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PROGRESS IN ELECTROCHEMICAL STORAGE FOR BATTERY SYSTEMS

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ABSTRACT

During the last decade, NASA and the Department of Defense have made a concerted effort to improve electrochemical systems for space use. The main areas of effort were (1) improvement of conventional systems, (2) development of fuel cells to practical power systems, and (3) a search for new systems that would provide gains in energy density but would offer comparable life and performance as conventional systems.

Improvements in sealed conventional systems have resulted in the areas of materials, charge control methods, a better understanding of cell operations and battery control, and specific process controls required during cell manufacture. Fuel-cell systems have been developed for spacecraft but the use of these power plants is limited. No new, high-energy-density systems have been developed into practical hardware for flight use.

For present and planned flights, nickel-cadmium, silver-zinc, and silver-cadmium systems will be used. Improvements in nickel-cadmium batteries have been applied in the medical and commercial areas. For very large usage, i.e., standby power or electric cars, the cost and scarcity of materials will restrict the use of these conventional systems.

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BATTERY SYSTEMS

On February 1, 1958, the United States placed its first satellite, Explorer 1, in orbit around the Earth. The satellite power system consisted of a solar array complemented by a mercuric-oxide primary storage battery. The first use of solar paddles and a rechargeable nickel-cadmium power system was on the Explorer 6 spacecraft, which was placed in orbit August 7, 1959. The batteries provided power during eclipse and had a design utilization of approximately 2 percent of the total 10-A-hr capacity flown.

On August 16, 1961, Explorer 12 was placed in orbit; this spacecraft contained the first silver-cadmium battery to be used in space. The battery consisted of 5-A-hr cells and provided an average power of 16 W. Its use was necessitated by the stringent magnetic requirements imposed upon the spacecraft subsystems.

Table 1 lists some early aerospace applications of various battery systems. Over the years, the requirements for secondary batteries have increased, whereas the need for primary batteries has decreased. Of the available electrochemical systems, the nickel-cadmium, silver-cadmium, and silver-zinc couples have become the mainstay of the space program. In particular, it is estimated that over 80 percent of the U.S. satellites launched to date have used nickel-cadmium batteries.

Although the silver-zinc couple was used as a source of energy storage as early as 1800, it was not until the 1920's that the first practical silver-zinc cell was developed. This cell incorporated a semipermeable membrane capable of reducing the effects of solubility of the

Table 1.—Early Aerospace Applications of Various Battery Systems

Satellite	Power supply	Battery applications	Launch date
Vanguard 1	Mercuric oxide/solar array	Primary	1958
Explorer 6	Nickel cadmium/solar array	Secondary	1959
Vanguard 3	Silver zinc	Primary	1959
Explorer 12	Silver cadmium/solar array	Secondary	1961
Explorer 32	Silver zinc/solar array	Secondary	1966

zinc electrode and migration of active material, which cause rapid deterioration in cell performance. Various improvements have been made in recent years, but the old problems associated with migration and electrode solubility are still the life-limiting factors with this system.

The silver-cadmium couple has been known for some time, but only since the early 1950's has intensive development been applied to this system. It is viewed as a compromise between the short-life, high-energy-density silver-zinc system and the long-life, low-energy-density nickel-cadmium system. It is presently the only secondary system available free of residual magnetic properties for moderate cyclic orbital applications.

The nickel-cadmium couple was first investigated in 1890. Since that time, various varieties of this couple have been developed; however, it was not until the mid-1930's that the Germans perfected the technology for a sealed nickel-cadmium cell. The advent of the hermetically sealed cell capable of tolerating moderate overcharge has been a major factor in the development of the nickel-cadmium cell into many commercial, military, and aerospace applications.

The energy output and life of a secondary battery are very dependent upon the cycle regime and the interacting effects of temperature, depth of discharge, overcharge, charge control methods, and variations associated with the manufacturing process. A comparison of the three systems illustrates some of the tradeoffs involved in selecting a particular battery type for a mission. (See table 2.)

A comparison of energy density for the three systems shows the silver-zinc system to have the greatest number of watt-hours per pound. Although the theoretical value of watt-hours per pound is impressive, a large differential still exists between this value and the watt-hours per pound actually obtainable on a single cell. No developments currently underway show any significant promise in reducing this difference. When cells are packaged into a

Table 2.–Typical Performance Parameters for the Three Secondary Battery Systems

Performance parameter	Silver-zinc	Silver-cadmium	Nickel-cadmium
Energy density (W-hr/lb):			
Theoretical	208	120	107
Actual per cell (2-hr rate)	40	20	12 to 15
Flight-packaged cells	30	14	8 to 10
Usable in flight[a]	7 to 8	4 to 5	2 to 3
Cycle life[b] (1000 cycles)	.4	3	12 to 18
Wet life (prelaunch) (yr)	1/2	1/2	>3
Permanent magnetic field (γ at 12 in.)	<1	<1	300 to 900[c]
Rank in usage for scientific satellites	3	2	1

[a]Estimated values dependent on specific application and mission requirements.
[b]Based on near-Earth orbit at 25-percent depth of discharge and 20° C.
[c]Very dependent on type and size of cell.

Table 3.—Silver Cells Used in Space Flight

Type of cell and program	Cell size, A-hr	Cells per battery	Batteries per satellite	Battery weight, lb
Silver-cadmium:				
Explorer	5	13	1	6.3
IMP[a]	5	13	1	6.9
AIMP[b]	11	13	1	10
OGO	12	24	2	50
Silver-zinc:				
Explorer 10	1 to 40	167	–	37
Explorer 17	1 to 200	–	13	150
Explorer 32(R)[c]	40 to 200	–	8	166

[a]IMP = Interplanetary Monitoring Platform.
[b]AIMP = Anchored IMP.
[c](R) = rechargeable.

battery, an additional loss of watt-hours per pound results from the added weight of the associated hardware required to package the cells and dissipate the heat generated in the battery during electrical operation. There is a further decrease in usable watt-hours per pound in flight because the usable energy density on a cyclic basis in much less than the packaged energy density; this is an effect of orbital parameters upon cycle life.

Mission requirements are the primary concern in the selection of a particular battery system. Both the silver-zinc and silver-cadmium systems have relatively short cycle lives when compared with the nickel-cadmium system. It is apparent that for near-Earth orbit application, the nickel-cadmium battery is the only practical energy-storage system when long-life requirements are imposed. Satellites with orbital periods of 6 hr or greater have used silver-zinc and silver-cadmium batteries and obtained an operation life of 1 year or longer. The use of silver-cadmium batteries is always dictated by a very stringent magnetic requirement.

Some satellite programs that have used the two silver systems are given in table 3. With the exception of the Orbiting Geophysical Observatory (OGO), all the satellites listed as using silver-cadmium batteries had orbital periods over 6 hr; the life of the OGO batteries in a near-Earth orbit application was less than 3 months. Both Explorers 10 and 17 used primary silver-zinc batteries. Very few rechargeable silver-zinc batteries have been flown in GSFC satellite programs. When long life and low residual magnetic fields are required on the same mission, a nickel-cadmium system is used, and the problems created by the large residual field inherent in this system are compensated by other design considerations.

Table 4 lists some of the GSFC programs that have used nickel-cadmium batteries as part of their power systems. The batteries for the Orbiting Astronomical Observatory (OAO) are to date the largest flown in a scientific satellite. The average load during eclipse is in the range of 500 W. With an average depth of discharge of approximately 14 percent, the batteries have provided eclipse power for over 13 000 orbits. Because of variations in depth of discharge, temperature, and orbit period for different missions, each application of a battery

Table 4.—Nickel-Cadmium Cells Used in GSFC Programs

Program	Cell size, A-hr	Cells per battery	Batteries per satellite	Battery weight, lb
Ariel 1	6	10	2	20
Nimbus	5	23	7	107
OGO	12	22	2	65
OAO	20	22	3	154
Tiros	5	21	3	40

Note: Nimbus and Tiros use a cylindrical cell design; all others use a prismatic design.

is unique, and all factors have to be considered before a particular battery type and design can be selected.

Although the size and power requirements of satellites have increased over the past decade, weight constraints have been reduced because of the increase in NASA's booster capability. However, power demands have grown from a few watts to a projected 25 kW for the Space Station, and the need for maximizing the usable watt-hours is again very real and must be accomplished without any sacrifice in life.

Programs currently under development or planned for the future have very large power requirements (table 5). It is apparent that the ampere-hour size of available cells must increase. The 20-, 36-, and 45-A-hr sizes listed in table 5 are a reality today. Work is currently in progress to develop the 100-A-hr size. In the future, the number of batteries per satellite will be increased, but the number of cells per battery will not be changed significantly. Perhaps more important, battery weight will be greatly increased.

The development of the Space Station, at least in concept, requires a 10-year battery life. There is no battery available today that will reliably meet this requirement. One alternative is resupplying the Space Station on a periodic basis. This will involve transporting batteries that weigh hundreds of pounds. The logistics of such an operation are hard to imagine. The best solution is to continue to develop the 10-year capability.

Currently, emphasis is being placed on process controls during the manufacturing of aerospace cells. It has been said that our ground test programs have not demonstrated the state-of-the-art capability of a particular battery system, but rather have demonstrated the capability of a particular manufacturer to make a particular lot of cells at a given time. For example, in one existing spacecraft program, the variation of battery performance in two different lots from one manufacturer required a design change in the battery-charger characteristics on the same series of spacecraft.

How did we get to where we are today? With the advent of the space program, a unique and immediate need for energy-storage capability was required of the battery manufacturer: unique in that it required unprecedented reliability, and immediate in that there was no time for extensive development programs. Today, space batteries are still

Table 5.—Nickel-Cadmium Systems Planned for Future Flights

Program	Cell size, A-hr	Cells per battery	Batteries per satellite	Weight per battery, lb	Projected launch date
Skylab:					
Apollo telescope mount	20	24	18	[a]110	1973
Airlock	36	30	8	125	1973
Department of Defense	45	22	4	([b])	([b])
Space Station[c]	100	28	16	380	1976

[a]Weight includes battery charger and discharge regulator.
[b]Information not available.
[c]Numbers based on preliminary study by McDonnell-Douglas, Report DRL 13, Vol. 5, Book I.

essentially a commercial product applied to space applications. There is some encouragement, however. Through the cooperation of battery manufacturers, the aerospace industry, the military, and NASA, manufacturing processes are being definitized and supporting documentation is being maintained to such a degree that the current generation of batteries is much more representative of the state of the art, more so perhaps than at any other time in the history of the space program.

The need for a 5- to 10-year battery life has presented new problems in battery testing. With the increase in life requirements, it is no longer practical to conduct actual tests for the full lifetimes of batteries. By the time the tests are complete, the design may in fact be obsolete. There is a great need for test techniques and methods of data analysis to provide reliable life predictions for space batteries. A goal is to test a battery for approximately 1 percent of its required life and then, with a high degree of confidence, predict the battery life within a few percent of that actually obtainable. Such test and data techniques are not available today.

Real-time tests have demonstrated capabilities for cycles of over 5 years. Ironically, there is little confidence in the ability to manufacture new cells identical to those that have completed the 5 years of testing.

Problems with the separator are common to all three battery systems discussed and have been around since storage devices were conceived. Today, improvements in battery separators are being made, but there are no real significant breakthroughs in sight. In most aerospace batteries, the separator material is the determining factor for battery life. The discussion of separator-related problems is not complete without pointing out a problem basic to all materials used in aerospace batteries: The volume required and the resources available for aerospace applications are very small compared to those for commercial applications. In the absence of economic motivation, it is difficult to generate technical interest in battery-related problems.

Since the start of the space program, wider usage has been made of battery systems. This is especially true in the medical field in the adaptation of rechargeable batteries for pacemakers and power sources for heart-assist devices. For large power requirements such as standby power, emergency power, and power for electric-propulsion vehicles, the cost and scarcity of materials required for all of the systems discussed does not provide any optimism for applying space battery technology to solving Earth-related problems.

FUEL CELLS

Fuel cells, conceived just after 1800 in England and Germany and constructed first in 1838 in Scotland, have enjoyed several cycles of popularity. The latest of these started about the middle of this century when large (kilowatt) working models were demonstrated in England and in the United States. Because of research support by the Department of Defense, and particularly engineering efforts for NASA, fuel cells are at last functional power plants. However, even though some efforts are underway to make them commercially competitive, they may remain specialty items of extremely limited use, mainly in space and perhaps for some defense purposes.

There is a reason for this limitation. Fuel cells are similar to conventional electrochemical cells in that an anodic reagent (a fuel) is oxidized electrochemically while a cathodic reagent (an oxidant) is being reduced. The main difference is that a conventional cell, or a battery of cells, is self-contained, whereas a fuel cell, or a battery of fuel cells, is only the reaction vessel. Its fuel and oxidant are stored outside, and the reaction product must be removed (fig. 1).

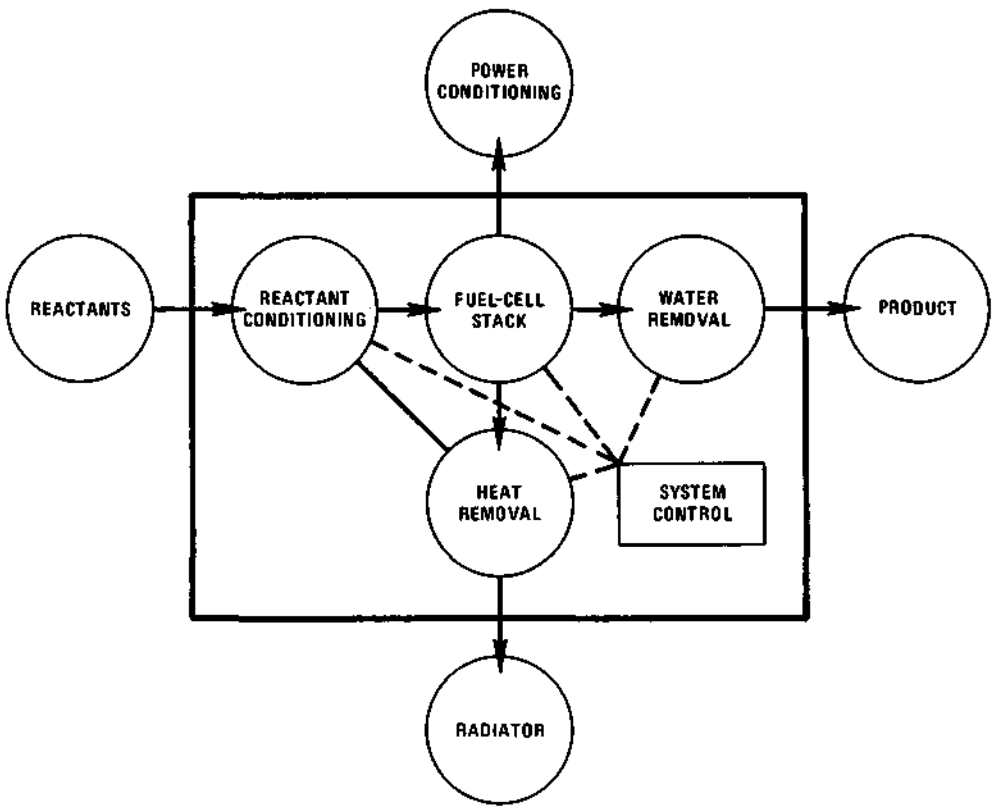

Figure 1.—Components of a fuel-cell system.

In this way, a fuel-cell power plant is like an engine; but, whereas an engine can take cheap, easily storable fuel, present fuel cells can only use expensive storable fuels, hydrazine and methanol, or a difficult-to-store fuel, hydrogen.

One of the commercial obstacles, therefore, is cost and storability of fuel, or the capability of the anode to use cheap, available fuel. A cheap synthesis of hydrazine or a good catalyst for oxidizing hydrocarbons at temperatures around 20° to 130° C is urgently needed.

The size and weight of today's fuel cells cannot compete with those of engines for mobile equipment. A power plant weighing 50 to 100 lb/kW or even more is impossibly heavy for missions lasting, at the most, a few hours between refueling. Even stationary power plants must stay within reasonable bounds of weight and volume since they, too, must compete with more conventional devices.

Compact fuel cells can be built, either by designing particularly thin cells or by operating thicker cells at what presently appear to be high power densities. Increasing the power density by over an order of magnitude immediately lowers the cost per kilowatt by more than a factor of 10. It is this cost per kilowatt, not (as often stated) the cost per pound, that is one of the major factors in determining the competitive status of fuel cells.

Another factor is the durability of the power plant, which is reflected in cost per kilowatt-hour. About 2000 hr is the maximum attained thus far. That is roughly equivalent to the operating life (not total life) of a private passenger automobile but to only about 1 percent of the life of a public utility plant.

Though size, weight, cost, and lifetime are not basically limited in any way, there appears to be no serious effort underway to confront these important problems. No easy instant solutions are in sight; but until a determined effort is made to overcome these barriers, it is meaningless to speculate on the future of industrial and commercial fuel cells.

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