THE C.G.E. CIRCULATING ZINC/AIR BATTERY: A PRACTICAL VEHICLE POWER SOURCE

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Summary

The currently proposed electric vehicle power sources are briefly summarized, and compared with the circulating zinc/air system. Based on current laboratory test data, this system should be capable of 110 Wh/kg, 80 W/kg in a 1 tonne urban vehicle and up to 125 Wh/kg in heavy duty applications, with lifetimes up to twice those for lead—acid systems. Despite its comparatively low recharge efficiency (40%) it will be capable of overall per km costs comparable to those for gasoline powered vehicles at current U.S.A. or untaxed European gasoline prices.

Introduction

For the E.E.C. countries and Japan, which consumed 35% of the O.E.C.D. primary energy requirement in 1973, 67% of primary energy was represented by imported oil*. The economic changes since 1973 have caused a massive investment in nuclear electricity, to eliminate reliance on this oil and its effect on balance of payments. The object in the E.E.C. countries is to limit the use of oil in the energy economy (from 60% in 1973 to 40% in 1985) [2] at the same time increasing oil production and reducing energy growth. The greatest saving (about 260×10^6 equivalent tonnes of crude oil equal to 43% of 1973 oil consumption) will be provided by nuclear power. About 31% of this nuclear generating capacity will be located in France [3], and will conserve a maximum of 80×10^6 tonnes of oil per year in that country.

A nuclear base-load will require smoothing for economic operation. One way in which this can be conducted, which will save additional imported petroleum, is by the use of electric vehicles. For example, an increase of

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*Figures are taken from ref. 1, using conventional equivalences.

overall utilization by 10% of the proposed French nuclear capacity* in 1985 will provide sufficient energy for 7,000,000 vehicles†, or about 25% of the French saturation level. This in turn will conserve a further 9×10^6 tonnes of gasoline††. If the electric vehicle has a per kilometre operating cost similar to that for an i.c. vehicle using untaxed gasoline, economics will be similar to those at present if the loss of gasoline tax receipts is made up by special electricity tariffs. We will examine below different possible power sources for electric vehicles. It is shown that the C.G.E. zinc–air slurry system is closer to application than other high-performance batteries, and promises to meet the cost and convenience goals required for wide application.

The C.G.E. circulating zinc–air system compared with other power sources

Generally accepted performance requirements for an operational capability per cycle of 3 hours, depending on the type of vehicle, are given in Fig. 1.

In spite of recent developments, the oldest and cheapest electrochemical storage system, the lead–acid battery, will always provide insufficient power to weight ratios. Performance figures for this battery are as follows [5] : 25 Wh/kg for standard traction batteries at the 3 hour discharge rate; 35 to 40 Wh/kg for improved prototype batteries, the best world figure announced being 55 Wh/kg. However, their service life is considerably reduced with respect to standard batteries (100 to 400 cycles against 1000 cycles). It is therefore highly probable that the applications of the lead–acid battery will be limited to the small utility car, for which short range per cycle need not be considered as an operational handicap. Conversely, the longer range per cycle and higher speed requirements for city cars, vans and urban buses require power sources in the region of 50 to 180 Wh/kg and 60 to 130 W/kg. At present, such batteries do not exist, though numerous studies have been undertaken to perfect the nickel/zinc, zinc/air, zinc/chlorine, sodium/sulphur and similar couples, together with fuel cells.

The nickel/zinc battery (60 to 80 Wh/kg and more than 150 W/kg [6])
Because of the technology involved, which is similar to that of conventional batteries, faster and less costly industrialization is expected compared with that of other systems currently under study. This is offset by its relatively modest energy density. This system is therefore being considered with interest by numerous organizations (including the C.G.E.) for the lower performance range. At present its industrial development is

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*Historic cumulative load factors for PWRs and BWRs are only 50% [3].
†Calculated for 1 tonne vehicles, 15,000 km/year, with 10% grid losses, 40% battery efficiency, and 150 Wh/tonne-km at motor (see below).
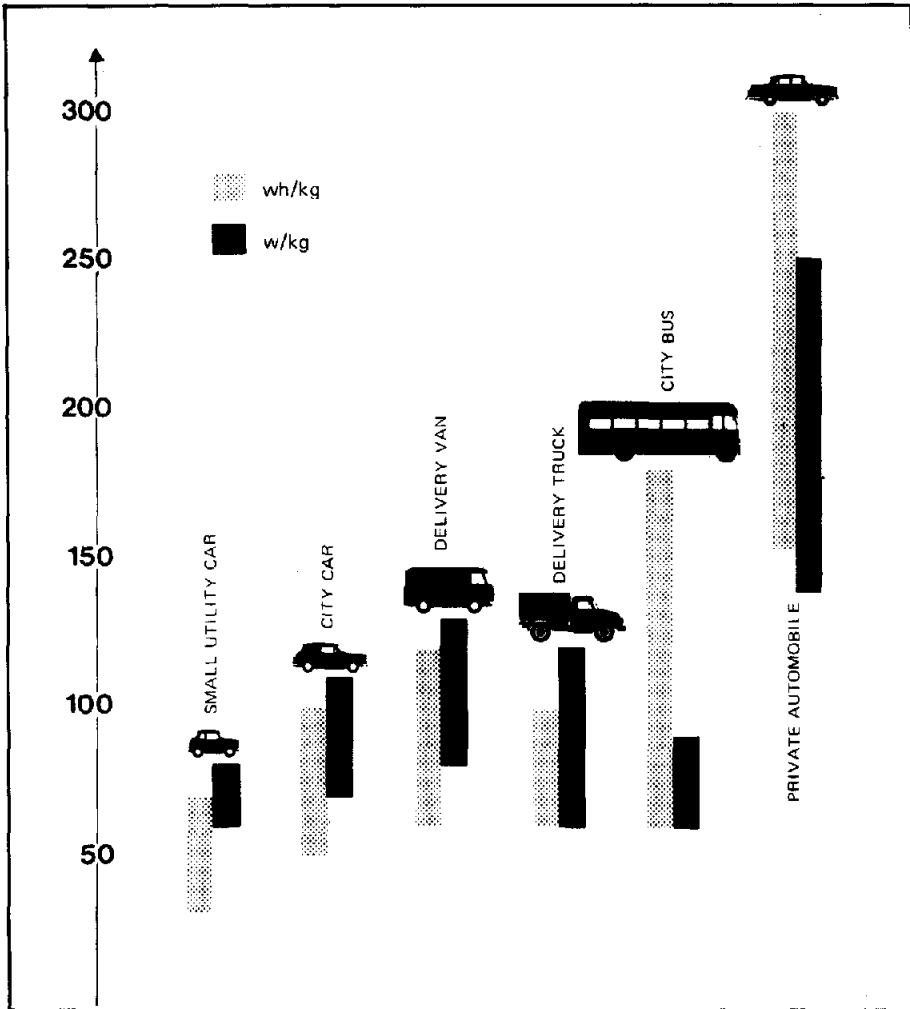††Based on 12 l/100 km; mean of urban and suburban use.

Fig. 1. Specifications of energy sources for electric vehicles [4].

held up by its inadequate cycle life, resulting from the solubility of the zinc electrode reaction products and resulting shape-change and dendrite growth phenomena [7].

Sodium/sulphur batteries

These batteries are currently being studied by the Ford Motor Company, E.S.B., T.R.W., General Electric and General Motors in the U.S.A. (the above in part financed by E.R.D.A. and E.P.R.I., [8]), Chloride Silent Power in Great Britain, Yuasa in Japan and the C.G.E. in France. The predicted performance of this system is extremely attractive (150 to 200 Wh/kg) and in excess of 6000 3-h cycles have been obtained in the laboratory [9]. However, a major drawback is its high operating temperature

(300° to 350 °C). Its development necessitates resolution of complex technological problems, such as special seals using new materials, corrosion resistance at high temperatures, and the fabrication of cheap, reproducible ceramic material. Its advantage is a very low primary materials cost ($ 2/kWh compared with $ 10/kWh for lead–acid).

If the system becomes technically successful, operation aboard a vehicle would still create supplementary problems such as start-up after prolonged stops, and the dangers presented by active materials in the event of accident. The same is true of related concepts (lithium/sulphur) [10]. Consequently, although initial research was undertaken by the Ford Motor Company (which originally developed this system) [11] with a view to electric vehicle uses, development of this type of battery is now oriented towards off-peak storage of electrical power.

Methanol/air and hydrogen/air fuel cells
These will be very attractive from the view-point of convenience (refuelability) and from their lack of the energy density restraint. Their theoretically high efficiency, compared with that of i.c. engines, is very attractive. However, in the present state of the art, their power densities are low and costs much too high. Further progress in the basic field of electro-catalysis is therefore required to increase current densities at constant voltage. It can be considered that their application to electric vehicles will only be possible in the distant future.

The zinc/chlorine battery
This battery, first described in 1887 [12] is being developed by Energy Development Associates and Gould Inc. [13]. It is an ambient temperature system with a highly attractive announced performance (~150 Wh/kg, 70 W/kg) [14]. Prototypes have been produced but service life is still very limited. In addition, reproducibility on an industrial scale has not yet been demonstrated. Also, it may be considered that the use of chlorine (as the unstable hydrate) in large quantities for applications involving the general public is an insurmountable barrier to further development in privately-owned electric vehicles.

The zinc/bromine battery
The system as so far described [15], is of little interest, since its average performance (60 Wh/kg, 70 W/kg) and charge conservation capability are poor. However, recent work has shown that efficient bromine storage and much lower self-discharge may be attained [16]. In spite of this its future is doubtful.

The zinc/air battery
Owing to its high theoretical energy density (1100 Wh/kg) and the abundance of the low cost active materials it uses, this system is still being studied in several electrochemical research centers.

The zinc/air couple
Theoretical energy density 1100 Wh/kg (lead–acid 170 Wh/kg)

Components	Problems in the zinc/air battery		Solutions used in the C.G.E. circulating zinc/air battery
	Fundamental problem	Consequence	
Zinc electrode	Zincate solubility: shape - change dendrite formation	Limited cycle life	Regeneration outside battery
Air electrode	Limited charge–discharge cycles due to deterioration of low-cost catalysts		
	Carbonate formation from atmospheric carbon dioxide	Lowered performance: passivation, damage to air electrode	Carbon dioxide elimination in regeneration process (outside generator)

Fig. 2. Problems with conventional zinc/air batteries: the C.G.E. solutions.

There are two major technical difficulties as far as the cycle life of the battery is concerned: solubility of the zinc electrode reaction products (as in nickel/zinc batteries) and rapid degradation of air electrodes with conventional low-cost catalysts during cycling. While some progress has been made in this area [17], in particular in relation to iron/air batteries [18], performance is still modest.

Faced with the impossibility of resolving these fundamental problems using low-cost technology, even after a long research effort, an alternative solution has been considered: the use of a circulating system using zinc powder suspended in the electrolyte, which is drained after discharge and reactivated externally (Sony in Japan [19], Battelle– Geneva [20], Citroen [21], and the C.G.E. [22]: other laboratories [23] studied particular aspects of the system). The Sony system was highly complex in design and the power density obtained was very low (20 W/kg). Work on this system was terminated in early 1974.

The Laboratoires de Marcoussis (C.G.E.) and S.A.F.T. devised an original and simple structure in 1972 based on tubular cells, which should provide an energy density of 100 Wh/kg and a power density of 80 W/kg for a service life in excess of 500 3-h cycles, which will meet performance specifications for city cars, delivery vans and urban buses. Since the fundamental difficulties of the conventional zinc/air battery have been resolved by means of the electrolyte–zinc powder circulation system (see Fig. 2), the C.G.E. circulating zinc/air system now appears as one of the few electrochemical power sources whose announced performance may lead to real technical success.

The Marcoussis approach has been to make use of those characteristics of zinc electrodes that appear as drawbacks in standard flate-plate type zinc batteries. For example, the high current densities and low polarization that are normally observed at alkaline zinc electrodes under conditions where the electrolyte is below zincate saturation level are used to give a high-performance zinc powder electrode. Addition of colloid stabilizers permits a threefold increase of the threshold concentration for zincate precipitation, at the same time increasing the passivation concentration by the same amount. This occurs in spite of the fact that the solution thus formed is colloidal. The useful limiting zincate concentration corresponds to 300 g zinc per litre of 12 N potassium hydroxide before passivation limits performance. Self-discharge of zinc powder in the electrolyte* is low: no complex zinc metering is needed. No separation of zinc oxide or zincate from the electrolyte is required in the battery. Finally, the use of a tubular system of constant diameter gives optimum hydrodynamic conditions under constant velocity turbulent flow of the zinc-electrolyte slurry. Auxiliary power is thus minimized, since pressure drops are low.

System description

The system is either a fuel cell with built-in electrochemical regeneration facility, or a pure fuel cell with external regeneration. If constructed and used in the first mode, its user will have the choice of classical recharge (as in a battery) or rapid emptying and refilling with fresh charge, according to his requirements. The built-in regenerator is a separate unit with an oxygen evolution electrode of different material and construction from that of the air electrode of the fuel cell, so that cheap catalysts are possible in both cases. The zinc powder regenerator is a small unit (see below) of similar construction to the fuel cell, and it makes use of the same electrolyte circulation system. In this mode, the system may be regarded as a three-electrode secondary zinc-air cell in which the ionic circuit is broken (by electrolyte transfer), rather than the electronic circuit (by switching), as in normal flate-plate cells.

The system is modular, and the power-producing section (tubular electrodes), and the energy storage section (reservoir) are capable of a great variety of geometrical arrangements to suit vehicle space and power and energy requirements. A schematic description of parts of the systems has been given previously [22, 24].

Electrodes
The electrodes are tubular, and consist (from inside to outside) of:
(a) a mild steel exmet, spot-welded to form a tube (this serves as the zinc current collector); (b) a fine gauze (mild steel), serving as a separator support,

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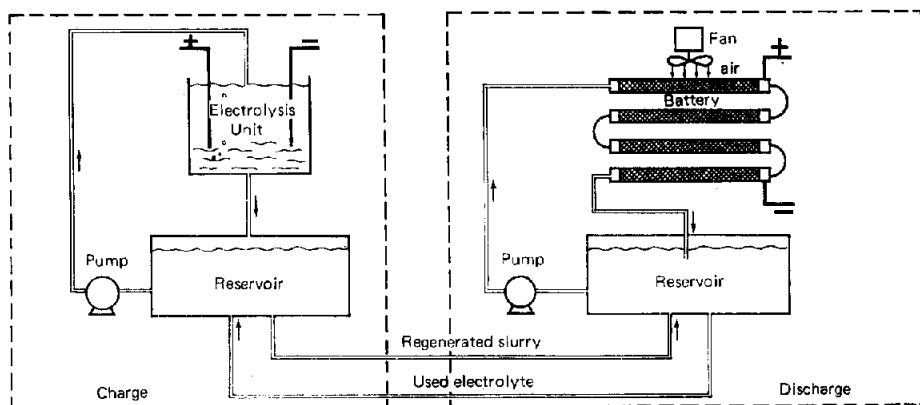*The zinc power-electrolyte slurry has the trademark Elozine.

Fig. 3. Schematic diagram of charge and discharge of the C.G.E. circulating zinc/air battery.

and preventing erosion of the latter by zinc particles; (c) a thin asbestos separator; (d) the air electrode; (e) a mild steel gauze inner current collector; (f) an outer mild steel exmet tube, serving as primary positive current collector. This is slid over the assembly in manufacture and compressed onto the tubular structure; (g) a porous Teflon outer coating.

The tube structure has been carefully optimized from the view-point of performance, cost and ease of manufacture. The key to its performance and lifetime is the air electrode structure, which consists of an extended Teflon bonded active carbon material. Electrode lifetimes are greater than 3000 working hours and, since tubes are empty on stand, no degradation occurs during these periods. The tubes and system are shown schematically in Figs. 3 - 5.

Typical current–voltage curves for individual tubes at 50 °C are given in Fig. 6, which shows the improvement in mean performance since 1973. The curve used as the basis of performance evaluation indicates a maximum power of 75 W/tube at 0.9 V. The gain in performance results from electrode and separator improvements: zinc electrode polarization is negligible (~ 20 mV at 300 mA/cm^2). Polarization is practically independent of the state of discharge of the system, but starts to increase rather suddenly as the solubility limit for zincate is approached. As for all fuel cells, Ah capacity is independent of rate.

Hydrodynamics

The tubular electrodes are connected in modules by plastic U-junctions. The system always presents a constant cross-section to the slurry flow. The modules consist of closely-spaced bundles of electrode tubes arranged with series electrolyte flow. The number of tubes per module is dependent on overall pressure drop: one pump is used at the exit of each module, so that the solution flows through under a pressure negative to that of atmospheric. This prevents weeping of the air electrode: however, for correct
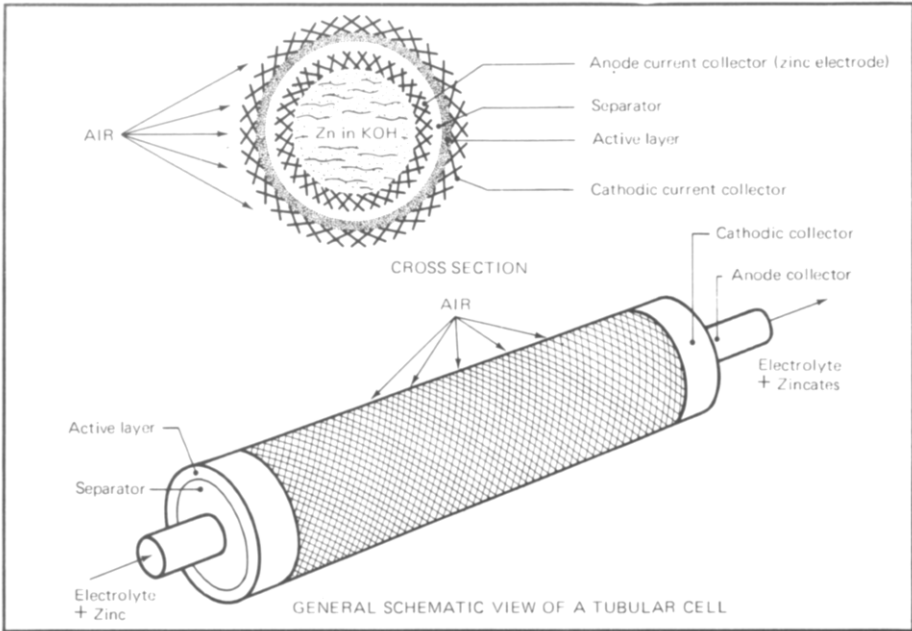
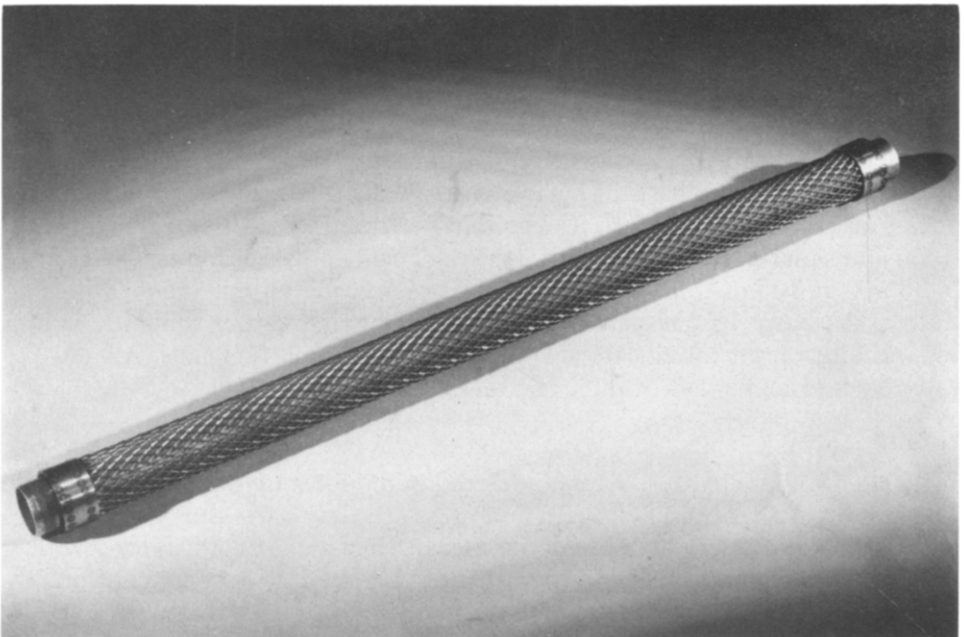Fig. 4. The C.G.E. circulating zinc/air battery general schematic view of a tubular cell and cross-section.
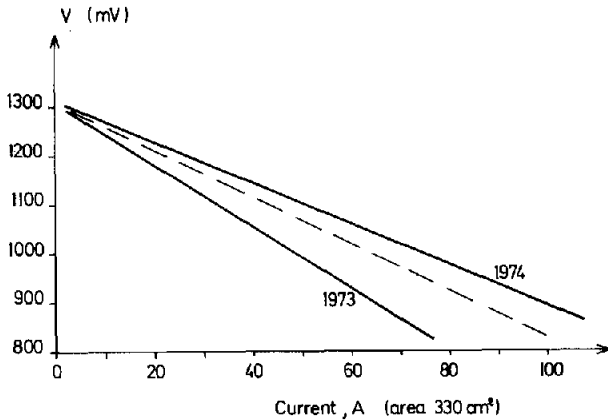

Fig. 5. A tubular cell.

Fig. 6. Current–voltage relationship for tubes at 50 °C, showing improvement in performance. The dashed line, — —, is used for all calculations.
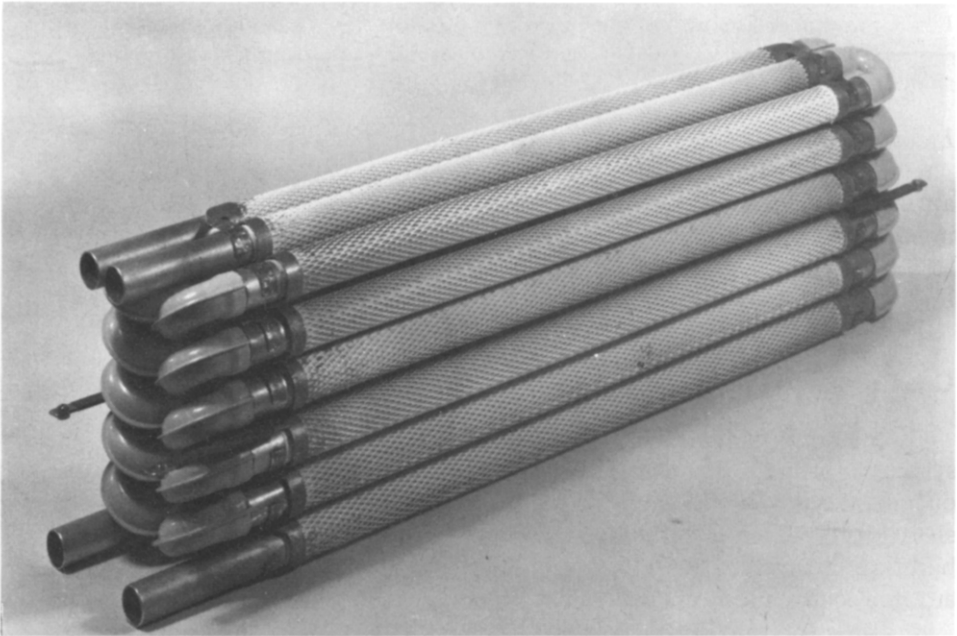

Fig. 7. Module.

functioning of the latter the total pressure drop across the system should be small. Typically, the flow rate is 0.8 m/s; this figure may vary according to application. A module is shown in Fig. 7. Modules are self-emptying under off conditions, and flow is started by the use of a small self-priming pump at the inlet to the group of modules constituting the battery. The latter serves as a choke under normal flow, and creates the correct negative internal pressure. All pumps are driven via a common belt.
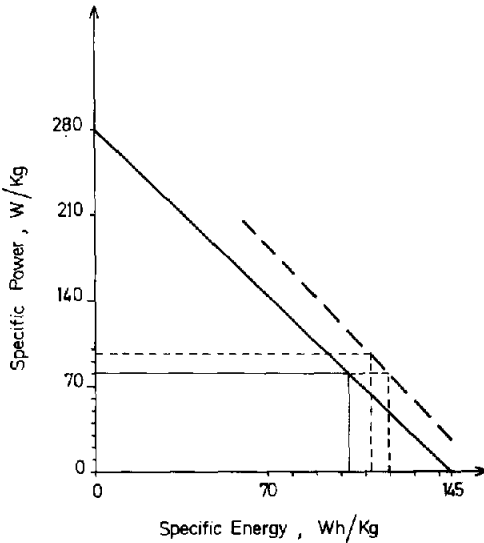
Fig. 8. Specific energy *vs.* specific power for systems. ———, calculation base (Fig. 6); – – – projected from 1974 data (Fig. 6). Requirements are for urban automobile.

Electrical connections

Electrodes within each module are series-connected. Modules are arranged in the battery in a paired configuration such that the slurry entering the first module is always at ground potential to avoid electrochemical losses or corrosion of the tubes or reservoir. Performance on the módule level currently corresponds to that for the broken line in Fig. 6.

Operation and system performance

The air flow through the modules serves to reject excess heat from the system. Normal air flow is 3 - 8 times stoichiometric, depending on power output. Air is given a cursory decarbonation by bubbling through the electrolyte, which is sufficient to prevent any problems due to carbonate build-up in the air electrodes. Normal working temperature is 50 - 55 °C, automatically maintained by air-flow control via a blower.

Using the maximum power datum as established above, maximum power for the optimized zero-capacity limiting case is about 280 W/kg, this includes all auxiliaries, electrode tubes and the supporting framework, together with a typically dimensioned reservoir. System maximum energy density for the zero-power limiting case is about 145 Wh/kg at nominal current densities. This is the figure for the zinc powder plus electrolyte only. These figures may improve by ~20% or more for limiting power density and ~10% for limiting energy density as air electrode performance is improved and remaining losses are reduced. Overall maximum power and nominal energy densities of real systems will lie along the lines shown in Fig. 8.
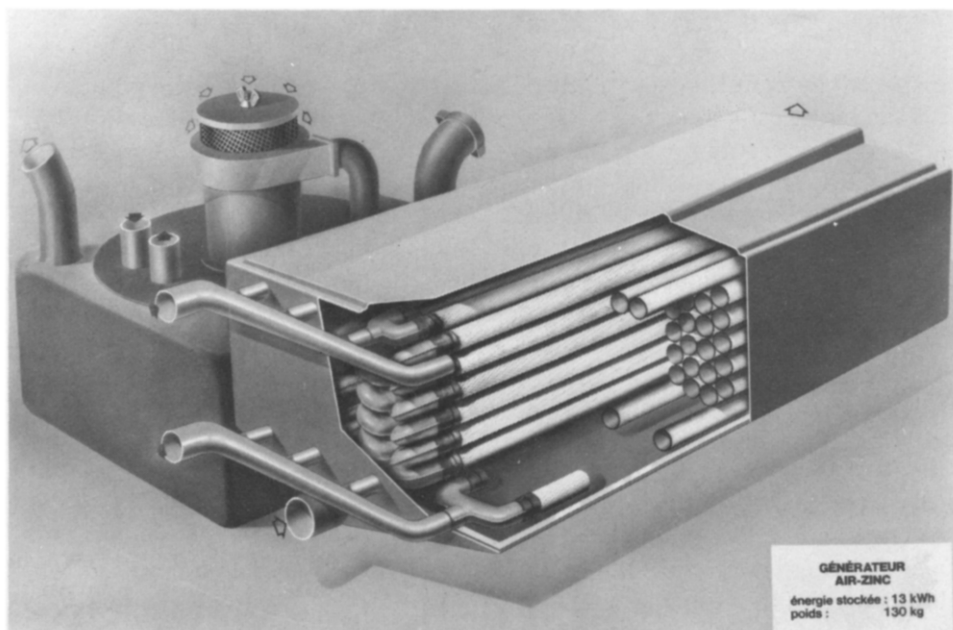
Fig. 9. Overall view of system concept.

Typical systems for automobiles will have a performance of 80 W/kg peak power and 110 Wh/kg energy density at nominal rates (this represents a 3-h discharge rate, approximately 80 mA/cm^2). Systems optimized for different rates and capacities will have different empty specific power characteristics (see below). These figures include losses due to circulating currents, which represent 1.0% of nominal power. Auxiliary power requirements are predicted to be 1.4% of full power output (5% of nominal) in scaled-up systems. Overall specific gravity is close to unity.

A proposed system is shown in Fig. 9.

Recharging

Spent electrolyte

Spent electrolyte typically contains 295 g/l zinc in the form of zincate, of which 280 g is regenerated on charge. 270 g ($\sim$270 Wh) are usable, 10 g representing a typical self-discharge loss. Long-term self-discharge losses on stand in quiescent solutions are not very much greater, since passivation of zinc occurs rapidly under these conditions. Typical increase in carbonate concentration per cycle is 2 × 10^{-2} mol/l. Approximately 50 charge–discharge cycles can be carried out before removal of carbonate is necessary (*e.g.* by barium hydroxide).

Internal recharging

Electrical recharging using an on-board auxiliary electrolyzer is indispensable from the view-point of marketing an electric vehicle equipped with the circulating zinc/air battery, owing to the cost of installing the logistic support required for external regeneration. Our realization of the fact that the "fast refuelling" argument would in itself probably be insufficient to overcome resistance to initial marketing of the system has resulted in the re-orientation of the programme to develop the on-board electrolyzer. Studies undertaken since the beginning of 1975 have illustrated the feasibility of electrical recharging. A prototype system consisting of a 1 kW generator and electrolyzer is at present under test.

The electrolysis unit which will be installed in the vehicle uses a modular construction of tubular electrodes of similar size to those in the fuel cell. The oxygen electrode containing non-noble metal, is at the outside of the system, the zinc powder electrode being a central rod. Laboratory experiments indicate a mean of 2.4 V on charge, at current densities that are several times higher than those for rated fuel cell performance. Since charging is over an 8 h period, the total electrolyzer area required for a full charge in this time is small compared with the total fuel cell area, so that the electrolyzer weight is under 10% of the total.

External recharging

This is an alternative for the fleet operator, and eventually for service-station use. External electrolysis units will be installed in central garage or other locations, and will be similar in principle to those in electrolytic zinc plants. They will be used in continuous operation to lower amortization costs (see below).

System economic survey

Over the next 5 to 10 years, the following variables must be represented as unknowns: comparative changes in zinc, gasoline and electrical kWh prices; taxes to be imposed on vehicles with different types of traction systems; regeneration costs. Any exact economic evaluation is therefore impossible; the overall system involves a battery whose principal application will be electric traction, and which is therefore totally dependent on the existence of this market, for which development programmes vary considerably from country to country. In addition, no prototype vehicles using the battery have been as yet been produced. Consequently, the available economic data and comments which follow must be used with caution.

Initial cost

Since the battery is power-limited, cost/kW is the important parameter. The investment cost of the zinc/air system for an annual production of

10,000 power sources (25 kW units) is estimated to be less than 200 FF ($ 45/kW). This will fall to less than $ 35/kW in high-volume production. This is equivalent to less than $ 4/lb of essentially mild steel and plastic hardware. A comparison with the initial cost and performance of a lead–acid battery, for three typical applications (same chassis weight and payload for both power sources) is given in Table 1.

The energy densities considered were 32.5 Wh/kg for lead–acid batteries and 100 to 125 Wh/kg for the zinc/air system, Elozine weight included, depending on the energy/power ratio for each type of vehicle. The most important part of the total cost involves the tubes and auxiliaries ("power" part), and it is seen that the cost advantage of the zinc/air system increases as the energy/power ratio increases, as in the case of heavy vehicles. Addition of an on-board electrolyzer will increase investment costs by about 10%.

Recharging cost

For recharging costs, we will consider two possible cases: (1) external recharging only (either fleet operation with central station recharge, or service station charging with sale to individuals; (2) recharge in vehicle. Central factory reprocessing is not considered, as slurry transport or zinc oxide separation costs more than offset the economics of reprocessing scale. We will assume an overall efficiency of 40% based on a mean discharge voltage of 1.23 V with total faradaic losses of 15%, charger efficiency 90%, and charge voltage equal to 2.4 V. The charger is assumed to be the motor control system. Investment costs (per kW installed) of $ 200 (heavy plant, 10 year depreciation) and $ 45 (tubular electrolyzer in vehicle, depreciated over fuel cell lifetime) are assumed for the service station and vehicle systems. Fiscal assumptions are given in Table 3. Results are given in Table 2.

Overall costs

To enable an overall cost comparison with lead–acid batteries to be made, we have assumed that more than one charging-cycle per day is used for lead–acid powered vehicles with utilization between 18,000 and 30,000 km/year. For more intensive use, spare recharged lead–acid batteries are necessary to give an equivalent daily range, leading to increased capital costs. Assumptions for zinc/air, lead–acid and gasoline powered vehicles are given in the Table 3. Results are shown in Fig. 10. No specific maintenance for either of the electrical power sources are considered. The auxiliary equipment of the zinc/air system (basically pumps) should offer a life equal to that of the vehicle. It should be noted that the estimated life of the zinc/air system modules is pessimistic (1000 h), since 3000 h lifetimes have already been obtained under laboratory conditions.

The estimates call for the following comments: (a) at present, an exact amortization calculation for the electric traction systems is not possible, since detailed design of the zinc/air battery traction system has yet

TABLE 1

Investment cost/performance comparison for different electric vehicles

	City car Chassis weight: 500 kg Useful load: 250 kg 30 h.p.		Delivery van Chassis weight: 1000 kg Useful load: 1000 kg 75 h.p.		Truck or minibus Chassis weight: 4500 kg Useful load: 3500 kg 180 h.p.	
	Lead–acid battery	C.G.E. circulating zinc/air battery	Lead–acid battery	C.G.E. circulating zinc/air battery	Lead–acid battery	C.G.E. circulating zinc/air battery
Battery volume (litres)	200	300	500	800	2000	2000
Elozine volume (litres)	–	100	–	310	–	910
Overall battery weight (kg)	400	250	1000	700	4000	2000
Elozine weight (kg)	–	180 (72%)	–	548 (79%)	–	1638 (82%)
kWh installed	13	26	32.5	80	130	238
Total vehicle weight (kg)	1150	1000	3000	2700	12,000	10,000
Range (km)*	50 to 80	100 to 170	50 to 80	120 to 200	50 to 80	100 to 170
Installed battery cost**	1	1.25	2.5	2.75	10	6
Installed cost/kWh	1	0.63	1	0.45	1	0.33

*Depending on driving cycle.
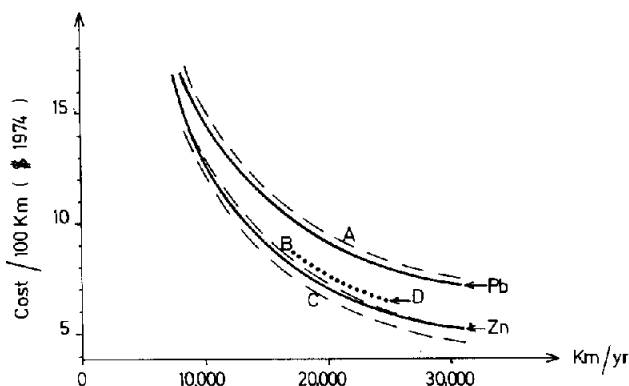**Based on unit cost of lead–acid battery for city car = 1.

Fig. 10. Calculated total cost/100 km lead–acid, zinc–air and gasoline systems. A, European gasoline costs (39 ¢/litre, $ 1.47/gallon); B, U.S. costs (15.4 ¢/litre, 58 ¢/gallon); C, untaxed U.S. costs (9 ¢/litre, 35 ¢/gallon); D, French costs minus tax (0.8 FF/litre, 68 ¢/gallon).

TABLE 2

Recharging costs

	On-board recharge	Recharge in service station
Installed power	4 kW	150 kW
Yearly energy use	3750 kWh	1.125×10^6 kWh
	(10,000 km/year, 0.15 kWh/km,) 40% eff.	(1.5 tonne zinc/day 300 days/year)
Electrolyzer (interest + depreciation)	$ 63/year	$ 5500/year
Labor	—	$ 14,400/year
Overhead	—	$ 13,680/year
Maintenance	—	$ 2200/year
Fixed costs/kg zinc	4.2 ¢	7.95 ¢
Overall cost/kWh (¢)	4.2 + 2.5 C	7.95 + 2.5 C
C = electricity cost/kWh		

to be formulated, and there are as yet no lead–acid traction systems in series production; (b) amortization of the zinc/air system per 100 km will be much less than that of a lead–acid battery, since its service life and energy storage capability is greater. Since zinc/air running costs are predicted to be lower that those based on European gasoline costs without tax, it will still be advantageous to the consumer if a kWh tax is initiated to replace gasoline revenues. Electricity prices used are reasonable estimates (1.2 ¢/kWh for PWR plant bus-bar costs in the 1980s [25]).

TABLE 3

Capital costs ($ 1974, 1 tonne vehicle)

	Chassis	Motor + controls	Battery	Amortization
Gasoline	2000	444 (motor only)		120,000 km
Lead–acid (9 kWh at C/1.5 rate)	2000	933	933	120,000 km 30,000 km
zinc/air	2000	933	444 (auxiliaries)	120,000 km
			384 (modules)	50,000 km

Electricity cost:	1.78 ¢/kWh (industrial); 3.56 ¢/kWh (domestic)
1 tonne vehicles:	energy requirement (at wheels) 15 kWh/100 km or 10 litres gasoline/100 km (Stockholm cycle conditions)
Gasoline prices:	see Fig. 10
Service life:	lead–acid, 500 cycles at 60 km/cycle zinc/air (modules), 500 cycles at 100 km/cycle zinc/air capital cost based on volume production
Maintenance:	electric vehicles: $ 167/year gasoline vehicle: $ 333/year
Insurance:	$ 289/year in all cases
Interest rate:	10%
Depreciation formula:	$A = Cr/1 - (1 + r)^{-K/k}$ A = yearly cost, C = capital cost, r = interest rate K = life (km); k = km/year travelled

Costs are converted from 1974 French francs, and will vary according to exchange rates: 4.5 FF = $ 1 has been assumed.

As far as zinc availability is concerned, a comparative analysis of global resources and the quantities required for the system shows that known zinc reserves will be largely sufficient to enable conversion of the whole of the world automobile pool into electric vehicles, for which the quantity of zinc required would be approximately double the present worldwide annual production. If 150,000 zinc/air urban vehicles per year are produced, the quantity of zinc required each year would represent only 5% of current French zinc production about 270,000 metric tons/year). These hypotheses assume no loss of zinc during vehicle operation. If a loss of 0.1% per cycle of zinc is considered (an optimistic value for external regeneration but reasonable for internal recharging), the quantity of zinc to be renewed per year for a constant vehicle pool would be less than 2% of the total quantity in the system inventory.

Conclusion

The C.G.E. circulating zinc/air system appears to be one of the rare medium-term solutions to the problem of the practical electric vehicle power source. Its advantages are that it presents an energy density three times higher than that of the lead–acid battery, with both lower first costs and lower amortized costs per kilometre. In addition, it has a special modular design using separation of the reaction cells ("power" function) and the slurry storage tank ("energy" function). This arrangement enables these two major system components to be located in different parts of the vehicle, thus providing better weight distribution and better use of available space. In addition, the quantity of energy (*i.e.* vehicle range) and power (*i.e.* maximum speed and acceleration) of the on-board system can be chosen independently of each other, a feature which is impossible with conventional batteries. Despite its low cost (about 160 FF/kW or \$ 35/kW, in quantities over 100,000 vehicle units/year) its energy efficiency is too low (40%) to envisage major applications other than electric traction (for example, off-peak energy storage).

The future of the system is therefore subject to development of the electric vehicle market. It is reasonable to consider that this will occur in the future, since it will be complementary to the emphasis on the replacement of imported oil by nuclear electricity. However, it is at present difficult to estimate a date for which electric vehicles will appear on the market in major quantities. It is unlikely that this will be before 1985, in view of the lead-time for vehicle development and for the widespread implementation of nuclear-based energy.

Acknowledgements

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