part of the utility grid-to-shaft efficiency of the Al-air battery is the battery's fuel cycle. The fuel cycle begins with alumina, which is used as a feedstock to an aluminum production process. The molten aluminum from the production process is cast and sheared into anode form for use in the battery. The anodes are then transferred to service stations, where they are installed in Al-air battery-powered vehicles. During the operation of an Al-air battery-powered vehicle, it would be necessary to remove hydrargillite, add water, and possibly add electrolyte three times during the life of one set of plates. Figure 3.1 illustrates this fuel cycle.

In order to develop cost and energy consumption estimates, it is necessary to assess energy consumption and the associated manufacturing and operational costs at each step of the fuel cycle. For estimation purposes, the fuel cycle is divided into three major parts (see Figure 3.1): 1) the service cycle, 2) hydrargillite reprocessing, and 3) anode manufacture. These three parts of the fuel cycle and the specific assessment methodologies for them are addressed in Sections 4.0, 5.0, and 6.0, respectively.

FIGURE 3.1. Fuel Cycle for the Aluminum-Air Battery

4.0 THE SERVICE CYCLE

During the operation of the Al-air battery, a reaction byproduct called hydrargillite is produced. A precise composition of the hydrargillite cannot be specified, because the separation processes involved within the battery system have not yet been finalized. The primary developer of the Al-air battery system, ELTECH Systems Corporation, has done experimental work in this area and developed some guidelines for the separation which would occur within the electric vehicle power cell.

The composition of the liquid phase entrained with hydrargillite upon removal from the battery will depend on whether the hydrargillite is washed with water, and if this is the case, how efficient this washing step is.^(a) Without washing, the liquid phase would be of the same composition as the battery's electrolyte, approximately 4 to 5 molar sodium hydroxide (NaOH) or potassium hydroxide (KOH).^(a) Currently, KOH is the preferred electrolyte.^(b) Due to the anticipated loss of electrolyte without washing, the battery's separation process will at least include a minimal washing step utilizing the make-up water.^(a)

While the quantity and chemical content of liquid entrained with the hydrargillite has not yet been finalized, it is estimated that it will vary between 15% and 30% of dry hydrargillite by volume, with the solution being approximately 1 molar alkaline. The value of 30% represents the liquid fraction based upon free settling; 15% includes some type of additional processing to remove water^(b). For the purpose of preparing the estimates presented in this study, a liquid fraction of 0.15 was assumed. A higher liquid fraction would increase hydrargillite storage space requirements at service stations and hydrargillite shipping costs to the reprocessing facility; it could possibly also require a liquid separation step before reprocessing.

(a) Personal correspondence with Lawrence Frank of ELTECH Systems Corporation, August 24, 1987.

(b) Personal communication with Marilyn Nicksa of ELTECH Systems Corporation, May 2, 1988.

The service cycle is the most difficult part of the fuel cycle to characterize, because there is no operating experience upon which to base cost estimates. Previous Al-air battery studies (Hudson and Putnam 1980; Cooper 1980; and Cooper 1984) have based estimates on similarities between the perceived Al-air battery-powered electric vehicle operation characteristics and the refueling and fuel taxation characteristics of an internal combustion automobile. There is no new information available pertaining to the service cycle since the most recent study (Cooper 1984) was completed, except for the change from 1600 km to 1200 km as the nominal driving distance between anode replacements. Therefore, Cooper's previous estimate was reviewed and updated to 1987 dollars. Where it was deemed appropriate, Cooper's methodology was revised or compared to alternative methodologies.

The service cycle includes four basic operations: 1) installation of the anodes, 2) removal of hydrargillite, 3) addition of water and electrolyte, and 4) shipment of the hydrargillite to a reprocessing facility. It is assumed that anodes are added in increments of 50 kg, the current design quantity. The installation of 50 kg of aluminum anode every three times hydrargillite is removed and water and electrolyte are added is the current baseline design. The actual distance between anode replacements will depend on the vehicle design, vehicle duty cycle, and battery system aluminum fuel efficiency. The relationship of importance is that 50 kilograms of anode are installed for every three discharges of hydrargillite and additions of water.

Cooper (1984) based the annual service center markup on aluminum anode fuel as being equivalent to the markup on gasoline for a vehicle of equivalent characteristics. For a gasoline-powered vehicle averaging 25 miles per gallon and 10,000 miles per year, the total annual markup up is \$40 based on the average service center markup of 10 cents per gallon. This is equivalent to a markup of \$0.004 per mile. As explained in Section 7.0, the \$0.004 per mile markup is equivalent to \$0.049 to \$0.076 per kilogram of anode for the range of vehicle efficiencies evaluated in this study. Cooper developed this estimate as a lower-bound limit. As an upper bound, Cooper estimated an applicable charge for anode installation. At a burdened labor rate of \$10 per hour and 15 minutes allowed for anode installation, a charge of \$2.50 was estimated. This charge would be in addition to the \$40 annual markup

estimated at the lower bound, which covers hydrargillite removal, addition of water and electrolyte, and service center expenses.

Cooper's anode installation estimate is for the installation of 81.6 kg of aluminum and is in 1984 dollars. Maintaining Cooper's methodology, but using a \$25 per hour (1987 dollars) burdened labor rate and 15 minutes for installing 50 kg of aluminum anode, PNL estimated the anode installation charge as \$6.25. The installation time is not anticipated to be significantly shorter for 50 kg than for 81.6 kg. Because both sets of anodes (50 kg and 81.6 kg) are unmanageable manually, a small jib crane would be required. The use of the crane effectively negates the weight difference for installation purposes.

The high end of Cooper's estimate is probably the most realistic of the two service station markup scenarios. It is highly likely that two types of Al-air battery-powered electric vehicle service centers would exist, if a large number of vehicles were placed in commercial service. The first type would be full-service centers which would be capable of installing plates, handling hydrargillite discharge, and adding water and electrolyte. The second type would only handle hydrargillite discharge and water and electrolyte addition. Because hydrargillite discharge and water and electrolyte addition occurs three times as often as plate installation, the second type of service facility would be more prevalent. The high end of Cooper's estimate is more realistic, because it directly covers the full cost associated with plate installation, while the low end of Cooper's estimate does not.

An alternative methodology is to assume a standard percentage markup on the wholesale price of the aluminum anodes, in addition to the anode installation charge. This percentage covers service station expenses and profit. Based on other high-turnover commodities, a 10% markup is assumed. The plate installation charge is again estimated as \$6.25, based on 15 minutes for installation and a \$25 per hour labor rate. This method treats the aluminum anodes as a commodity rather than as a fuel. While the anodes have generally been treated as a fuel in previous studies, it is quite possible they will not be treated as such if the Al-air battery develops a commercial market.

In addition to the refueling charges, Cooper equated the annual fuel taxes paid by a gasoline-powered vehicle to be applicable to an Al-air battery-powered vehicle of equivalent characteristics. Following Cooper's logic, using the long-term average for fuel taxes of \$0.30 per gallon (see Table 3.1), and assuming equivalence to a 25-mile-per-gallon gasoline-powered vehicle that travels 10,000 miles per year, the net tax per mile is \$0.012.

An alternative method of taxation is to assume a tax based on a percentage of retail cost. As shown in Table 4.1, the long-term fuel tax rate is 39%. This rate would be applied to the aluminum anode cost after the retail markup.

Shipping of the hydrargillite to the reprocessing facility is estimated to cost \$0.0292 per kg of anode. This estimate assumes a standard weight-limited load of 45,000 lbs, a shipping distance of 125 miles, and a per-mile shipping cost of \$1.45. The average shipping distance of 125 miles is based on a study (Hudson and Putnam 1980) that estimated the average shipping distance in a mature Al-air battery-powered electric vehicle market.

Direct energy consumption during the service cycle is limited to hydrargillite transportation energy. Based on energy consumption of 1110 Btu/ton·mile (Cooper 1984), the total energy consumption per shipment is 3.12×10^6 Btu (3.29×10^6 kJ). At 3.29 kg of hydrargillite per kg of aluminum produced (Hudson and Putnam 1980), the transportation energy consumption is 529 kJ/kg·Al.

In summary, the costs associated with the service cycle aspects have been examined such that four estimates are possible. The bases for the four estimates are as follows:

1. Assume the station markups include a dollar-per-mile markup, an anode installation charge, and a percentage for taxes.
2. Assume the station markups include a dollar-per-mile markup, an anode installation charge, and a dollar-per-mile tax charge.
3. Assume the station markups include an anode installation charge, a general percentage markup, and a percentage for taxes.
4. Assume the station markups include an anode installation charge, a general percentage markup, and a dollar-per-mile tax charge.

Using these bases, the four service-cycle estimates as a function of kilograms of aluminum and miles traveled were developed. These estimates do not include the estimated shipping cost of \$0.0292 per kg:

1. $\$0.004/\text{mile} + \$0.125/\text{kg} \cdot \text{Al} + 39\%$ of the total, including anode purchase cost
2. $\$0.004/\text{mile} + \$0.125/\text{kg} \cdot \text{Al} + \$0.012/\text{mile}$
3. $\$0.125/\text{kg} \cdot \text{Al} + 10\%$ of the anode purchase cost + 39% of the total, including anode purchase cost
4. $\$0.125/\text{kg} \cdot \text{Al} + 10\%$ of the anode purchase cost + $\$0.012/\text{mile}$.

Based on the additional information presented in Section 7.0, these estimates can be converted to the following four estimates, respectively, for alloy anodes made using 99.99% Al base-metal:

1. \$1.13 to \$1.09 per kg of anode
2. \$0.36 to \$0.46 per kg of anode
3. \$1.30 per kg of anode
4. \$0.50 to \$0.58 per kg of anode.

These estimates include the estimated shipping cost of \$0.0292 per kg•Al. The range of the estimates arises from the variation of costs over the vehicle electricity-to-road mile efficiency range of 12.3 to 19 kWh/mile.

TABLE 4.1. Long-Term Gasoline Taxes Versus Retail Cost

Year	Retail Cost Leaded Gas Current Dollars (Cents/Gal.)	Tax Current Dollars (Cents/Gal.)	Tax 1987 Dollars (Cents/Gal.)	Percent of Retail (%)
1949	20.3	6.5	30.28	32.02
1950	20.1	6.7	30.59	33.33
1951	20.3	6.9	29.55	33.99
1952	20.2	7.2	30.39	35.64
1953	21.4	7.3	30.34	34.11
1954	21.5	7.5	30.79	34.88
1955	21.4	7.7	30.94	35.98
1956	21.6	8.3	32.32	38.43
1957	22.1	8.9	33.51	40.27
1958	21.4	9	33.32	42.06
1959	21.2	9.3	33.64	43.87
1960	21	10.1	35.95	48.10
1961	20.5	10.3	36.32	50.24
1962	20.4	10.2	35.32	50.00
1963	20.1	10.3	35.14	51.24
1964	20	10.4	34.94	52.00
1965	20.8	10.4	34.20	50.00
1966	21.6	10.5	33.45	48.61
1967	22.6	10.6	32.78	46.90
1968	23	10.7	31.70	46.52
1969	23.9	10.9	30.71	45.61
1970	24.6	11.1	29.68	45.12
1971	25.2	11.2	28.52	44.44
1972	24.4	11.7	28.61	47.95
1973	26.9	11.9	27.51	44.24
1974	40.4	12.8	27.19	31.68
1975	45.5	11.2	21.77	24.62
1976	47.4	11.6	21.43	24.47
1977	50.7	11.5	20.08	22.68
1978	53.1	9.5	15.44	17.89
1979-82(a)				
1983	90.6	25.1	28.50	27.70
1984	84.8	28.1	30.76	33.14
1985	84.2	27.3	28.95	32.42
1986	57.2	28.5	29.48	49.83
AVG.			30.12	39.41

(a) Consistent data for the years 1979 to 1982 were not obtainable from the U.S. Department of Commerce or the Energy Information Administration.

Sources: U.S. Department of Commerce 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1985, 1986, and 1987; Energy Information Administration 1987b.

5.0 HYDRARGILLITE REPROCESSING

Upon delivery to a hydrargillite reprocessing facility, the damp hydrargillite is assumed to have a liquid content of 15% by volume. This liquid is approximately a 1 molar alkali solution. The reprocessing steps used must refine the hydrargillite to a commercially pure cell-grade alumina. This will allow its use as a feedstock for the manufacture of new anodes. This chapter assesses the cost and associated direct energy consumption from the time the damp hydrargillite is delivered to a reprocessing facility, through the processing steps, until a commercial cell-grade alumina is achieved. An alternative operating scenario has suggested disposal of the hydrargillite instead of reprocessing. The ramifications of such a scenario are discussed in this chapter.

In current aluminum manufacturing, commercial-grade alumina is usually obtained from the processing of bauxite into alumina. The commercial process by which bauxite is refined into alumina is called the Bayer process. Specifically, the Bayer process consists of digesting bauxite in a hot caustic soda solution, removing insoluble impurities, precipitating hydrated alumina ($\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$), and finally transforming the precipitate by calcination to commercially pure alumina (i.e., a few hundredths of one percent of impurities) (Shen 1981, p. 12). Figure 4.1 presents a schematic of the Bayer Process.

To generate one (metric) tonne of molten aluminum, 1.90 to 1.95 tonnes of alumina are required (Shen 1981, p. 14). For calculational purposes, the average of this range, 1.925 tonnes, is used. Based on one tonne of aluminum production, the energy inputs attributed to the Bayer process based on "best-practice" are presented in Table 5.1.

For recycling hydrargillite into alumina, it is theorized that processing would strongly resemble the last few steps of the Bayer process. Previous cost and energy consumption estimates for hydrargillite reprocessing have assumed that only the calcining step will be required. Because it is likely that the hydrargillite has an entrained 1 molar alkali solution, first washing, then calcining will be required at a minimum. Currently, the alkali

FIGURE 5.1. Schematic of the Bayer Process

TABLE 5.1. "Best Practice" Energy Inputs to the Bayer Process

<u>Energy Input</u>	<u>Energy Value</u>
Steam to Digester	23×10^6 kJ/tonne·Al(a)
Fossil Fuel to Calciner	3.2×10^6 kJ/tonne·Al(b)
Other Energy	2.3×10^6 kJ/tonne·Al(a)

(a) Shen 1981, p. 14.

(b) Lussky 1980, p. 73.

solution preferred by the battery developer is potassium hydroxide (KOH).^(a) The Hall process would be less tolerant to the presence of KOH than it would be to the alternative alkali, sodium hydroxide (NaOH). Whichever electrolyte is finally selected, if alkali concentrations are too high for producing aluminum anodes of acceptable purity, excess electrolyte must be removed from the hydrargillite in a washing step before calcining.

A second technical issue identified by Sen (1988) relates to the size of the hydrargillite particles upon removal from the battery's separator. Currently, hydrargillite particles produced by the Al-air battery system's separator are 10 microns in size. The battery developer's goal is a particle size of 40 microns. Even particles of 40 microns are unacceptable for use in the Hall process. There are two reasons for this. First, alumina is often fed to the Hall (reduction) cells using screw feeders, which become jammed when handling small particles. New reduction cell capacity is likely to include pneumatic transport of alumina. In this type of transport system, small alumina particles cause fluidization effects, which inhibit proper transport.^(b) Second, the alumina is added to the reduction cells by being dropped from an opening above the cell. Alumina of small particle sizes tends to form dust clouds in the potroom rather than settling into the molten contents in the cell. Aluminum companies generally prefer alumina particle sizes of 45 to 150 microns. The small particle problem is easily

(a) Personal communication with Marilyn Nicksa, ELTECH Systems Corporation, May 5, 1988.

(b) Personal communication with Gary Tarcy, Alcoa Aluminum Company, May 5, 1988.

remedied during calcining. By carefully controlling the calcining temperature, the water entrained in the hydrargillite is driven off, and the hydrargillite particles agglomerate into alumina particles of adequate size.

A third technical issue is the possibility of ever-increasing impurity levels of impurities, particularly iron, caused during repeated processing through the fuel cycle. Assuming proper handling of the hydrargillite during transport to the reprocessing facility, iron contamination is most likely to occur within the Hall cell. In the Hall cell, iron often is unintentionally added in small amounts by iron tools used in the aluminum production process and iron rods that can be used to support the carbon anodes used in the reduction cell. However, this addition of iron is expected to be counter-balanced by the volatilization of some iron as iron oxides, which escape from the reduction cell during the aluminum production process. Therefore, it is anticipated that iron levels will stay relatively low through repeated fuel cycles.

Because there is uncertainty as to exactly what process steps would be required, two hydrargillite reprocessing scenarios have been evaluated: 1) calcining only, and 2) washing and calcining. Evaluation of the direct energy consumption during hydrargillite reprocessing is a straightforward process. As shown in Table 5.1, the energy inputs to the Bayer process are divided into three categories: steam to digester, fossil fuel to calciner, and other energy. Because none of the hydrargillite reprocessing scenarios use a digester, the steam to digester energy input is not applicable to hydrargillite reprocessing. However, both scenarios include calcining; therefore, 3.2×10^6 kJ/tonne·Al can be attributed to both hydrargillite reprocessing scenarios. The "other energy" category represents energy consumption by process pumps, motors, conveyors, etc.; that was assumed to be divided equally among the ten Bayer process steps presented in Figure 5.1. This is equivalent to approximately 230,000 kJ/tonne·Al per Bayer process step. Assuming this relationship holds true, the two hydrargillite reprocessing scenarios would use a total of 0.23×10^6 , and 0.46×10^6 kJ/tonne·Al of "other energy," respectively. Direct energy consumption for each scenario is presented in Table 5.2.

TABLE 5.2. Direct Energy Consumption of Hydrargillite Reprocessing Scenarios

Scenario	Direct Energy Consumption, kJ/tonne-Alumina
#1 calcining	3.43×10^6
#2 calcining and washing	3.66×10^6

Hydrargillite reprocessing is assumed to take place in a dedicated facility that has an annual production capacity of one million tons (0.91 million tonnes) of alumina. A capital and operating cost estimate was prepared for each of the reprocessing scenarios postulated. The estimates are based on cost data presented in Cost Estimate of the Bayer Process for Producing Alumina (Kramer and Peters 1983). To determine the total reprocessing cost per tonne of alumina produced, the plant capital cost per tonne of alumina production capacity was multiplied by a fixed charge rate (FCR_p), the working capital cost per tonne of alumina production capacity was multiplied by a second fixed charge rate (FCR_{wc}), and the variable operating cost per tonne of alumina was added to the sum of these two values. This yields the total reprocessing cost of hydrargillite per tonne of alumina produced. Details of the economic methodology are presented in Appendix A.

For the reprocessing scenario that assumes calcining only, the total estimated capital cost for the calcining plant, including working capital, is \$109.4 million. Table 5.3 presents the capital cost estimate for the calcining plant. The estimated operating costs for the calcining plant are \$29.23 per tonne of alumina produced. Table 5.4 presents the total annual operating cost estimate. Details of the capital and operating cost estimates are presented in Appendix B. To determine the total reprocessing costs, the plant capital cost (including working capital) was multiplied by a fixed charge rate of 0.11, and this value was added to the estimated operating costs. This yields a total reprocessing cost of \$42 per tonne of alumina produced, which is equivalent to \$81 per tonne of aluminum produced.

TABLE 5.3. Capital Investment Cost Estimate for a Calcining Facility for Hydrargillite Reprocessing

<u>Cost Elements</u>	<u>1987 dollars</u>
Installed Capital Equipment	\$36,104,700
Field Indirects	3,610,500
Engineering	3,971,500
Administration	1,985,800
Contingency	6,850,900
Contractor's Fee	2,626,200
Plant Facilities	5,515,000
Plant Utilities	6,618,000
Working Capital	41,401,000
Capitalized Startup Costs	<u>672,800</u>
Total Capital Investment	\$109,356,400

TABLE 5.4. Annual Operating Cost Estimate for a Calcining Facility for Hydrargillite Reprocessing

<u>Cost Elements</u>	<u>1987 dollars</u>
Utilities	\$19,527,400
Direct Labor	756,200
Plant Maintenance	3,351,300
Payroll Overhead	904,500
Operating Supplies	335,100
Indirects	<u>1,643,000</u>
Total Annual Operating Cost	\$26,517,500

For the reprocessing scenario that assumes washing and then calcining, the total estimated capital cost for the calcining plant (including working capital) is \$117.3 million. Table 5.5 presents the capital cost estimate for the washing/calcining plant. The estimated operating costs for the plant are \$31.08 per tonne of alumina produced. Table 5.6 presents the operating cost estimate. Details of the capital and operating cost estimates are presented in Appendix B. To determine the total reprocessing costs, the plant capital cost, including working capital, was multiplied by a fixed charge rate of 0.11, and this value was added to the estimated operating costs. This yields a total reprocessing cost of \$45 per tonne of alumina produced, which is equivalent to \$87 per ton of aluminum produced.

TABLE 5.5. Capital Investment Cost Estimate for a Washing/Calcining Facility for Hydrargillite Reprocessing

<u>Cost Elements</u>	<u>1987 dollars</u>
Installed Capital Equipment	\$38,307,900
Field Indirects	3,830,800
Engineering	4,213,900
Administration	2,106,900
Contingency	7,268,900
Contractor's Fee	2,786,400
Plant Facilities	5,851,500
Plant Utilities	7,021,800
Working Capital	45,230,300
Capitalized Startup Costs	<u>713,900</u>
Total Capital Investment	\$117,332,300

TABLE 5.6. Annual Operating Cost Estimate for a Washing/Calcining Facility for Hydrargillite Reprocessing

<u>Cost Elements</u>	<u>1987 dollars</u>
Utilities	\$20,863,900
Direct Labor	756,200
Plant Maintenance	3,555,600
Payroll Overhead	943,500
Operating Supplies	355,600
Indirects	<u>1,724,700</u>
Total Annual Operating Cost	\$28,199,500

One operating scenario for the Al-air battery suggests disposal rather than reprocessing of the hydrargillite. This is viable in the near term when only a small number of Al-air batteries would be in operation. However, in the long term, the use of a large number of Al-air batteries would create tremendous demands on the supply of primary aluminum. Therefore, recycling of the hydrargillite would be required to maintain a stable primary aluminum market and a stable supply of replacement anodes.

In a study (Hudson and Putnam 1980) that included market penetration estimates, it was projected that in a production year in which sales of

3 million aluminum-air battery-powered automobiles occurred(a) and five million were already in operation, the following demands would be placed on the aluminum industry:

- primary aluminum required for anodes in new cars would equal 224,800 metric tonnes (247,280 tons)
- recycled aluminum for replacement aluminum anodes to support the eight million vehicles in the fleet would equal 6.53 million metric tonnes (7.20 million tons).

These projections assume a 19.6 km/kg·Al (12.2 miles/kg·Al) vehicle efficiency. The demand projections for replacement anodes would be inversely proportional to vehicle efficiency. The demand for primary aluminum for initial anodes (247,280 tons) represents a 1.8% increase over the 27.7 billion pounds of aluminum produced in the world in 1987 (Light Metal Age 1988, p. 45). This demand would develop over 5 to 10 years and could be met by aluminum producers. The demand created by the need for replacement anodes is another matter. The 7.20 million tons of replacement anodes represents an 52% increase in demand from 1987 world aluminum production. This demand would exert significant pressures on world aluminum prices, and therefore, the price of primary aluminum could increase dramatically. For these reasons, disposal of hydrargillite and purchase of new aluminum is a poor scenario to pursue in the long term. If a major market penetration of Al-air battery-powered vehicles occurs, dedicated hydrargillite and anode manufacture plants would provide a more stable supply base.

Table 5.7 summarizes the two viable long-term hydrargillite reprocessing scenarios examined in this chapter, calcining, and washing and calcining. Given the accuracy of the estimates, the difference between the two scenarios is negligible. For the purpose of generating the total fuel cycle estimates, the average energy consumption and cost of the two scenarios was used. The conversion factor used to convert energy consumption to a kWh/tonne·Al basis was 10550 kJ/kWh.

(a) As a point of reference, 1986 new car sales in the U.S. totaled 11,450,000 (U.S. Department of Commerce 1987).

TABLE 5.7. Direct Energy Consumption and Cost Estimates for
Reprocessing of Hydrargillite

<u>Scenario</u>	<u>Energy Consumption</u>	<u>Reprocessing Cost</u>
#1	3.43×10^6 kJ/tonne·Al = 325 kWh	\$81 per tonne of aluminum
#2	3.66×10^6 kJ/tonne·Al = 347 kWh	\$87 per tonne of aluminum

6.0 ANODE MANUFACTURE

Currently, the production of primary aluminum consists of two major processes, the refinement of bauxite ore into commercially pure alumina (Al_2O_3) and the reduction of alumina to form molten aluminum and byproducts. The most common reduction process and the one examined in this review is the Hall-Heroult process. Several aluminum manufacturing process improvements were reviewed to identify the potential for reduction in the direct energy consumption of anode manufacture.

When purified alumina is reduced to molten aluminum using the Hall-Heroult process (commonly called the Hall process in North America), the alumina is dissolved in an electrolytic cell filled with molten cryolite. Through the use of electrical current, the alumina is reduced. In addition to electricity, energy is supplied to the Hall cell through a consumable carbon anode. The oxygen from the alumina reacts with the carbon anode of the cell to form carbon dioxide, which is emitted from the cell. The aluminum is heavier than the electrolyte in the cell and, therefore, settles to the bottom of the bath. When a sufficient amount of aluminum has settled, it is siphoned from the bath. The molten aluminum is then sent to a holding furnace until it is shipped to nearby plants or to a casting operation. A Hall process schematic is presented in Figure 6.1. The "best-practice" energy inputs associated with the production of one tonne of aluminum are presented in Table 6.1, based on prebaked anode technology. (An alternative anode technology is Soderberg. This technology avoids the use of molding, rodding, and baking processes at the expense of lower cell efficiency. Consequently, the technologies are roughly equivalent in cost and energy consumption.)

In a study by Reynolds Aluminum (McMinn and Branscomb 1981), it was concluded that the lowest-cost anode plates could be made by going directly from molten Hall cell metal to a continuous caster, where an anode strip is formed. A shearing machine cuts the strip into the appropriate lengths.

FIGURE 6.1. Hall Process Schematic

TABLE 6.1. "Best Practice" Energy Inputs to the Hall Process

<u>Input</u>	<u>Energy Value</u>
Electricity to classifying process	220 kWh/tonne·Al
Electricity to mixing process	110 kWh/tonne·Al
Fossil fuel to mixing process	0.53×10^6 kJ/tonne·Al
Electricity to mold pressing	275 kWh/tonne·Al
Electricity to rodding process	220 kWh/tonne·Al
Fossil Fuel to baking process	0.22×10^6 kJ/tonne·Al
Electricity to the Hall Cell	13,305 kWh/tonne·Al
Electricity to the holding furnace	110 kWh/tonne·Al
Fossil fuel to holding furnace	5.0×10^6 kJ/tonne·Al

Finally the anodes are packaged for shipment. Table 6.2 presents the energy consumption estimates associated with the continuous casting of one tonne of aluminum anodes.

TABLE 6.2. Energy Inputs to the Continuous Casting/Shipping Process

<u>Input</u>	<u>Energy Value</u>
Electricity to casting	125 kWh/tonne·Al
Electricity to shearing	53 kWh/tonne·Al
Electricity to packaging	92 kWh/tonne·Al
Fossil fuel to shipping	0.16×10^6 kJ/tonne·Al

The total energy consumption during aluminum production is 14,240 kWh plus 5.75×10^6 kJ per tonne of aluminum produced. In addition, the casting/shipping process requires 270 kWh/tonne·Al and 0.16×10^6 kJ/tonne·Al. The total primary energy consumption is therefore 14,510 kWh/tonne·Al plus 5.9×10^6 kJ/tonne·Al. Using a conversion factor of 10,550 kJ/kWh, total direct energy consumption is equivalent to 15.1 kWh/kg·Al.

The cost of anode production was estimated by adjusting the time-averaged cost of the standard aluminum ingot to reflect the differences in anode production from standard ingot production. The cost of aluminum ingot used as the basis is the average "real-dollar" market cost of aluminum over the past twenty years. The cost for each year of this period is presented in Table 6.3. The time-adjusted average cost is \$0.72/lb (\$1.59/kg) (1987 dollars). Table 6.4 presents the adjustments made to the time-adjusted

TABLE 6.3. Aluminum Ingot Prices from 1967 to 1987 (cents per pound)

Year	Actual Price		1987 dollars	
	Producer ^(a)	Market ^(b)	Producer	Market
1967	25	-	77	-
1968	26	-	77	-
1969	27	-	76	-
1970	29	-	78	-
1971	29	-	74	-
1972	26	21	64	51
1973	25	26	58	60
1974	34	43	72	68
1975	40	35	78	68
1976	45	41	83	76
1977	52	48	91	84
1978	54	51	88	83
1979	61	71	91	106
1980	72	76	99	104
1981	76	60	95	75
1982	76	47	90	55
1983	78	68	89	77
1984	81	61	88	67
1985	81	49	86	52
1986	81	56	84	58
1987	-	71	-	71
Average			82	72

(a) Annual average of major producers' quoted prices for unalloyed primary aluminum ingot.

(b) Annual average market or spot prices as reported by Metals Week.

average ingot cost to develop the anode cost estimate. The final delivered cost estimate as presented in Table 6.4 is \$1.67/kg. The cost estimate of \$1.67/kg is the total amount incurred during each fuel cycle. This estimate does not include the value of the base alumina that is not consumed during the fuel cycle. The base alumina travels through the fuel cycle being used to produce aluminum, converted to hydrargillite, and reprocessed to alumina. The value of alumina is \$0.308/kg·Al (see Table 6.4). Adding this value to the anode fuel cycle cost of \$1.67/kg yields a wholesale anode cost of \$1.98 for alloyed anodes made from 99.99% Al. The wholesale cost of unalloyed 99.5% Al anodes is estimated as \$1.80. The wholesale cost is important when

TABLE 6.4. Anode Cost Estimate (1987\$)

Time-adjusted delivered cost of Al ingot	\$1.588
Less ingot casting costs ^(a)	-0.060
Less the cost of new alumina sayer ^(b)	-0.308
Plus continuous casting costs ^(c)	+0.211
Plus shearing and stacking ^(d)	+0.060
Plus purity cost ^(e)	+0.106
Plus alloy enhancement cost ^(f)	+0.073
Total cost of the anode per fuel cycle ^(g)	\$1.67

- (a) Based on a 1980 estimate by LLNL using engineering judgment. The LLNL estimate of \$0.043/Kg was adjusted to 1987\$ using GNP implicit price deflators.
- (b) Based on 1.925 tonnes of alumina per tonne of aluminum and a market price for alumina of \$160 per tonne (Arthur D. Little 1988).
- (c) Based on a 1980 estimate by Reynolds Aluminum (McMinn and Branscomb 1981). The Reynolds estimate of \$0.15 was adjusted to 1987\$ using GNP implicit price deflators.
- (d) Based on a 1980 estimate by Reynolds Aluminum (McMinn and Branscomb 1981). The Reynolds estimate of \$0.043 was adjusted to 1987\$ using GNP implicit price deflators.
- (e) Based on a 1980 estimate by Reynolds Aluminum (McMinn and Branscomb 1981). The Reynolds estimate of \$0.077 was adjusted to 1987\$ using GNP implicit price deflators.
- (f) Based on a 1980 estimate by Reynolds Aluminum (McMinn and Branscomb 1981). The Reynolds estimate of \$0.053 was adjusted to 1987\$ using GNP implicit price deflators.
- (g) This value represents the total cost incurred per kilogram of anode manufactured including delivery to the service center. It reflects the credit given for hydrargillite.

determining service station markups and taxes, while the fuel cycle cost of the anode is important when attributing costs to the operation of the Al-air battery.

There is significant potential for improvements in Hall cell technology that will reduce electricity consumption. The baseline energy consumption assumed in this study is 13,305 kWh/tonne·Al (13.31/kg·Al) (see Table 6.1). One potential energy consumption Hall cell retrofit currently being developed

by the Pacific Northwest Laboratory is the use of inert anodes with titanium diboride cathodes. A second energy-reducing aluminum production technique being developed is the compact bipolar cell. These two technologies could reduce cell energy consumption to 12 kWh/kg and 9.7 kWh/kg, respectively, which could reduce the direct energy consumption for anode production by 1.31 kWh/kg and 3.61 kWh/kg. The former technology is the more likely of the two to achieve near-term application. Using carbothermic reduction for aluminum production was also examined for its potential impacts on the anode fuel cycle. If this technology were developed to its full potential anodes could be produced for roughly 11 kWh/kg (Arthur D. Little 1988).

In summary, from receipt of the raw materials through aluminum production to final anode delivery to a service center, the cost attributed to one fuel cycle while using an alloy anode with 99.99% Al base metal is estimated as \$1.67 per kg. The corresponding attributable cost of using an unalloyed 99.5% Al anode is \$1.49/kg. The wholesale cost of these same anodes is \$1.98/kg and \$1.80/kg, respectively. Production of the anode requires 15.1 kWh per kg. There is potential for energy consumption associated with anode production to be reduced in the near future to 13.8 kWh/kg·Al, 11.5 kWh/kg·Al, or possibly 11.0 kWh/kg·Al.

An important point to note is that currently 99.999% Al-base metal is required for anode production to suppress hydrogen production rates. Production of such metal would require an additional purification process; however, cost data on such processes was not obtainable. Therefore, the optimistic assumption of 99.99% will suffice.

7.0 THE COMPLETE FUEL CYCLE

The aluminum anode fuel cycle consists of three parts: 1) the service cycle, 2) hydrargillite reprocessing, and 3) anode manufacture. To estimate the total direct energy consumption and the total cost for the use of aluminum anodes in Al-air battery-powered vehicles, the component estimates for each of the three parts of the fuel cycle are summed to yield total direct energy consumption and cost.

Four approaches were taken to estimate the costs associated with the service cycle:

1. allowing \$0.004 per vehicle mile for service center markup, \$0.125 per kilogram of aluminum for plate installation, and 39% of the total retail cost for taxes
2. allowing \$0.004 per vehicle mile for service center markup, \$0.125 per kilogram of aluminum for plate installation, and \$0.012 per vehicle mile for taxes
3. allowing \$0.125 per kilogram of aluminum for plate installation, 10% of anode cost for general service markup on anodes, and 39% of the total retail cost for taxes
4. allowing \$0.125 per kilogram of aluminum for plate installation, 10% of anode cost for general service markup on anodes, and \$0.012 per vehicle mile for taxes.

In addition, \$0.0292/kg·Al for shipping the hydrargillite to the reprocessing facility must be added. Direct energy consumption attributed to the service cycle is limited to transportation of the hydrargillite to a reprocessing facility. This energy consumption is estimated as 529 kJ/kg·Al.

Two hydrargillite reprocessing scenarios were evaluated: 1) calcining the hydrargillite into alumina acceptable for use in the Hall process; and 2) first washing, then calcining the hydrargillite into alumina acceptable for use in the Hall process. Given the accuracy of the estimates, the difference between the two scenarios was found to be negligible. For developing the total fuel-cycle energy consumption and cost estimates, the average of the two scenario estimates was used. The values for energy consumption and hydrargillite reprocessing cost are 3.55×10^6 kJ/tonne·Al and \$84 per tonne of aluminum, respectively. Using a conversion factor of 10,550 kJ/kWh and

converting to a per-kilogram basis yields an energy consumption estimate of 0.34 kWh/kg·Al and a cost of \$0.084/kg·Al.

The process of anode manufacture using the reprocessed hydrargillite is estimated to consume 14,510 kWh and 5.95×10^6 kJ of direct energy per tonne of aluminum and cost \$1.67/kg. Of this \$1.67, only \$0.179 is attributed to higher purity levels and alloy enhancement. These estimates represent the incremental costs of the anode fuel cycle. The wholesale price of the anodes would be \$1.98/kg for the alloyed 99.99% Al base-metal anode and \$1.80/kg for the 99.5% Al anode based on a \$0.308/kg value of the hydrargillite. Based on this information, as long as base-metal purity requirements do not exceed 99.99% aluminum, common alloying agents are used, and alloying agents do not complicate hydrargillite reprocessing, the use of alloying agents and high-purity aluminum is not a prime cost driver. There is potential for a reduction in direct energy consumption of 1.31 kWh/kg·Al and possibly 3.61 kWh/kg·Al by using inert anodes with titanium diboride cathodes and compact bipolar cells, respectively, in the anode manufacturing process. Both of these technologies are currently under development. Development of carbo-thermic aluminum production processes could potentially reduce total anode manufacturing energy consumption to 11 kWh/kg.

Summing the direct energy consumption contributors, the total energy consumption for the fuel cycle is estimated as 14,510 kWh and 10×10^6 kJ per tonne of aluminum. Using a conversion factor of 10,550 kJ/kWh, this is equivalent to 15.5 kWh/kg·Al. There is high potential for reduction to 14.2 kWh/kg·Al or possibly 11.9 kWh/kg·Al. ELTECH Systems estimates the aluminum-to-electricity efficiency over the SAE J227a drive cycle as 3.8 kWh/kg. Using this data, the net efficiency of using an aluminum-air battery for one complete fuel cycle is calculated by dividing the net battery system output of 3.8 kWh/kg·Al by the direct energy consumption of the fuel cycle. This yields a net battery efficiency of 25% and 27% or 32%, if developing improvements in aluminum processing come to fruition.

Table 7.1 presents a matrix of cost estimates for the complete fuel cycle. As shown in the table, to prepare final cost estimates on a dollar-per-kilogram basis, an assumption must be made to relate the number of miles

TABLE 7.1. General Fuel Cycle Cost Estimates

<u>Service Cycle</u>	<u>Hydrargillite Reprocessing</u>	<u>Anode Manufacture</u>
1. \$0.0292/kg + \$0.004/mile + \$0.125/kg + 39% on total retail cost	\$0.084/kg	\$1.49 unalloyed 99.5% & \$1.67 alloyed 99.99%
2. \$0.0292/kg + \$0.016/mile + \$0.125/kg +		
3. \$0.0292/kg + \$0.125/kg + 10% on anode wholesale cost + 39% on total retail cost		
4. \$0.0292/kg + \$0.125/kg \$0.012/mile + 10% on anode wholesale cost		

traveled to the number of kilograms of aluminum used. This aluminum-to-road mile efficiency will depend of the final vehicle design and weight of the Al-air battery-powered vehicle. Since the vehicles have not yet been designed and aluminum-to-road mile efficiencies are likely to vary among models and intended duties, cost estimates for three different aluminum-to-road mile efficiencies were prepared. Using the battery discharge efficiency of 3.8 kWh/kg·Al and assuming electricity-to-road mile efficiencies of 0.20, 0.26, and 0.31 kWh/mile, the aluminum-to-road mile efficiencies of 19, 14.6, and 12.3 miles/kg·Al (30.6, 23.5, and 19.8 km/kg·Al) were estimated.

Applying the electricity-to-road mile efficiencies to the estimating relationships presented in the cost matrix (Table 7.1), estimates for 99.5% aluminum anodes and alloyed 99.99% base-metal aluminum anodes were generated. The breakdowns for the 99.5% and 99.99% anodes are presented in Tables 7.2 and 7.3, respectively. Based on the high and low estimate for each efficiency and both aluminum grades, the expected ranges for the cost of the anodes are shown in Table 7.4.

TABLE 7.2. Anode Cost Estimate for Alloy with 99.99% Aluminum Base Metal

	<u>19 mile/kg (30.6 km/kg)</u>	<u>14.6 mile/kg (23.5 km/kg)</u>	<u>12.3 mile/kg (19.8 km/kg)</u>
1.	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(19 \text{ mile/kg})(\$0.004/\text{mi}) +$ $\$0.125/\text{kg} +$ $\$0.314/\text{kg} * 39\% +$ $(\$1.98/\text{kg})(0.39) +$ $\$1.67/\text{kg}$ $\$2.88/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(14.6 \text{ mile/kg})(\$0.004/\text{mi}) +$ $\$0.125/\text{kg} +$ $\$0.297/\text{kg} * 39\% +$ $(\$1.98/\text{kg})(0.39) +$ $\$1.67/\text{kg}$ $\$2.86/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(12.3 \text{ mile/kg})(\$0.004/\text{mi}) +$ $\$0.125/\text{kg} +$ $\$0.287/\text{kg} * 39\% +$ $(\$1.98/\text{kg})(0.39) +$ $\$1.67/\text{kg}$ $\$2.84/\text{kg}$
2.	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(19 \text{ mile/kg})(\$0.016/\text{mi}) +$ $\$0.125/\text{kg} +$ $\$1.67/\text{kg}$ $\$2.21/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(14.6 \text{ mile/kg})(\$0.016/\text{mi}) +$ $\$0.125/\text{kg} +$ $\$1.67/\text{kg}$ $\$2.14/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(12.3 \text{ mile/kg})(\$0.016/\text{mi}) +$ $\$0.125/\text{kg} +$ $\$1.67/\text{kg}$ $\$2.11/\text{kg}$
3.	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $\$0.125/\text{kg} +$ $(0.10)(\$1.98/\text{kg}) +$ $\$0.436 * 39\% +$ $(\$1.98/\text{kg})(0.39) +$ $\$1.67/\text{kg}$ $\$3.05/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $\$0.125/\text{kg} +$ $(0.10)(\$1.98/\text{kg}) +$ $\$0.436 * 39\% +$ $(\$1.98/\text{kg})(0.39) +$ $\$1.67/\text{kg}$ $\$3.05/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $\$0.125/\text{kg} +$ $(0.10)(\$1.98/\text{kg}) +$ $\$0.436 * 39\% +$ $(\$1.98/\text{kg})(0.39) +$ $\$1.67/\text{kg}$ $\$3.05/\text{kg}$
4.	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(19 \text{ mile/kg})(\$0.012/\text{mi}) +$ $\$0.125/\text{kg} +$ $(0.10)(\$1.98/\text{kg}) +$ $\$1.67/\text{kg}$ $\$2.33/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(14.6 \text{ mile/kg})(\$0.012/\text{mi}) +$ $\$0.125/\text{kg} +$ $(0.10)(\$1.98/\text{kg}) +$ $\$1.67/\text{kg}$ $\$2.28/\text{kg}$	$\$0.084/\text{kg} +$ $\$0.0292/\text{kg} +$ $(12.3 \text{ mile/kg})(\$0.012/\text{mi}) +$ $\$0.125/\text{kg} +$ $(0.10)(\$1.98/\text{kg}) +$ $\$1.67/\text{kg}$ $\$2.25/\text{kg}$

TABLE 7.3. Anode Cost Estimate for 99.5% Aluminum

<u>19 mile/kg (30.6 km/kg)</u>	<u>14.6 mile/kg (23.5 km/kg)</u>	<u>12.3 mile/kg (19.8 km/kg)</u>
1. \$0.084/kg + \$0.0292/kg + (19 mile/kg)(\$0.004/mi) + <u>\$0.125/kg +</u> \$0.314/kg * 39% + (\$1.80/kg)(0.39) + \$1.49/kg \$2.63/kg	\$0.084/kg + \$0.0292/kg + (14.6 mile/kg)(\$0.004/mi) + <u>\$0.125/kg +</u> \$0.297/kg * 39% + (\$1.80/kg)(0.39) + \$1.49/kg \$2.60/kg	\$0.084/kg + \$0.0292/kg + (12.3 mile/kg)(\$0.004/mi) + <u>\$0.125/kg +</u> \$0.287/kg * 39% + (\$1.80/kg)(0.39) + \$1.49/kg \$2.59/kg
2. \$0.084/kg + \$0.0292/kg + (19 mile/kg)(\$0.016/mi) + \$0.125/kg + \$1.49/kg \$2.03/kg	\$0.084/kg + \$0.0292/kg + (14.6 mile/kg)(\$0.016/mi) + \$0.125/kg + \$1.49/kg \$1.96/kg	\$0.084/kg + \$0.0292/kg + (12.3 mile/kg)(\$0.016/mi) + \$0.125/kg + \$1.49/kg \$1.93/kg
3. \$0.084/kg + \$0.0292/kg + \$0.125/kg + <u>(0.10)(\$1.80/kg) +</u> \$0.416 * 39% + (\$1.80/kg)(0.39) + \$1.49/kg \$2.77/kg	\$0.084/kg + \$0.0292/kg + \$0.125/kg + <u>(0.10)(\$1.80/kg) +</u> \$0.416 * 39% + (\$1.80/kg)(0.39) + \$1.49/kg \$2.77/kg	\$0.084/kg + \$0.0292/kg + \$0.125/kg + <u>(0.10)(\$1.80/kg) +</u> \$0.416 * 39% + (\$1.80/kg)(0.39) + \$1.49/kg \$2.77/kg
4. \$0.084/kg + \$0.0292/kg + (19 mile/kg)(\$0.012/mi) + \$0.125/kg + (0.10)(\$1.80/kg) + \$1.49/kg \$2.14/kg	\$0.084/kg + \$0.0292/kg + (14.6 mile/kg)(\$0.012/mi) + \$0.125/kg + (0.10)(\$1.80/kg) + \$1.49/kg \$2.08/kg	\$0.084/kg + \$0.0292/kg + (12.3 mile/kg)(\$0.012/mi) + \$0.125/kg + (0.10)(\$1.80/kg) + \$1.49/kg \$2.06/kg

TABLE 7.4. Range of Anode Cost Estimates

<u>Miles/kg (km/kg)</u>	<u>Alloyed 99.99%</u>	<u>Unalloyed 99.5%</u>
19 (30.6)	\$2.21 - \$3.05/kg	\$2.03 - \$2.77/kg
14.6 (23.5)	\$2.14 - \$3.05/kg	\$1.96 - \$2.77/kg
12.3 (19.8)	\$2.11 - \$3.05/kg	\$1.93 - \$2.77/kg

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APPENDIX A

ECONOMIC ANALYSIS METHODOLOGY FOR
THE DETERMINATION OF HYDRARGILLITE REPROCESSING COSTS

APPENDIX A

ECONOMIC ANALYSIS METHODOLOGY FOR THE DETERMINATION OF HYDRARGILLITE REPROCESSING COSTS

The economic methodology used for the determination of hydrargillite reprocessing costs is based on a real-1987-dollar analysis, as opposed to a nominal-dollar analysis. The basic formula for calculating the unit cost per ton of alumina produced from reprocessing is as follows:

$$(PCC)(FCR_p) + (WC)(FCR_{WC}) + OC = R \quad (A.1)$$

where: PCC = the plant capital cost per ton of alumina capacity
FCR_p = the annualized fixed charge rate for plant capital
WC = the working capital per ton of alumina capacity
FCR_{WC} = the annualized fixed charge rate for working capital
OC = the annual operating cost per ton of alumina produced
R = the reprocessing cost per ton of alumina produced.

The values for PCC, WC, OC, and R depend on the particular plant design. The determination of these values is discussed in Appendix B. The determination of the FCRs is discussed in this appendix.

The fixed charge rate is the factor which, when multiplied by the present value of the capital investment, determines the contribution of the capital investment toward the annualized plant cost. The annual plant cost divided by plant capacity yields the annualized cost per unit of product produced. The formula for the FCR is as follows:

$$CRF((1 - \tau(DPF) - ITC) / (1 - \tau)) + \beta \quad (A.2)$$

where CRF = the capital recovery factor
 τ = the tax rate
DPF = the real depreciation factor

ITC = the investment tax credits

β = the additional tax rate and insurance (Doane et al. 1976).

The 1986 Tax Reform Act eliminated investment tax credits; therefore, ITC is equal to zero. The term is included in the formula because, at some future time, investment tax credits may be reintroduced. The combined state and federal tax rate (τ) is assumed to be 39.1 percent (Brown et al. 1987). Additional taxes and insurance (β) are estimated as 2 percent (Doane et al. 1976, Brown et al. 1987). The FCR equation incorporates an implicit assumption that taxes and insurance (β) are paid with before-tax dollars, while the return on capital is paid with after-tax dollars. The CRF is calculated as follows:

$$k / (1 - (1 + k)^{-N}) \quad (A.3)$$

where k = the real discount rate

N = the project life (Doane et al. 1976).

The discount rate used in the estimates developed in this study is 6.0 percent, which is the real after-tax discount rate for general industry (Brown et al. 1987). A project life of 21 years was used. This is the average economic life of equipment used in the nonferrous metal industry (Brown et al. 1987). Making these substitutions into the CRF equation yields a CRF of 0.085. The depreciation factor (DPF) represents the present value of future depreciation credits. It is determined by summing the deflated nominal depreciation credits established by IRS for each depreciable project year. Determination of the DPF requires the determination of the appropriate IRS depreciation schedule and an inflation rate.

The estimated economic life for equipment used in the nonferrous metals industry is 21 years (Brown et al. 1987). This corresponds to an IRS asset depreciation range (ADR) class life of fourteen years. For projects with ADR class lives of more than ten years but less than sixteen years, a modified ACRS depreciation schedule of seven years is applicable. This depreciation schedule is presented in Table A.1. The depreciation schedule is in nominal

dollars at initial investment time; therefore, the values in the schedule must be deflated to allow for the devaluation of the dollar between the initial investment time and the tax year of recovery. This deflating was performed using an inflation rate of 3.1 percent (Brown et al. 1987). Table A.2 presents the deflated depreciation schedule. The total presented in Table A.2 is the DPF.

TABLE A.1. Modified Seven-Year ACRS Depreciation Table for 1987 and Beyond

<u>Year</u>	<u>Depreciation Percentage</u>
1	14
2	25
3	17
4	13
5	11
6	10
7	10
Sum	100

Source: Brown et al. 1987.

TABLE A.2. Discounted and Modified Seven-Year ACRS Depreciation Table for 1987 and Beyond

<u>Year</u>	<u>Depreciation Percentage</u>
1	14.0
2	24.2
3	16.0
4	11.9
5	9.7
6	8.6
7	8.3
Sum	92.7

Applying the FCR methodology and assumptions outlined above, the fixed charge rates for plant capital (FCR_p) and working capital (FCR_{wc}) can be determined as shown below:

$$FCR_p = 0.085((1 - 0.391 \cdot 0.9275 - 0)/(1 - 0.391) + 0.02) = 0.11. \quad (A.4)$$

When calculating FCR_{WC} , the variable DPF is zero because working capital is a non-depreciable investment. In addition, working capital is fully recovered in nominal dollars at the end of the project life; therefore, the raw FCR calculated from the general equation must be discounted over the project life. This yields an effective FCR_{WC} as follows:

$$FCR_{WC} = (0.085((1 - 0.391 \cdot 0 - 0)/(1 - 0.391) + 0.02)(1 - (1/1.06^{21}))) = 0.11. \quad (A.5)$$

APPENDIX B

CAPITAL AND OPERATING COST ESTIMATES FOR
CALCINING AND WASHING/CALCINING FACILITIES FOR HYDRARGILLITE REPROCESSING

APPENDIX B

CAPITAL AND OPERATING COST ESTIMATES FOR CALCINING AND WASHING/CALCINING FACILITIES FOR HYDRARGILLITE REPROCESSING

These capital cost estimates are for a hydrargillite calcining facility and a hydrargillite washing/calcining facility that have production capacities of 1 million (English) tons of alumina per year. The estimates are in 1987 dollars. All costs are based on data presented in Cost Estimate of the Bayer Process for Producing Alumina-Based on 1982 Equipment Prices (Kramer and Peters 1983). The equipment costs in this report were updated to 1987 dollars using the Marshall & Swift equipment cost indices.

Table B.1 presents a breakdown of the capital cost estimate for the calcining facility. Equipment costs are divided into two sections: one for equipment cost data gathered on an uninstalled basis and the other for equipment cost data gathered on an installed basis. Equipment cost data that are on an uninstalled basis (the feeders) have additional costs allocated to them for installation labor, foundations, buildings, structures, instrumentation, electrical subsystems, piping, painting, and a miscellaneous category. Equipment cost data gathered on an installed basis (silos and calciners) are added to the sum of the uninstalled equipment costs and their installation and support costs. This yields a total direct cost for the plant of \$36,104,700.

TABLE B.1. Capital Investment Cost Estimate for a Calcining Facility
for Hydrargillite Reprocessing

Uninstalled Equipment Items	EQUIPMENT	LABOR	TOTAL
Feeders	85,300	12,800	98,100
TOTAL	85,300	12,800	98,100
Total equipment cost x factor indicated:			
Foundations, 0.321			31,500
Buildings, 0.002			200
Structures, 0.05			4,900
Instrumentation, 0.15			14,700
Electrical, 0.062			6,100
Piping, 0.40			39,200
Painting, 0.050			4,900
Miscellaneous, 0.10 (Kramer and Peters 1983)			<u>9,800</u>
Subtotal			111,300
Installed Equipment			
Calciners			\$17,825,600 ^(a)
Silos			<u>18,069,700</u>
Subtotal			35,895,300
TOTAL DIRECT COST			36,104,700
Field indirect, 10.0% of total direct cost			<u>3,610,500</u>
Total construction cost			39,715,200
Engineering, 10.0% of total construction cost			3,971,500
Administration and overhead, 5.0% of total construction cost			<u>1,985,800</u>
Subtotal			45,672,500
Contingency, 15.0% of above subtotal			<u>6,850,900</u>
Subtotal			52,523,400

- (a) The calcining equipment, which includes washing equipment, is estimated to cost \$20,028,800. Robert A. Rand of Alcoa, in a personal communication on June 7, 1988, roughly estimated that the washing equipment contributed 10% to 12% of the total capital cost. Based on this information, 11% was deducted from the calcining equipment estimate of \$20,028,800 to exclude unnecessary washing equipment.

TABLE B.1. (contd)

Contractor's fee, 5.0% of above subtotal	<u>2,626,200</u>
Subtotal	55,149,600
Plant facilities (10%)	5,515,000
Plant utilities (12%)	<u>6,618,000</u>
Total Plant Cost	67,282,600
FIXED CAPITAL COST (assuming overnight construction period) (i.e., no interest or escalation during construction)	67,282,600
Working Capital:	
Raw materials and supplies	8,749,400
Product and in-process inventory	10,928,900
Accounts receivable	10,928,900
Available cash	<u>10,793,800</u>
WORKING CAPITAL COST	41,401,000
Capitalized startup costs	<u>672,800</u>
Subtotal	<u>42,073,800</u>
TOTAL CAPITAL COST	109,356,400

Field indirects, which are estimated as 10% of the direct cost, cover field supervisors, temporary construction facilities, rental construction equipment, and payroll overheads. Project engineering is estimated as 10% of the total construction cost. An additional 5% of the total construction cost is added to cover administration and overheads. To the subtotal of all these costs, a 15% contingency is added. Subtotaling again, an estimated contractor's fee of 5% is added. The total of all these costs, plus 10% and 12% for plant facilities and utilities, respectively, yields the total plant cost. Capitalized startup costs are estimated as one percent of the total plant cost (Kramer and Peters 1983). The grand total represents the depreciable investment.

In addition to these costs, a working capital allowance is estimated to include the value of the following four items: 1) raw materials and

supplies for 30 days, 2) product and in-process inventory (total operating cost for 30 days), 3) accounts receivable (total operating cost for 30 days), and 4) available cash (direct expenses for 30 days) (Kramer and Peters 1983). Working capital is a non-depreciable investment that is recovered at the end of the project life.

The cost to reprocess hydrargillite, not the value of the hydrargillite, has been the focus of this study. This approach was taken because the reprocessing costs are more certain than the market price, which would be affected by numerous factors external to the actual reprocessing cost. For estimating the operating costs associated with the anode, the reprocessing cost is the most relevant cost, because if the market value of the hydrargillite is temporarily high, the higher value of the hydrargillite at discharge would be largely offset by the higher cost of replacement anodes. Therefore, the consumer would mainly be affected by the actual reprocessing costs and not the market value of hydrargillite. The value of hydrargillite is needed, however, to estimate the appropriate amount of working capital required by the reprocessing facility.

To determine the value of hydrargillite for use in the working capital estimate only, the value of hydrargillite is assumed to be the current cost of alumina less hydrargillite reprocessing costs. A current cost of alumina of \$145 per ton (\$160 per tonne; Arthur D. Little 1988) was used. Working capital is estimated as \$6,403,500 (i.e., \$0 for raw materials; \$2,179,500 for product and in-process inventory; \$2,179,500 for accounts receivable; and \$2,044,500 for available cash), plus the following:

1. the value of a 30-day raw material supply of hydrargillite
2. the value of a 30-day supply of hydrargillite for in-process inventory
3. the value of a 30-day supply of hydrargillite for accounts receivable
4. the value of a 30-day supply of hydrargillite for direct expenses. This totals to \$6,403,500 plus the value of a 120-day supply of hydrargillite. Allowing "R" to equal the reprocessing cost, the value of hydrargillite is $$(145 - R)$ per ton of alumina produced. This yields a working capital estimate of $\$6.4035 + \$(145 - R)(120/365)$ per ton of alumina produced per year.

Based on the economic methodology presented in Appendix A, the reprocessing cost, R, is equal to the following:

$$\begin{aligned} & (\text{plant capital cost per ton of annual alumina production}) \\ & \quad (\text{fixed charge rate}) + \\ & (\text{working capital per ton of annual alumina production}) \\ & \quad (\text{fixed charge rate}) + \\ & \text{annual operating cost per ton of alumina production.} \end{aligned}$$

Substituting the plant capital cost of \$67.96/annual·ton, a fixed charge rate of 0.11, working capital of \$6.4035/annual·ton + \$(145 - R)(120/365)/annual·ton, a working capital fixed charge rate of 0.11, and adding the operating cost of \$26.52/ton, the equation yields a value for "R" of \$38.55 per ton of alumina produced (\$42.50 per (metric) tonne of alumina produced). Using this value of "R", working capital is estimated as \$41,401,000 (see Table B.1).

A breakdown of the operating costs excluding the purchase cost of the hydrargillite is presented in Table B.2. The price of fossil fuel is the dominating utility cost. The amount of fossil fuel consumed is 3.11×10^6 Btu/ton·Al (3.43×10^6 kJ/tonne·Al)(see Table 5.7) which is equivalent to 5.99×10^6 Btu/ton·alumina. Based on a primary energy cost of \$3.26 per MBtu (1987 dollars) (EIA 1987a) and an annual production level of 1×10^6 tons of alumina, the annual energy cost is \$19,527,400. Direct labor is estimated at \$15 per hour for 5 workers per shift and 3 shifts per day. Direct labor supervision is 15% of direct labor. Plant maintenance labor and materials are each estimated as 2.264% of the total plant cost. Maintenance supervision is 20% of maintenance labor. Payroll overhead is 35% of the operating payroll. Operating supplies are estimated as 10% of plant maintenance. Finally, indirects are estimated as 40% of the direct labor and maintenance (Kramer and Peters 1983). The total annual operating cost is \$26,517,500.

TABLE B.2. Total Annual Operating Cost for a Calcining Facility for
the Reprocessing of Hydrargillite

DIRECT COST:

Utilities:	
Fossil Fuel	\$19,527,400
Direct Labor:	
Labor @ 15/hr	657,600
Supervision (15% of labor)	<u>98,600</u>
	756,200
Plant Maintenance:	
Labor (2.264% of total plant cost)	1,523,300
Supervision (20% of maintenance labor)	304,700
Materials (2.264% of total plant cost)	<u>1,523,300</u>
Total	3,351,300
Payroll overhead, 35% of above payroll	904,500
Operating supplies, 10% of plant maintenance	<u>335,100</u>
	1,239,600
TOTAL DIRECT	24,874,500
INDIRECT COST (40% of direct labor and maintenance)	<u>1,643,000</u>
TOTAL ANNUAL OPERATING COST	26,517,500
TOTAL ANNUAL OPERATING COST, \$/ton·Al	51.05
TOTAL ANNUAL OPERATING COST, \$/ton·alumina	26.52
TOTAL ANNUAL OPERATING COST, \$/ton·hydrargillite	15.52
TOTAL ANNUAL OPERATING COST, \$/tonne·Al	56.29
TOTAL ANNUAL OPERATING COST, \$/tonne·alumina	29.23
TOTAL ANNUAL OPERATING COST, \$/tonne·hydrargillite	17.11

Table B.3 presents a breakdown of the capital cost estimate for a washing/calcing facility. Equipment costs are broken into two sections, one for which the equipment cost data were gathered on an uninstalled basis and the other for equipment cost data gathered on an installed basis. Equipment cost data that are on an uninstalled basis (the feeders) have additional costs allocated to them for installation labor, foundations, buildings, structures, instrumentation, electrical subsystems, piping, painting, and a miscellaneous category. Equipment cost data gathered on an installed basis, silos and calciners, are added to the sum of the uninstalled equipment costs and their installation and support costs. This yields a total direct cost for the plant of \$38,307,900.

Working capital is estimated as \$6,811,600 (i.e., \$0 for raw materials; \$2,317,800 for product and in-process inventory; \$2,317,800 for accounts receivable; and \$2,176,000 for available cash), plus the following:

1. the value of a 30-day raw material supply of hydrargillite
2. the value of a 30-day supply of hydrargillite for in-process inventory
3. the value of a 30-day supply of hydrargillite for accounts receivable
4. the value of a 30-day supply of hydrargillite for direct expenses.

This totals to \$6,811,600 plus the value of a 120-day supply of hydrargillite. Allowing "R" to equal the reprocessing cost, the value of hydrargillite is \$(145 - R) per ton of alumina produced. This yields a working capital estimate of $\$6.8116 + \$(145 - R)(120/365)$ per ton of alumina produced per year.

Based on the economic methodology presented in Appendix A, the reprocessing cost, R, is equal to the following:

$$\begin{aligned}
 & (\text{plant capital cost per ton of annual alumina production}) \\
 & \quad (\text{fixed charge rate}) + \\
 & (\text{working capital per ton of annual alumina production}) \\
 & \quad (\text{capital recovery factor}) + \\
 & \text{annual operating cost per ton of alumina production.}
 \end{aligned}$$

TABLE B.3. Capital Investment Cost Estimate for a Washing/Calcining Facility for Hydrargillite Reprocessing

Uninstalled Equipment Items	EQUIPMENT	LABOR	TOTAL
Feeders	85,300	12,800	98,100
TOTAL	85,300	12,800	98,100
Total equipment cost x factor indicated:			
Foundations, 0.321			31,500
Buildings, 0.002			200
Structures, 0.05			4,900
Instrumentation, 0.15			14,700
Electrical, 0.062			6,100
Piping, 0.40			39,200
Painting, 0.050			4,900
Miscellaneous, 0.10 (Kramer and Peters 1983)			<u>9,800</u>
Subtotal			111,300
Installed Equipment			
Calciners			\$20,028,800
Silos			<u>18,069,700</u>
Subtotal			38,098,500
TOTAL DIRECT COST			38,307,900
Field indirect, 10.0% of total direct cost			<u>3,830,800</u>
Total construction cost			42,138,700
Engineering, 10.0% of total construction cost			4,213,900
Administration and overhead, 5.0% of total construction cost			2,106,900
Subtotal			<u>48,459,500</u>
Contingency, 15.0% of above subtotal			<u>7,268,900</u>
Subtotal			55,728,400
Contractor's fee, 5.0% of above subtotal			<u>2,786,400</u>
Subtotal			58,514,800

TABLE B.3. (contd)

Plant facilities (10%)	5,851,500
Plant utilities (12%)	<u>7,021,800</u>
Total Plant Cost	71,388,100
FIXED CAPITAL COST (assuming one-year construction period) (i.e., no interest or escalation during construction)	71,388,100
Working Capital:	
Raw materials and supplies	9,604,700
Product and in-process inventory	11,922,500
Accounts receivable	11,922,500
Available cash	<u>11,780,600</u>
WORKING CAPITAL COST	45,230,300
Capitalized startup costs	<u>713,900</u>
Subtotal	<u>45,944,200</u>
TOTAL CAPITAL COST	117,332,300

Substituting the plant capital cost of \$72.102/annual·ton, a plant capital fixed charge rate of 0.11, working capital of \$6.8116/annual·ton + \$(145 - R)(120/365)/annual·ton, a working capital fixed charge rate of 0.11, and an operating cost of \$28.20/ton, the equation yields a value for "R" of \$40.65 per ton of alumina produced (\$44.83 per tonne of alumina produced). Using this value of "R", working capital is estimated as \$45,230,300 (see Table B.3).

A breakdown of the operating costs, excluding the purchase cost of the hydrargillite, is presented in Table B.4. The price of fossil fuel is the dominating utility cost. The amount of fossil fuel consumed is 3.32×10^6 Btu/ton·Al (3.66×10^6 kJ/tonne·Al) (see Table 4.7), which is equivalent to 6.39×10^6 Btu/ton·alumina. Based on a primary energy cost of \$3.26 per MBtu (1987 dollars) (EIA 1987a) and an annual production level of 1×10^6 tons of alumina, the annual energy cost is \$20,831,400. Direct labor is estimated at \$15 per hour for 5 workers per shift and 3 shifts per day. Direct labor supervision is 15% of direct labor. Plant maintenance labor and materials

are each estimated as 2.264% of the total plant cost. Maintenance supervision is 20% of maintenance labor. Payroll overhead is 35% of the operating payroll. Operating supplies are estimated as 10% of plant maintenance (Kramer and Peters 1983). Lastly, indirects are estimated as 40% of the direct labor and maintenance. The total annual operating cost is \$28,199,500.

TABLE B.4. Total Annual Operating Cost for a Washing/Calcining Facility
for the Reprocessing of Hydrargillite

DIRECT COST:

Utilities:	
Fossil Fuel	\$20,831,400
Water	32,500
Direct Labor:	
Labor @ 15/hr	657,600
Supervision (15% of labor)	<u>98,600</u>
	756,200
Plant Maintenance:	
Labor (2.264% of total plant cost)	1,616,200
Supervision (20% of maintenance labor)	323,200
Materials (2.264% of total plant cost)	<u>1,616,200</u>
Total	3,555,600
Payroll overhead, 35% of above payroll	943,500
Operating supplies, 10% of plant maintenance	<u>355,600</u>
	1,299,100
TOTAL DIRECT	26,474,800
INDIRECT COST (40% of direct labor and maintenance)	<u>1,724,700</u>
TOTAL ANNUAL OPERATING COST	28,199,500
TOTAL ANNUAL OPERATING COST, \$/ton·Al	54.29
TOTAL ANNUAL OPERATING COST, \$/ton·alumina	28.20
TOTAL ANNUAL OPERATING COST, \$/ton·hydrargillite	16.50
TOTAL ANNUAL OPERATING COST, \$/tonne·Al	59.85
TOTAL ANNUAL OPERATING COST, \$/tonne·alumina	31.08
TOTAL ANNUAL OPERATING COST, \$/tonne·hydrargillite	18.20

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