Title
FUTURE TRENDS IN ADVANCED BATTERIES FOR AUTOMOBILE PROPULSION

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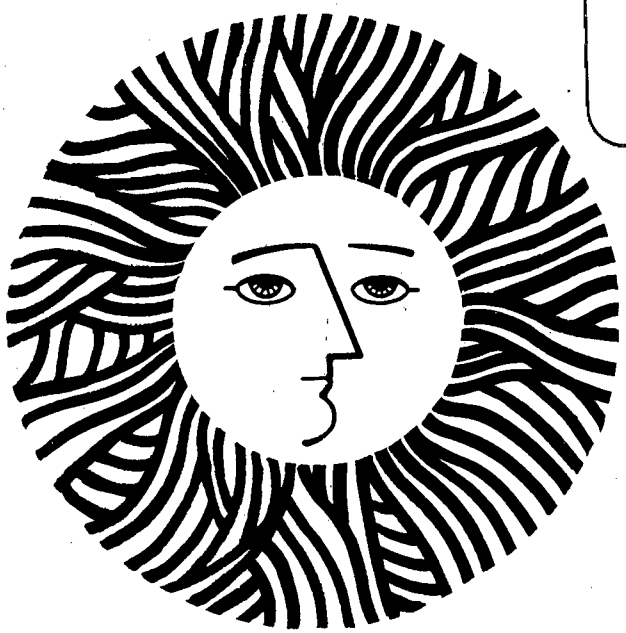

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I. INTRODUCTION

In order to establish a basis for perspective with regard to the discussion below, it is useful to examine the incentive for advanced battery development in terms of the possible market for vehicle propulsion batteries. The automobile market in the U.S. alone is about $100 billion per year, corresponding to about 10 million vehicles per year. If only 10 percent of the market were to be captured by electric vehicles, and 20% of the cost of the electric vehicle is the battery, then this would represent a $2 billion per year battery market. This is to be compared to an estimated $1.5-2 billion per year market for SLI batteries, both as replacements, and in new vehicles. Thus, only a 10% market penetration by EV's would more than double the rechargeable battery market--a rather large incentive!

The impediments to the development of such an attractive electrochemical energy conversion business can be grouped into three important categories: performance (W-h/kg, W/kg), durability (cycle life, lifetime), and cost ($/kWh). If the electrochemists and electrochemical engineers can solve the problems in these three categories, then there exists an extremely attractive opportunity for the development of a multibillion dollar per year market, starting in the 1980's. General Motors repeatedly has announced its intention to offer for sale an urban electric auto (like a Chevette) in 1985, indicating that there could indeed be an electric vehicle battery market developing. This intention can materialize only if at least marginally acceptable batteries are available.

The initial performance goals for a marketable electric vehicle (again, according to GM) include a range of about 150 km, and a speed of 80 km/h. This translates into a specific energy of at least 70 Wh/kg, and a peak specific power of 100-150 W/kg. The battery lifetime should be at least 3 years, or 300 deep (80+% depth of discharge) cycles, and the cost should be no greater than $100/kWh.* A number of cells under development have shown the capability of meeting the performance goals, but none has met the performance, durability, and cost goals simultaneously. This is our challenge!

II. BATTERIES FOR THE NEXT TWO DECADES

Reflection on the rate of development and implementation of new electrochemical energy conversion technologies reveals that it requires at least two decades for new systems to reach commercial significance. As an example, the fuel cell was under intensive development for space application throughout the 1960's, but still has not reacned commercial markets. Some advanced batteries have been under development for over a decade, and are not very close to commercialization now. Based upon these observations, it is likely that the electric vehicle batteries that may be used in the next two decades are already being investigated.

The advanced batteries that have the best chance of finding application in electric automobiles in the next twenty years include advanced versions of the Pb/PbO_2 cell, with a specific energy above 40 Wh/kg. This cell will probably make use of a circulating electrolyte to promote H_2SO_4 transport into the electrode, and advanced current collector designs to maximize the specific power. Good progress in these areas has been reported already.

The Fe/KOH/NiOOH cell has received renewed development effort in the last decade, with significant gains in specific energy, now approaching 50 Wh/kg, and under test in several electric vehicles. The issues of low efficiency and high cost remain to be resolved, but this battery may be interesting for industrial and mining vehicles, and perhaps some commercial vehicles.

The Zn/KOH/NiOOH cell has been a popular candidate for electric automobiles because of its relatively high specific energy (60-75 Wh/kg), but it suffers from short cycle life of the zinc electrode (100-200 deep cycles), and the relatively high cost of the NiOOH electrode. Because of the high performance of this cell, efforts on the zinc electrode will probably continue.

*1981 dollars.

High-temperature systems offer the next significant increase in specific energy, to values above 100 Wh/kg. The high-temperature cell closest to automotive application now is the $LiAl/LiCl$-KCl/FeS cell, which operates at 450°C. Full-sized cells have demonstrated a specific energy of 100 Wh/kg. Similar (but lower-specific-energy) cells have cycle lives of 300+ deep cycles. The costs now are high, but projections fall below $100/kWh. Even higher performance is available from the $Li_4Si/LiCl$-KCl/FeS_2 cell (450°C), which is in an earlier stage of development: 70-80 Ah single cells of 120-180 Wh/kg, up to 700 deep cycles. A specific energy of 200 Wh/kg seems within reach, and would correspond to a vehicle urban driving range of 400 km, or a shorter range, with a smaller, less costly battery. Other high-temperature possibilities include the Na/S cell (350°C) which uses a sodium-ion conducting ceramic ($Na_2O \cdot 11Al_2O_3$) tube or glass (sodium borate) hollow fiber electrolyte. These cells have irreproducible lives, of up to several hundred cycles, and suffer failure with thermal cycling. The specific energy of Na/S cells falls in the 100-200 Wh/kg range, depending on cell design.

There are other options available, but they seem less promising. These include metal/air cells, which suffer from the low efficiency of the air electrode (large overvoltages for both discharge and recharge reactions, over 0.3 V for each). Fuel cells have the same problem, and all of the flow systems, including metal/halogen systems tend to be complex and bulky.

III. DIRECTIONS FOR THE PERIOD BEYOND THE YEAR 2000

As some of the systems that are known now are implemented, the improvements in specific energy and specific power will probably catalyze our thinking about new opportunities for electrochemical energy conversion, and focus our thinking in a number of areas. It is to be expected that there will be a continuing desire for lighter-weight, more energetic reactants. For use at negative electrodes, hydrogen and lithium will remain attractive; at positive electrodes sulfur, oxygen and perhaps fluorine, and low-equivalent-weight compounds containing them will receive more attention. Electrolytes for such systems will be non-aqueous, with an emphasis on ambient-to-moderate temperatures (up to 200°C). These higher specific energy cells will allow much more design flexibility: lower cost, smaller batteries of moderate driving range, with an option for more range, to 400 or 500 km at added cost. As the electric vehicle field matures, there is to be expected a shift toward fuel-cell powered vehicles, perhaps using H_2 from NH_3, or a similarly convenient source. In principle, the fuel cell vehicle could be a full-performance, general-use vehicle, providing that cost and lifetime goals can be met. Electrocatalysis and materials remain problems.

Many new materials will be required, both active (e.g. reactants, electrocatalysts, electrolytes), and inactive (current collectors, cases, separators). More sophisticated alloys and compounds will be required to meet all of the conflicting demands. Some needs include electrolytes (solid and liquid) for use with pure lithium electrodes (liquid or solid), materials for use with sulfur as current collectors, seals, containers, special tailored separators for use with specific electrodes such as lithium, aluminum, magnesium, zinc. It seems clear that molecular engineering will be pressed into prominence as we tax our materials capabilities more and more.

Electrochemical cell design will reach much higher levels of sophistication as cell modeling abilities and computing speed and capacity increase. Multiparametric optimization of cell designs will become rather common. Advances in understanding and modeling cell failure will be accelerated. As cells become more compact, it will be necessary to place more emphasis on detailed understanding and prediction of heat, mass, and momentum transport in cells and batteries, in order to avoid catastrophic failures due to overheating in highly energetic batteries. It will be less feasible to operate near ambient temperatures, and those capable of operating at moderately elevated temperatures will be more prominent.

As batteries become larger and more widely used, maintenance-free operation becomes essential, a necessity. Many systems will be sealed, gas-tight, with internal gas recombination.

Molecular engineering techniques should be brought to bear on the very difficult problems to be solved in the development of fuel cells. Electrocatalysts of low-cost, plentiful materials are needed. For the very complex oxygen electrode, it seems probable that a combination of tailored and matched electrocatalysts will be necessary. The hydrogen electrode also requires less costly electrocatalysts. If compact, inexpensive hydrogen storage (or simple, fast preparation from another fuel such as NH_3 or CH_3OH) is developed, then there will develop a market for fuel-cell powered vehicles.

The future of electrochemistry and electrochemical engineering in using our energy resources most effectively is limited only by our ingenuity!

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