Lawrence Livermore Laboratory

High Performance Metal/Air Fuel Cells

Part 1 - General Review

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Abstract

Metal/air fuel cells are reviewed in terms of their potential application in electric vehicles. Attention is focused on those metals (light alkali and alkaline earth metals, and aluminum) which, in combination with oxygen, have theoretical energy densities (2-13 kWh/kg-metal) exceeding that of gasoline (utilized in automobiles at 2-3 kWh/kg). Lithium and aluminum have yielded 8- and 4 kWh/kg, respectively, in laboratory experimental cells. The slurry Zn/air system achieves 0.85 kWh/kg-Zn in prototype vehicle cells and is reviewed for comparison. Calcium can probably yield 1.8 kWh/kg-Ca, but its potential as a fuel has not yet been fully explored. The remaining metals appear to be unsuitable for use in aqueous electrolyte fuel cells.

The discharge characteristics of lithium, aluminum, and (possibly) calcium/air cells indicate the potential for (1) electric vehicles of the highway performance and minimum range (300 miles) of sub-compact automobiles; (2) rapid refueling for unlimited range extension; and (3) the storage in the fuel cell of sufficient metal for ranges in excess of 1000 miles. Barriers to the concept are the economic necessity of recycling cell reaction products (except in the case of calcium), the expansion or creation of vast metal production industries, and the change-over of existing service station infrastructures to allow electric vehicle servicing.

The energy efficiency of a transportation system using aluminum was estimated using data on the current aluminum production industry. The total (coal to road-load) energy conversion efficiency is roughly 7-9% -- comparable to that projected for the use of synthesized gasoline (H-Coal process) in an internal combustion engine. The efficiency of aluminum production is likely to improve in the future.

An estimate of the cost of fuel cell ownership and operation is derived, relying heavily on the current selling price of aluminum and lithium, and on the performance and projected cost of the slurry air cathode. At \$1.06/kg-Al, the cost of aluminum production makes the greatest contribution (65%) to the total estimated cost of ownership and operation of an aluminum/air cell: 3.0-3.6¢/km, assuming 5.5 kWh/kg-Al utilization. Cost of fuels transportation and handling are below 10% of the total cost.

The hypothetical introduction in 1985 of one-million electric vehicles using aluminum would require an expansion of the domestic production by about 4% (cf., 8%/y average for the last decade). On the other hand, no comparably sized industries for lithium or calcium production exist -- a formidable barrier to the use of these metals in the intermediate term.

The relative rarity of lithium would complicate the recycling process by necessitating low materials losses per cycle. The availability of lithium ore resources is also potentially a problem. In contrast, the extreme abundance of calcium suggest a potentially important role for this metal, should it prove suitable for use in an aqueous electrolyte fuel cell.

HIGH PERFORMANCE METAL/AIR FUEL CELLS

1. Introduction

This report will review metal/air fuel cell systems in terms of their potential applications as automotive power sources. We will restrict our discussion to a relatively small number of systems of demonstrated or potentially high performance: those based on the metals, Li, Mg, Ca, Al, Na, K, and Zn. In addition, all systems considered here utilize aqueous electrolytes. The standard cell voltages (for reaction with oxygen) and the theoretical energy densities of these systems are listed in Table I. We have chosen these metals for consideration because, as fuels for metal/air systems, they have energy densities (2-13.3 kWh/kg) comparable to gasoline (2.3 kWh/kg at 18% engine efficiency.) We have excluded those metals with energy densities below 1 kWh/kg and certain metals (e.g., Be, Sc, and Ti) which are either extremely rare, toxic, or (to our knowledge) showing no promise as high rate anodes. Some of the systems (Zn/air, Na/air) have been developed as electrically regenerative systems. However, as a vehicle power source, the mechanically refuelable mode of operation has distinct advantages. The hydrogen/air fuel cell is included for the sake of comparison.

2. Metal/Air Fuel Cells as Automotive Power Sources: Advantages and Disadvantages

A fuel cell is extremely attractive as a power source for a vehicle for a number of reasons. Mechanical rechargeability allows rapid and convenient extension of vehicle range. The power delivered by the cell is independent of the total stock of fuel; consequently, performance does not depend on the depth of discharge of the system. The quantity of fuel initially stocked may be matched to the intended range, being limited only by the considerations of gross vehicle weight. The operator has confident knowledge of the "state of charge" and range of the vehicle, being able to directly measure the total weight, volume, etc., of unused fuel on board at any given time. The weakest parts of the system may be removed and replaced periodically, without loss of the entire power source. All of these advantages are well-known features of the gasoline automobile, which has set a perhaps irrevocable standard of performance for private transportation.

There are further advantages of a fuel cell intended for refueling by mechanical recharge alone. There is a considerable relaxation of design constraints when the system is designed for the sole function of discharge. The anode need last only a single half-cycle rather than maintain an unchanged electrochemical, physical, and morphological nature over many hundreds of cycles.

The removal of the site of fuel production to a fixed industrial plant renders the vehicle's constraints of plant size and weight, allows the energy and economic advantages of large scale production, and allows continuous process evaluation and control. An industrial metal production plant may operate continuously, in principle, at 100% capacity. In contrast, any on-vehicle fuel production plant lies idle 75% of the time.

In addition, an industrial plant may make use of direct chemical or thermal energy (as in the case of aluminum production) in lieu of a portion of electrical energy exclusively used by a secondary battery. Thus a portion of the 60-70% losses incurred during the production of electricity may be recovered. Ultimately, electricity and metal production sites could operate in close proximity and coordination to reduce the losses due to waste heat and to eliminate the 10% losses incurred during power transmission and urban distribution.

Recycling of the fuel cell reaction product is an inherent part of the fuel cell concept. The energy balance and economic aspects of the entire cycle of fuel production, transport, consumption, and recycling are the key issues. Metal fuels must be of extremely high energy density in order that the costs of handling and transport are not prohibitive. For lithium, aluminum, and possibly calcium, the costs should be comparable to that of gasoline, insofar as the energy densities are comparable. In the initial stages of introduction of a hypothetical calcium/air transportation system, explicit recycling of calcium hydroxide would be unnecessary due to competing uses of the reaction products: the cement industry alone in 1985 would consume approximately 100 MT/y of calcium as lime³¹ compared to the ~ 1 MT/y calcium required for a fleet of one million vehicles.

A fundamental barrier to the use of metal fuels on a large scale is the required expansion of metal production capacity and, ultimately, of electric generation capacity as well. However, this should be less of a problem in the case of aluminum. A one-million vehicle per year entry rate of an aluminum/air fleet in 1985 would require only a 4-5% increase in the projected primary production capacity (10 MT/y) and a corresponding increase of electric power generation of only 0.1%.³⁰ In contrast, the projected U.S. production capacity for lithium in 1985 is only 7,400 tons -- 3% of that needed for a one-million vehicle fleet. At present there is virtually no calcium production industry.

3. Current and Projected Performance of Metal/Air Fuel Cell Systems

Fuel cell systems based on anodes of zinc, lithium, sodium, and aluminum have been investigated to various extents as automotive power sources. Of these only the Zn/air system developed by C.G.E. has been brought to an advanced engineering level of development where predictions of cost and performance may be made with some confidence. Earlier review of these and other systems are available¹. Current cell data is given in Table II, while estimated performance and cost figures for comparison of Li and Al systems to Zn are made in Tables III and V.

The C.G.E. Zinc-Slurry Fuel Cell. A number of attempts to develop an automotive Zn/air system have been made, variously involving fixed plate cells^{2,3}, zinc-oxygen cells in pressurized containers⁴, and fluidized-bed or zinc-slurry reactors⁵⁻⁸. The Compagnie General d'Électricité (C.G.E., Marcoussis, France) have brought to an engineering state of development a system featuring a circulating slurry of zinc (300 g/l) in 12 N KOH---trade-named "Elozine". The system is designed to operate either as a mechanically rechargeable system or as a regenerative fuel cell using an onboard recharge unit.

The electrochemistry is of special interest. Silicon dioxide (14 g/l) is dissolved in the electrolyte and serves as a colloidal stabilizer for thermodynamic threshold for zincate precipitation. The zinc particles discharge without measurable polarization or passivation up to 300 mA/cm².

The slurry is circulated at high rates (1 m/s) through tubular reactors (2 cm diameter by 1 m long) consisting of concentric tubes of current collectors, a separator, an air cathode, and structural support. The tubes comprise the basic unit of the power plant and deliver 25 A (0.08 A/cm²) at 1.22 V and 75 W peak. The system operates at 55°C, allowing for heat rejection without the need for a separate radiator unit. Performances of 110 Wh/kg at the 37 W/kg rate, and 80 W/kg peak have been demonstrated. (However, as with any fuel, the energy density depends on the quantity of fuel stocked. In principle, the energy density of the C.G.E. system could approach the limit of 145 Wh/kg---the energy density of the Elozine fuel alone.)

Cell life is expected to be approximately 2000 hr of operating time at 0.08 A/cm^2 , based on tests under simulated zincate concentration cycling. The actual operating life of the cathode in a vehicle's duty cycle was not measured, but is likely to be less due to deterioration upon standby. The overall energy conversion efficiency is 40% (including all losses). A 250 kg unit would furnish 27 kWh to propel a small vehicle for a range of 150 km (100 miles).

The total selling price has been estimated by C.G.E. at \$42/kWh for the 26 kWh unit.* The tabular reactors would cost \$1.90 each under large scale production (6600/yr).*

C.G.E. has recently abandoned the zinc/air fuel cell concept for general use private automobiles for two fundamental reasons. Because the range of the vehicle is quite low (150 km for the vehicle described in Table III) a large number and a high density of recharging and servicing sites would be needed; this was judged to be prohibitively expensive. Secondly, the low energy conversion efficiency (40%) makes it a poor competitor with the future Na/S battery, which should offer similar range capabilities, albeit without range extension.

Lithium/Air Fuel Cell. Under ERDA contract, the lithium-air fuel cell is being developed by Lawrence Livermore Laboratory and by Lockheed Missile and Space Company⁹, both as a potential automotive power source and as a model for other active metal fuel cells. Fundamental research into the unusual behavior of the lithium electrode in aqueous electrolytes has been conducted by Littauer and coworkers^{10,12} and by this author^{13,14}. Considerable knowledge of the behavior of lithium anodes has been obtained from earlier work on $\text{Li/H}_2\text{O}$ and $\text{Li/H}_2\text{O}_2$ fuel cells intended for marine or emergency, land-based power sources^{15,16}.

The lithium/aqueous- LiOH electrode shows an open circuit potential of -2.87 V (vs. Hg/HgO) a linear polarization (slope, 0.5 ohm-cm^2) and an abrupt passivation above the diffusion-limited current density, which may vary from as low as 0.03- to over 4 A/cm^2 depending on the flow rate and electrolyte concentration. Experimental Li/air cells show open circuit voltages of 2.9 V, and 2.4-2.6 V at 0.1 A/cm^2 . Practical Li/air cells require flowing electrolyte and electrolyte concentration control via precipitation of Li^+ as Li_2CO_3 . The Faradaic efficiency of the dissolution is equal to the ratio of external to diffusion-limited current, and values of 95% are consistently obtained by control of the current density and mass-transfer conditions. However, the operating temperature (40°C) must be raised to allow for adequate heat rejection under certain driving conditions.

*1974 dollars

The energy density of lithium as utilized in these cells is enormous (9 kWh/kg)--sixty times that of Elozine and three times that of gasoline (at 30 mpg, 250 Wh/mile). Sufficient metal may be stored onboard for vehicle ranges of 1500 km (30 kg).^{*} The limiting factor in range is the weight of the CO₂ precipitant necessary for concentration control. In Table III design parameters are given for two nominal ranges: 533 km and 800 km between refuelings of CO₂ and draining of a slurry of lithium carbonate reaction production. System specifications are based on (1) intensive cell properties (voltage, efficiency, current and power densities, temperature); (2) the weights of reactants and additional water; and (3) the weights of plumbing, pumps, storage tanks, and fuel cell hardware, derived from the designs of existing Li/H₂O and Li/H₂O₂ fuel cells.

Aluminum/Air Fuel Cells. Aluminum/air batteries and fuel cells have been pioneered by Zaromb¹⁷⁻²⁰ and are currently under investigation by Despic²¹ and Littauer⁹. Early experimental cells showed voltages of 1-1.5 V and Faradaic efficiencies of 60-100% (at current densities from 3.5-140 mA/cm²)¹⁷⁻¹⁸. Faradaic efficiency increased and cell voltage fell off rapidly with increasing current density. The net result was that maximum discharge energy efficiencies were approximately 30%. These results were obtained only with surface amalgamation and in conjunction with dissolved ZnO and organic inhibitors. The electrolytes were concentrated base, KOH or NaOH. Electrode potentials showed polarization of from 1 to 1.4 V.

Recently Despic reported work in neutral 2N NaCl solutions on aluminum anodes alloyed with trace (0.1% or less) quantities of In, Ga, or Tl, which reportedly brought the electrode potential of Al to within 550 mV of the equilibrium potential at a current density of 30 mA/cm². (The actual surface pH levels adjacent to the electrodes, however, are difficult to determine for the neutral bulk electrolyte; nevertheless, the electrode potentials were on the order of -1.3-1.4 V vs. SCE, compared with a theoretical of about -1.9 V vs. SCE.) Faradaic efficiencies were reported as "high". Cell voltages were approximately 0.6V, indicating voltage efficiencies of about 22%--the losses being associated with the air cathode's poor performance in NaCl solution, and, to a lesser extent, with the polarization of the anode. The work by Despic constitutes a fundamental advance in Al/air technology, due to the low polarization obtained at high efficiencies.

^{*}Assuming an energy demand of 155 Wh/km for a vehicle of nominal design and gross weight of 1000 kg; we have limited the power source weight to 250 kg.

Littauer and coworkers recently reported work on an aluminum alloy which yields cell voltages of 1.4 and 1.2 V at current densities of 0.1 and 0.2 A/cm², respectively, with Faradaic efficiencies of up to 96%. The electrolyte consisted of 6M KOH and <0.05 M Na₂Sn(OH)₆. The alloy has been designated NUSCAL Alloy MRLA-6 and yields 4 kWh/kg. If the polarization of the anode could be reduced to below 0.4 V, as in the case of lithium, the Al/air system could yield 5.5 kWh/kg.

Aluminum is a particularly attractive fuel because (1) its relative abundance allows for some losses in recycling; (2) there is a large domestic industry (6 Mtons/yr now, 10 Mtons/yr 1985) for aluminum production from alumina; (3) the achieved performance of an aluminum/air single cell is 4 kWh/kg-Al, allowing ranges of approximately 1500 km with inventories of 60 kg; (4) the insolubility of Al - (OH)₃ in water and the possibility of on-vehicle regeneration of the electrolyte without precipitants other than water should allow extensive ranges between servicing (~500 miles) and, hence, a minimal service infrastructure.

Magnesium/Air Fuel Cells. There have been a number of attempts to develop a magnesium anode for use in aqueous electrolytes. Magnesium tends to passivate at a pH greater than 9, and the large volume of sludge is generally a problem²². Pure magnesium exhibits a so-called "negative difference effect" the rate of parasitic corrosion is directly proportional to the net current drawn through the anode, so that Faradaic efficiency of the anode is constant²³. Overall discharge energy efficiencies are low (below 30%) due to a stubborn 0.8-0.9 V polarization of the electrode, and the polarization of the air cathode in neutral electrolytes. Faradaic efficiencies of 80% have been obtained by alloying with Al, Zn, Ti, etc., and with the use of soluble corrosion inhibitors^{24,25}.

Calcium/Air Fuel Cell. Very little work has been done on the calcium electrode for use in an aqueous electrolyte fuel cell. In a neutral methanol/water solution, voltage efficiencies were high (65-70%), while the Faradaic efficiencies were only 20-30% at 0.01 A/cm²²⁶. This author is currently studying the calcium electrode in alkaline electrolytes containing high concentrations of halides²⁷. Electrode voltage may be as low as -3.0 V vs SCE in 2N NaOH, 0.02 N NaCl. Like lithium, calcium shows a low resistance linear polarization up to a limiting anodic current at which passivation occurs. Unlike magnesium, the Faradaic efficiency increases with current density to over 90% at potentials of -1.5 V vs S.C.E.

Assuming an air cathode polarization of 0.5 V, the maximum energy efficiency obtained to date would be about 40% (based on anode polarization and Faradaic efficiency data obtained at 0.1 A/cm^2 in alkaline electrolytes using "off the shelf" calcium (99%). Despite these initially promising results, firm conclusions are not yet possible concerning the potential use of calcium as an electrochemical fuel.

Sodium/Air Regenerative Fuel Cell. The sodium/air cell developed by Atomics International has the following cell diagram:

$\text{Na(l)}/\text{NaOH}, \text{NaNH}_2, \text{NaI (fused)}/\text{Na(Hg)} \dots \text{Na(Hg)}/\text{aq. NaOH}/\text{air-cathode}.$

The cell operates at a uniform temperature of 130° with the sodium amalgam (concentration, 2 at.% Na) entrapped in a thin (0.1-0.3 mm) porous nickel frit. The standard cell voltage is 2.72 V. The total energy conversion efficiency is approximately 60% for operation at 120 mA/cm^2 , and Faradaic efficiency is essentially 100%. For fuel cells designed to operate 8 hr periods, the energy densities are 240 to 300 Wh/kg at an 8-h rate.²⁸

For automotive applications, the cell has three fundamental drawbacks:

(1) There is no convenient way for rapid mechanical refueling of the liquid sodium; (2) to operate at reasonable rates, the amalgam electrode must be very thin--introducing the possibility and rupture and explosive mixture of water, NaNH_2 , and liquid sodium; (3) at these temperatures mercury is volatile enough to cause both a health hazard and a continuous loss of an expensive material.

4. Energy Conversion Efficiency

Of the metal fuels under consideration, only aluminum is now produced on scale where estimates of the total energy conversion efficiency (from coal to fuel cell terminals) can be made with confidence. There is no simple "turn-around" energy conversion efficiency of an aluminum cell for direct comparison with that of a secondary battery, as electrical, thermal and chemical process energies are used in the production of aluminum. Table IV gives the energy costs for using aluminum in a transportation system, assuming that coal is the primary energy source. The range of values for aluminum production is that of contemporary (1975) industry using the pre-baked anode technology;³⁰ the lower limit is also that of an advanced and economical Soderberg process (self-baking anode).²⁹ The aluminum recycling plant is assumed to operate in conjunction with a coal-burning electricity generation plant operating at 35% efficiency.* At a projected aluminum fuel value of 5.5 kWh/kg-Al, the energy conversion efficiency with today's practices would be 11.4%. As the cost of electricity rises relative to other process costs, the figure should rise well above 12%. (The value, 12%, would also apply to an electric storage battery operating on household current at roughly 40% turn-around efficiency, assuming a 95% efficient rectifier.)

It is interesting that the transport of aluminum and $\text{Al}(\text{OH})_3$ slurry over a distance of 480 km (round trip) lowers the energy conversion efficiency by only 0.3-0.4% -- a consequence of the efficiency of rail freight and the extremely high energy density of aluminum. A similar result obtains for calcium or lithium.

When the motor, transmission, and utilization efficiencies are taken into account, the total energy conversion efficiency would be approximately that of synthetic gasoline, assuming that coal is the primary energy resource. Alternative routes for the use of coal in automotive transportation are shown in Table V for two vehicles of comparable performance. Again, it should be emphasized that the efficiencies of aluminum production are for current practices which reflect a pre-oil embargo balance of energy and process costs, and are therefore likely to be conservative.

*For new generation of coal-burning plants; current average is about 32% (reference 34).

5. Cost Estimates

Cost estimates for metal/air fuel cell systems are difficult because of the uncertainties in the service station handling costs and the projected performances of the cells (in terms of energy per unit fuel). The cost of the air-cathodes (per unit of charge-passed under actual vehicle duty cycles and standby) is also uncertain. Nevertheless, the cost of the fuel is well known in the case of aluminum, and the experience of the developers of the zinc-slurry fuel cell provides a reasonable basis for the estimates of electrode and hardware costs.^{7,8}

In Table VI, three hypothetical systems are compared: the C.G.E. Zn/air battery (used as an electrically regenerative system), the Li/air, and the Al/air, at the projected performances of 0.85, 9.0, and 5.5 kWh/kg-metal, respectively. (Currently achieved in unit cells are specific energies of 0.85, 8.3, and 4.0 kWh/kg-metal). Costs are expressed in terms of ¢/kWh-delivered at cell terminals and in cost per unit of travel, assuming 0.155 kWh/km-travel at cell terminals. The cost of refueling is dominated in the cases of Li/air and Al/air by the cost of metal production from cell reaction products, which is an order of magnitude greater than the combined costs of transportation and handling of cell fuels and reaction products. Metal fuels and precipitants, and reaction product concentrates (50 vol-% water) were assumed transported for a distance of 200 km (rail) and 40 km (truck) average distances, one-way. It is assumed that the anodes are cast directly from the effluent of the aluminum or lithium electrolysis cells, and that the cost of this fabrication step is negligible compared to the cost of metal production. Also, we have added no explicit "mark-up" to the metal sold at service stations; rather, this mark-up is included in the \$10/h wage plus overhead. (The total handling cost is comparable to that of gasoline at 5¢/gal). By way of comparison, a gasoline vehicle of the same road-load energy demand (0.120 kWh/km) has a fuel cost of 3.0 ¢/km (for gasoline at \$1.25/gal, before taxes), assuming 18% engine efficiency and 85% transmission/drive-train efficiency on cycle J227-aD. The total fuel costs for the Zn, Li, and Al systems are 2, 3.4-7, and 2.5-2.6¢/km, respectively, for an identical vehicle road-load and a total drive-train efficiency of 78% (on J227-aD).

The cost of the initial investment in metal fuel plus make-up for material losses during recycling is significant only in the case of lithium.

To estimate the cost of air cathodes (per unit energy delivered) we have assumed as the worst case the estimated selling price of the C.G.E. air cathode tubular reactions ($\$75/\text{m}^2$, 1977 dollars), but lasting 500 hours of operating time -- one-quarter of their tested life of 2000 hours.⁸ The lower limit assumes an air cathode of the same operating life in a vehicle, but costing $\$25/\text{m}^2$ ($\$11.30/\text{m}^2$ materials, $\$5.60$ manufacturing, 50% profit).³² Neither electrodes use noble metal catalysts. The cost of fixed hardware ($\$9/\text{kg}$) was given by C.G.E. and applies to the fuel cell's plumbing, storage and settling tanks, an air and an electrolyte pump, control units, and permanent current collectors.⁸

A more accurate estimation of costs must await the development and life testing of an actual prototype Li or Al fuel cell. Nonetheless, we find these results are quite encouraging, particularly for the Al/air system.

6. Conclusions

At the present time, only two metal fuels have demonstrated energy densities in experimental cells which exceed that of gasoline (utilized at 2.3 kWh/kg in an engine of 18% efficiency). These metals are Li (at 8.3 kWh/kg-Li) and Al (at 4.0 kWh/kg-Al). Projections of maximum performance of 9 kWh/kg-Li and 5.5 kWh/kg-Al are consistent with probable limitations in anode and air-cathode polarizations at 0.1 A/cm^2 . Calcium (currently yielding 1.8 kWh/kg-Ca) has been insufficiently investigated for solid conclusions concerning its potential in aqueous electrolyte fuel cells.

The total energy efficiency of a transportation system using metal fuels is one of several critical factors in judging feasibility. Only aluminum is now produced on a scale (6 Mton/y) where the energy efficiency of a transportation system might be accurately predicted. For aluminum utilized in a cell at 4-5.5 kWh/kg-Al, the total energy conversion efficiency (coal to road-bed) is 7-9%. This is roughly comparable to the use of syncrude/gasoline (H-Coal Process) in an internal combustion engine.

The future energy efficiency of aluminum production is of extreme importance. No doubt, as the cost of energy rises relative to other industrial costs, improvements will be made in energy efficiency. It is beyond the scope of this report, however, to predict these improvements.

The cost of operation and ownership of a metal-air fuel cell may be divided into two parts: (1) fuel costs, i.e., the cost of producing, delivering, and installing the metal, and the cost of recycling the reaction products; and (2) the amortized cost of cell hardware and cathodes.

The fuel cost is dominated (90%) by the cost on a large scale of producing the metal from the reaction product. This is known accurately only for aluminum: 78¢/kg. An order of magnitude lower is the cost of pumping slurry (at gasoline rates) and installing electrodes. Although gas station attendants would be required to learn new practices, the existing infrastructure could probably accommodate with little change the collection of the reaction product slurries and the infrequent (at 1500 km intervals) installation of plates. The cost of transportation of the metals

and reaction products for a modeled roundtrip distance of 480 km is 3% of the selling price of the metal in the case of aluminum.

A major uncertainty is the cost of air cathodes for use in these systems and the actual frequency of their exchange. The 2000 h test life for assembled batteries of the C.G.E. tubular reactors would probably not be obtained under actual vehicle use patterns, due to standby losses. We have assumed one-quarter of this life; the costs of the C.G.E. tubular reactors (as upper limits); and that estimated for the Giner, Inc. cathode (as lower limit). The air-cathode cost issue is an important one and can only be resolved by the construction and life testing of a range of single-cell units under simulated vehicle use patterns.

Nevertheless, the single most important factor is probably the cost of metal production. This is well-known in the case of aluminum and dominates (at 65%) the estimated total cost of operation and ownership of the fuel cell.

A barrier to the use of metal fuels in the required investment in new metals production facilities. In the case of aluminum, a maximum possible introduction rate of one million vehicles per year in 1985 would require a 4% increase in primary production capacity (cf. average yearly growth rate of 8%/y for the last decade). For this reason alone, aluminum/air cells would seem most attractive for the intermediate term, should development as vehicle power sources be successful.

Metal/air fuel cell systems are intended to provide full performance electric vehicles with range, drivability, and rapid refueling capabilities of current compact automobiles. Consequently, such vehicles should be compared with other full-performance vehicles envisioned for a future without cheap gasoline: most notably, automobiles burning gasoline refined from syncrude. Ultimately we would have to consider the complex issues of relative industrial pollution, vehicle emissions, total cost of vehicle ownership and operation, and the economics of the buildup of a large scale syncrude/gasoline or metals production industry.

TABLE I. THEORETICAL ENERGIES OF METAL/AIR SYSTEMS

Metal	Net cell reaction (basic electrolyte)	Standard cell voltage (V)	Theoretical Specific Energy (kWh/kg) based on weight of:	
			Metal	Cell reactants
Li	$\text{Li} + 1/2 \text{H}_2\text{O} + 1/4 \text{O}_2 = \text{LiOH}$	3.45	13.3	3.9
H ₂	$1/2 \text{H}_2 + 1/4 \text{O}_2 = 1/2 \text{H}_2\text{O}$	1.23	33.0	3.7
Mg	$\text{Mg} + \text{H}_2\text{O} + 1/2 \text{O}_2 = \text{Mg(OH)}_2$	3.09	6.8	2.8
Al	$\text{Al} + 3/2 \text{H}_2\text{O} + 3/4 \text{O}_2 = \text{Al(OH)}_3$	2.70	8.1	2.8
Ca	$\text{Ca} + \text{H}_2\text{O} + 1/2 \text{O}_2 = \text{Ca(OH)}_2$	3.42	4.6	2.5
Na	$\text{Na} + 1/2 \text{H}_2\text{O} + 1/4 \text{O}_2 = \text{NaOH}$	3.11	3.6	2.1
(Gasoline*)	$(\text{C}_8\text{H}_{18} + 12.5 \text{O}_2 = 9\text{H}_2\text{O} + 8\text{CO}_2)$	-	(2.3*)	-
K	$\text{K} + 1/2 \text{H}_2\text{O} + 1/4 \text{O}_2 = \text{KOH}$	3.33	2.3	1.6
Zn	$\text{Zn} + \text{H}_2\text{O} + 1/2 \text{O}_2 = \text{Zn(OH)}_2$	1.65	1.3	0.9
Fe	$\text{Fe} + \text{H}_2\text{O} + 1/2 \text{O}_2 = \text{Fe(OH)}_2$	1.28	1.2	0.8

*Gasoline has an effective energy density of 2.3 kWh/kg in an engine of 18% energy conversion efficiency; Efficiency is that of a 60 HP, 4 cylinder internal combustion engine operating at average load of test cycle, J227-AD. Assumed thermal value of gasoline, 12.5 kWh/kg.

TABLE II. CELL PERFORMANCE DATA

Achieved:

System and Description	Cell Voltage at (V)	Current Density (A/cm ²)	Faradaic Efficiency	Anode Potential at 0.1 A/cm ² (V)	Comments
Zinc-slurry/air (Compagnie Generale d'Electricite (CGE))	1.22 0.91	0.08 0.30	0.85	(0.02 V polarization)	Operating temperature 50-55°C; uses slurry of Zn in 12 N-KOH ("Elozine"); regenerative
Li/Air (Lockheed Missiles and Space Co.) flowing 4-5 M LiOH (ambient temperature)	2.4-2.6	0.10	0.95	-2.81 to -2.58 V vs. Hg/HgO (0.34-0.54 V polarization)	Faradaic efficiency equal to ratio of actual current to anodic limiting current. Operating temperatures to 45°C with use of methanol and alloying agents.
Al/Air 6M KOH, 0.05M Na ₂ SO ₄ (OH) ₆ ; flowing electrolyte	1.4	0.10	0.95	-1.4 V vs. SHE (~ 1 V polarization)	Ambient temperature, basic electrolyte
Al/Air 2M NaCl Al alloyed with < 2 ppt In, Ga, or Tl	0.75 0.6	0.03 0.10	(Not given)	-1.26-1.5 V vs. SCE	Gel formation in electrolyte; neutral electrolyte
Ca/Air CH ₃ OH/H ₂ O; (NH ₄) ₂ SO ₄ ⁺ LiCl ³	2.4 2.0	0 0.01 to 0.02	0.2-0.3	(Not given)	Current density limited to 0.1 A/cm ² by polariza- tion of air electrode.
Mg/Air, neutral salt solutions	<1.3	<0.03	<0.7	~ 1 V	Mg-Al-Zn alloys
Na/Air	2.1	0.12	~ 1	N/A	T = 135°C; regenerative; Amalgam electrode separating aqueous, fused salt cells

TABLE III. PERFORMANCE AND INITIAL COST PROJECTIONS OF METAL/AIR SYSTEMS

	<u>CGE-Zn/air</u>	<u>Li/air^a</u>	<u>Li/air^b</u>	<u>Al/air^c</u>
<u>Cell Operating Conditions</u>				
Cell voltage (V)	1.23	2.4-2.6	2.4-2.6	1.9-1.45
Current density (A/cm ²)	0.08-0.3	0.2-0.3	0.2-0.3	0.2-0.3
Temperature (°C)	50-55	40-50	40-50	-
Faradaic efficiency	0.85	0.95	0.95	0.95
<u>Performance Specifications^c</u>				
Average power (kW)	9	22	22	22
Peak power (kW)	20	30	30	30
Range (km)--metal inventory	155	1600	1600	1600
Range (km)--electrolyte servicing	155	533	800	800
Energy capacity (minimum range between servicing) (kWh)	27	83	124	124
<u>System Specifications</u>				
Area of cathode (m ²)	7.7	4.4	4.4	5.7-7.6
Weight of components				
Metal fuel	32	30	30	45-62
Precipitant ^d	0	38	57	23-32
Electrolyte	148	25	35	42-58
Fixed hardware (including cathode)	70	79	89	110-140
Total	250	172	211	220-292
<u>Initial Cost of System</u>				
Cathode (@ \$75/m ²)	578	330	330	428-591
Metal fuel	64	765	765	48-66
Precipitant	0	4	6	0
Fixed hardware (@ \$9/kg)	630	711	801	990-1260
Total	1272	1810	1902	1466-1920
Initial cost/power (peak) (\$/kW-peak)	64	60	63	49-64
Initial cost/minimum energy capacity ^e (\$/kWh)	47	22	15	12-16
<u>Energy Efficiency (Discharge Cycle Only)</u>	58	68	68	68-50
<u>Average Energy and Power Density^e</u> (Wh/kg @ W/kg)	108 @ 36	480 @ 130	590 @ 100	560 @ 100
<u>Peak Power Density (W/kg)</u>	80	170	140	140

a. Scaled for 533 km range between electrolyte exchanges.

b. Scaled for 800 km range between electrolyte exchanges.

c. Range is for current and maximum projected performances of 50 and 68% efficiency of discharge.

d. Precipitant is CO₂ for Li/air system; H₂O for Al/air system.

e. Note: "energy density" is an ambiguous concept for a fuel cell, as it depends on the weight of fuel stocked; hence quantities derived from energy-density figures reflect the design considerations, not fundamental electrochemical properties.

TABLE IV. ENERGY COSTS OF THE PRODUCTION AND DISTRIBUTION OF ALUMINUM
(PRIMARY ENERGY SOURCE: COAL)

	Energy Costs	
	10 ⁶ BTU/ton-Al	kWh/kg-Al
1. <u>Production of Aluminum from Al(OH)₃</u> [*]		
a. Alumina reduction (electrical energy)	(43-56)	(14-18)
Alumina reduction (assuming an electrical generation efficiency of 35% from coal)	122-160	39.6-51.6
b. Thermal value of carbon anode	12.5-16.7	4.0-5.4
c. Energy for baking anode	2.3-5.5	0.7-1.8
d. Energy for calcining alumina (conversion of Al(OH) ₃ ·H ₂ O to Al ₂ O ₃)	7-10	2.3-3.2
<u>Total process energy</u>	143.8-192.2	46.6-62.0
2. <u>Energy of Transport of Aluminum and Cell Reaction Products</u> ^{**}	0.9	0.3
3. <u>Total Energy Cost (Coal to Fuel Cell)</u>	145-285	47-62

* Energy costs of aluminum production are for pre-baked anode technology, ranges for the current (1975) industry.³⁰ Lower limit of electrical energy costs is also that of an advanced Soderberg process.²⁹

** Assumed transport distances: 200 km (one way) rail; 40 km (average, one way) by truck; energy costs of transportation (diesel fuel): 0.13 Wh/kg-km, rail; 0.72 Wh/kg-km, truck; materials transported: Al and Al(OH)₃ + 50%-vol 5N KOH.³³

TABLE V. ENERGY CONVERSION EFFICIENCY: COAL TO ROAD-LOAD EFFICIENCY

Notes:

- a. Upper limit: H-Coal Process (projected)³⁴; lower limit, current S. African (SASOL) Process.³⁵
- b. Assumed matrix: 200 km rail plus 40 km truck, one-way distances.
- c. Data for 4 cylinder, 60 HP I.C.E. engine, run on test cycle SAE J227-(AD); standard transmission.
- d. Data is for current generation of pre-baked or self-baking industry (1975), see Table IV.
- e. Same matrix for fuel distribution as with gasoline.
- f. Range of battery discharge efficiencies is that of the state of art (50%), and that projected from basic electrochemical considerations (68%).
- g. Efficiency is the product of efficiencies of motor/generator, electrical control, transmission, and differential on SAE J227-(AD) test cycle.
- h. We have neglected the energy costs of coal mining and transport, which should be about the same for both cases.

TABLE VI. ESTIMATION OF COSTS OF OWNERSHIP AND OPERATION
OF SELECTED METAL/AIR FUEL CELL SYSTEMS

	C.G.E. <u>Zn/air</u>	<u>Li/air</u>	<u>Al/air</u>
1. <u>Specific Energy of Anode Fuel</u> (kWh/kg-fuel) (a)	0.145	9	5.5***
2. <u>Costs of Refueling (\$/kg-fuel)*</u>			
Metal fuel (b)	(1)	25.5	1.06
Credit for reaction products (c)	-	{ -22.0 to -24.0	-0.28
Precipitant (d)	-	0.35	-
Transportation of fuels and reaction products (e)	-	0.06	0.03
Handling at service station (f)	-	0.10-0.15	0.06-0.10
3. <u>Total Cost of Refueling (¢/kWh)**(g)</u>	10	22-45	16-17
4. <u>Total Cost of Initial Fuel Investment and Replenishment (¢/kWh)**(h)</u>	0.3	4.6	0.3
5. <u>Hardware Costs (¢/kWh)**</u>			
Air cathode (i)	4.3-12.8	1.0-3.0	1.3-3.8
Fixed hardware costs (j)	2.5-3.3	2.5-3.3	2.5-3.3
6. <u>Total Cost of Operation and Ownership</u> (sum of 2-5) (¢/kWh)**	17-26	30-56	20-24
7. <u>Total Cost of Operation and Ownership</u> (¢/km) (k)	2.4-4.0	4.6-8.7	3.0-3.8

* Units ¢/kg-fuel refer to the cost of each service or material per unit weight of metal fuel.

** Units ¢/kWh refer to the cost per unit of energy delivered at fuel cell terminals.

*** For simplicity, we have assumed the maximum projected efficiency (68%) for the Al/air cell. For S.O.A. cells, the cost figures should be multiplied by 1.38.

NOTES ON COST ESTIMATIONS IN TABLE VI.

- (a) Specific energies of fuels: Elozine; 0.145 Wh/kg-slurry (corresponding to 0.85 kWh/kg-Zn). Li/air: S.O.A., 8-8.5 kWh/kg-Li; projected, 9 kWh/kg-Li. Al/air: S.O.A., 4 kWh/kg-Al; projected, 5.5 kWh/kg-Al.
- (b) Selling price for Li and Al are currently \$25.5 and \$1.06/kg. (Chemical Marketing Reporter, July 11, 1977); cost of refueling for Zn/air not itemized, as system is used as a secondary (electrically rechargeable) fuel cell. No cost of electrode fabrication is assumed for plates cast and rolled from the effluent melt.
- (c) Credit for reaction products is estimated to be the current selling price (per kg of metal) of the feed-stock of the current metal production process (hydrated alumina or LiCl): \$3.63/kg-LiCl (\$22.04/kg-Li) or \$130/tonne hydrated alumina (\$0.28/kg-Al). The upper credit limit for lithium reaction product (\$24.0/kg-Li) assumes a \$1.50 value-added during the production of Li--derived from the current efficiency and cost of large scale aluminum production (value added, \$0.784/kg-Al).
- (d) Carbon dioxide is assumed to sell for \$0.11/kg--half the current selling price due to saturation of the market with CO₂ produced during the reduction of Li₂CO₃. The cost charged for the water used as the precipitant in the aluminum fuel cell is negligible.
- (e) The following transportation matrix is assumed: rail freight: 200 km at 0.002¢/kg-km; two-trailer trucking rates: 40 km at 0.004¢/kg-km. Rail costs correspond to the current cost of shipment of steel from Los Angeles to San Francisco (400 miles), two-18 tonne truck trailers per rail car. Truck costs apply to trucking rates for same distance. 10.71 kg-material/kg-Li; 5.33 kg-material/kg-Al.
- (f) Handling charges at service station. Hourly-wage plus profit and overhead: \$10.00. Cost of pumping slurry at 5 gal/min determines electrolyte handling costs. Cost of replacing plates (at 15-30 sec/plate) determines metal refueling costs. Li: 6 ℓ of slurry/kg-Li = \$0.05/kg-Li for electrolyte handling; 35 plates at 15-30 sec each, 30 kg total weight = \$0.05-0.10/kg-Li; total \$0.1-0.15/kg-Li. Al: 2.4 ℓ slurry (50%-volume solids) per kg-Al = \$0.02/kg-Al; 45 plates at 15-30 sec per plate; total weight, 45 kg: \$0.04-0.08/kg-Al; Total: \$0.06-1.10/kg-Al.

NOTES ON COST ESTIMATIONS IN TABLE VI. (continued)

- (g) Total cost of refueling per unit of energy delivered is calculated on basis of energy density of fuel. For Elozine, an energy efficiency of 40% and an electricity cost of \$0.04/kWh are assumed.
- (h) Assuming 0.5% material losses per cycle of 1600 km; 160,000 km vehicle life-time. 0.155 kWh/km, at cell terminals.
- (i) Cost of Air cathode. Upper limit cost: estimated selling price of C.G.E. tubular reactors (\$59/m² or \$1.90/unit) adjusted to 1977 dollars is \$75/m². Assume 500 h operating life (1/4 of 2000 h test life).⁸ Lower limit (non-noble metal catalyzed) air-cathode cost: Giner, Inc.³² - materials plus manufacturing cost of \$17/m² + 50% profit; operating life of 500 h. Areas of electrodes: Zn/air: 7.7 m², Li/air: 4.4 m²; Al/air 5.7 m². Average power of cells: Zn/air: 9 kW; Li/air: 22 kW; Al/air: 22 kW.
- (j) Cost of hardware: \$9/kg; assumed 160,000 km life and 0.155 kWh/km cell output. Derived from selling price of hardware for C.G.E. system, converted to 1977 dollars.^{7,8}
- (k) We have converted cost per kWh-delivered to cost per km-traveled with the assumption of 0.155 kWh/km at fuel cell terminals. (This corresponds to a road load of 0.12 kWh/km.)
- (l) For the C.G.E. system, we have assumed that the power source will be used as a secondary power source, with electrical charging on board, using residential power at 4¢/kWh.

References:

1. K. D. Beccu, "The Characteristics of Metal-Air Systems," (Chapter VII-3 in From Electrocatalysis to Fuel Cells, ed. G. Sandstede; University of Washington Press, Seattle; 1972; p. 321.)
2. R. Witherspoon, E. Zeitner, H. Schulte, "Experimental Vehicular Zinc-Air Battery with Replaceable Anodes," Proc. Intersoc. Energy Convers. Eng. Conf., p. 96 (1971).
3. W. Egli, "Zinc-Oxygen Battery Experimental Power Plant for Automotive Propulsion," Guld General Atomic, San Diego, Ca; Gulf-GA-A10775 (Sept. 1971).
4. M. Klein, "Secondary Zinc-oxygen Batteries," Final Report June 1972-June 1973; publ. Nov. 1973.
5. G. Caprioglio, A. Weinberg, "Fabrication and Initial Testing of An Experimental Zinc-Oxygen Battery for Electric Vehicles," Proc. of Intersoc. Energy Convers. Eng. Conf. p. 140 (1971).
6. H. Baba, "A New Zinc-Air Fuel Battery System," SAE Transactions, Paper No. 710237 (1971).
7. A. J. Appleby, J. P. Gabano, "Current Status and Prospects of the Zn-Air and Na-S Batteries in France," Proc. Symp. and Workshop on Adv. Battery Res. and Design p. A-49 (March 22-24, 1976).
8. A. J. Appleby, J. Jacquelin, and J. P. Pompon, "Current Status of the CGE Circulating Zinc-Air Vehicle Battery," Spring Meeting of the Electromchemical Society; Philadelphia, May 1977; paper #316.
9. Lockheed Missiles and Space Company, "Follow-on Proposal for Development of the Lithium-water-air Battery for Automotive Propulsion," LMSC-D084831; June 8, 1977.
10. E. L. Littauer and K. C. Tsai, "Anodic Behavior of Lithium in Aqueous Electrolytes, 1. Transient Passivation," J. Electrochem. Soc., 123, 773 (1976).
11. E. L. Littauer and K. C. Tsai, "Anodic Behavior of Lithium in Aqueous Electrolytes, 2. Mechanical Passivation," J. Electrochem. Soc. 123, 964 (1976).
12. E. L. Littauer, K. C. Tsai, "Corrosion of Lithium in Alkaline Solution," to be published in the J. Electrochem. Soc., 1977.

References:

13. John F. Cooper, Pamela K. Hosmer, and Robert V. Homsy, "The Anodic Behavior of Lithium in Aqueous Lithium Hydroxide Solutions," Fall Meeting of the Electrochemical Society, Las Vegas; October 1976.
14. J. F. Cooper, P. K. Hosmer, and R. V. Homsy, "The Anodic Behavior of Lithium in Aqueous Lithium Hydroxide Solutions," to be published in J. Electrochem. Society.
15. E. L. Littauer and J. J. Redlien, "The Lithium-Water Electrochemical Cell as a Marine Power Source," Proc. 9th Intersoc. Energy Conv. Eng. Conf., 1974.
16. H. J. Halberstadt, E. L. Littauer and E. S. Shaller, "Physical and Economic Considerations of the Lithium/Water Marine Battery," Proc. 10th Intersoc. Energy Conv. Eng. Conf. 1975.
17. Solomon Zaromb, "The Use and Behavior of Aluminum Anodes in Alkaline Primary Batteries," J. Electrochem. Soc. 109, 1125 (1962).
18. S. Zaromb and R. A. Foust, "Feasibility of Electrolyte Regeneration in Al Batteries," J. Electrochem. Soc. 109, (1962).
19. L. Bockstie, D. Trevethan, and S. Zaromb, "Control of Al Corrosion in Caustic Solutions," J. Electrochem. Soc., 110, 267 (1963).
20. R. A. Foust, Abstract 49, Electrochemical Society, Boston, 1962.
21. A. R. Despic, D. M. Drazic, S. K. Zecevic, and T. D. Grozdie, "Problems in the Use of High-Energy-Density Aluminum-Air Batteries for Traction," paper #24; 10th International Power Sources Symposium, Brighton, England, 1976.
22. C. Mueller, F. Bowers, "The Control of Insoluble Magnesium Compounds Formed During Seawater Battery Discharge," J. Electrochem. Soc., 118, 394 (1971).
23. R. Glicksman, "Anodic Dissolution of Magnesium Alloys in Aqueous Salt Solutions," J. Electrochem. Soc., 106, 83 (1959).
24. C. E. Kent, W. W. Carson, "Metal-Air Systems. 1. Magnesium-Air Cells," Proc. 20th Annual Power Sources Conference, May 1966; see also, R. P. Hamlen, E. C. Jerabek, J. C. Ruzzo, and E. G. Siwek, "Anodes for Refuelable Magnesium-Air Batteries," J. Electrochem. Soc., 116, 1588 (1969).

References:

25. J. F. King, "A New Alloy for Magnesium Seawater Primary Batteries," Proc. 25th Power Sources Conference, PSC Publ. Comm. Red Bank N. J.; p. 35 (1972).
26. A. Charkey, G. A. Dalin, Proc. 20th Annual Power Sources Conference, PSC Publ. Comm., Red Bank, N. J. (1966).
27. John F. Cooper and Pamela K. Hosmer, "The Behavior of the Calcium Electrode in Aqueous Electrolytes," paper to be presented in Fall Meeting of the Electrochemical Society, Atlanta, 1977.
28. L. A. Heredy, H. L. Recht, and D. E. McKenzie, "The Atomics International Sodium-Air Cell," Symp. on Power Systems for Electric Vehicles, Columbia University, N. Y. April 1967; see also U. S. Patents #3,472,745; 3,472,746; and 3,507,703.
29. _____, "Aluminum Cell Modifications Cut Energy Use," Chem. Eng. News, August 4, 1975.
30. J. W. Stamper and H. W. Kurtz, "Aluminum," (Mineral Facts and Problems, Bureau of Mines, Bulletin 667; U.S. Dept. of the Interior; 1975).
31. B. Brown. "Cement," (Mineral Facts and Problems, Bureau of Mines, Bulletin 667; U.S. Dept. of Interior; 1975).
32. Private communication by David P. Bloomfield (Giner, Inc., 14 Spring Street, Waltham, Mass., to John F. Cooper; June 30, 1977). The 50% profit estimation was made by this author.
33. U. S. Department of Transportation, Summary of National Transportation Statistics, Annual Report, June 1976; see also C. and J. Steinhart, Energy--Sources, Use, and Role in Human Affairs (Duxbury Press, North Scituate, Mass., 1970; p. 224.)
34. E. M. Dickson, et al., "Synthetic Liquid Fuels Development: Assessment of Critical Factors," ERDA 76-129/1.4, May 1977.
35. W. Tipler, "Energy Economics of Automotive Power Generation," SAE Technical Paper #750761; 1975 SAE Off-Highway Vehicle Meeting; Milwaukee, Wisc., September 8-11, 1975.

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