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# ADVANCED ELECTROCHEMICAL ENERGY SOURCES FOR SPACE POWER SYSTEMS — A REVIEW*

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## Summary

This paper surveys the state-of-the-art of advanced electrochemical energy sources for space use.

For individual cases we have to decide between primary cells, secondary cells, and fuel cells.

Primary cells provide power needs for up to a few weeks and also serve as spare (reserve) batteries. Since 1960 the advanced alkaline silver oxide–zinc batteries have been developed with a specific energy of 350 W h/kg, and during the last ten years the non-aqueous lithium battery has become a potential competitor with a specific energy of 450 W h/kg.

Secondary batteries will in the future continue to be the most important electrochemical energy source. We can distinguish between first (conventional), second (new) and third (non-aqueous) generations.

At present, the classical NiOOH/Cd battery is the only rechargeable system for use with solar cells in missions requiring long life (5 - 10 years). Among the new systems, the best appears to be the hermetically sealed $NiOOH/H_2$ battery. We expect a high-cycle life ($\geqslant 10\,000$) and high energy density (up to 65 W h/kg). It will probably be introduced around the year 1980. All the non-aqueous lithium and sodium storage systems are still under development either in the single cell or the laboratory prototype stage.

For projects involving manned space flights the direct $H_2/O_2$ fuel cell will continue to be in wide practical use. At present the power density is 50 - 70 W/kg and the maintenance-free lifetime for alkaline systems is 2 000 - 3 000 hours.

## 1. Introduction

Since 4th October 1957, when the flight of Sputnik 1 took place, practically all of the space vehicles launched have relied on electrochemical

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power sources. Until now the power system of each space vehicle has been individually optimized, and we have to decide between primary, secondary, and fuel cells. For several reasons, special attention has to be given to greater payload outputs, longer duration, and lower cost. Naturally, this fact has had a corresponding influence on the field of research and development of suitable energy supply systems.

Advanced electrochemical storage devices which might offer essential improvements in energy and/or power density have been investigated for a considerable time. Figure 1 shows a number of combinations of anode and cathode materials which are of practical interest for secondary batteries. We propose to divide battery systems into first, second, and third generations.

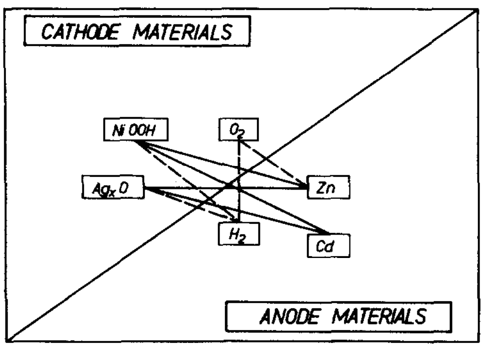


**Fig. 1. Cathode and anode materials for first and second generation secondary spacecraft batteries.**

The first generation includes the classical systems which are already used for space missions; *viz.*, the metal oxide/metal couples NiOOH/Cd, $Ag_xO$/Cd and $Ag_xO$/Zn.

The second generation (new systems), which can be divided into metal oxide–metal, –gas and gas–gas batteries, has already shown practical importance with the use of $H_2/O_2$ fuel cells. The use of NiOOH/$H_2$ secondary batteries will be the next step.

The third generation (Fig. 2), "exotic" systems (especially non-aqueous), should find first practical use in the form of lithium primary batteries with high energy density.

However, in any event, an ideal battery for space (and earth), which would be one with high specific power, high specific energy, long life, high reliability, and 100% utilization of active materials, cannot be achieved. Battery design varies widely depending on mission requirements, and, on average, reflects a compromise between capacity, activated wet standing life, operating temperature range, surge capability, weight, and volume. Generally, the specific power and specific energy of the different electrochemical batteries increase with the ampere-hour capacity.

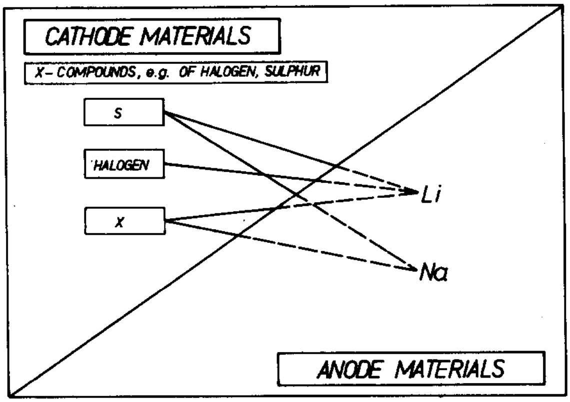


Fig. 2. Cathode and anode materials for third generation secondary spacecraft batteries.

## 2. Primary electrochemical systems

In 1957, with the advent of Sputnik 1, primary electrochemical batteries acquired a primary role as a power source for space missions. At present, they continue to serve the bulk of short term power needs (up to a few weeks) and act as spare batteries for emergency situations and special cases.

Since the 1960's the silver oxide–zinc primary battery has been developed to the point where it has an absolutely dominant role for space purposes among primary battery systems. There are more than 100 different varieties with energy densities ranging as high as 350 W h/kg. The cell is non-magnetic and capable of quite high discharge rates. Silver–zinc batteries employing silver(II) oxide (AgO) electrodes attain the highest specific energy density, but the discharge at low rates takes place in two stages, showing voltage plateaux (1.72 and 1.55 V cell voltage) which render voltage regulation for the battery stack more difficult.

Silver oxide electrodes are especially destructive to the organic separator. Therefore, and for other reasons such as self discharge, in reserve batteries the active electrode materials are separated from the electrolyte during long term storage and are automatically activated before use.

It should be mentioned also that in early satellites, mercuric oxide–zinc primary cells were used having a specific energy of about 110 W h/kg and a very good volumetric specific energy of up to 450 W h/litre.

During the last 10 years the non-aqueous lithium battery has been developed as a potential competitor to silver oxide–zinc batteries [1]. Prototypes reached a specific energy of 450 W h/kg with lithium anodes and halogen or sulfur compounds as cathode.

The zinc–oxygen system, employing cryogenic oxygen [2], was already being considered for space application twenty years ago. The practical ultimate specific energy appears to be in the range 400 - 500 W h/kg. The main problem lies with the "open" lifetime (self discharge, corrosion, sealing). According to our results [3] an "open" lifetime of at least 3 - 4 months can be realized at a specific energy of up to 350 W h/kg (without oxygen).

In the case of special primary batteries, the so-called "single shot" systems must be mentioned. High performance thermal batteries, *e.g.*, $Ca/CaCrO_4$–eutectic LiCl–KCl electrolyte, as a power source in rockets, missiles and other ordnance, reach a specific power of about 0.5 kW min/kg, and 0.11 kW min/l for a discharge time of 20 - 50 seconds. The aqueous ammonia-activated reserve battery with zinc or magnesium as anode, and silver chloride, lead oxide or other cathode materials, can be discharged in 20 - 30 min. These batteries have achieved about 15 W h/kg. Single shot battery types work within a wide temperature range and can be activated within a time of 0.3 to a few seconds.

## 3. Secondary electrochemical systems

We can predict without doubt that in the future the solar cell array/ electrochemical storage battery power system will be the main energy source for spacecraft. Consequently, the improvement and development of rechargeable batteries is one of the most important aims of modern electrochemistry. This includes storage systems for low orbits as well as for high orbits (especially synchronous satellites), deep space probes and other projects. In all cases, we expect a weight reduction and an increase in the cycle life. Table 1 uses a 1 500 kg synchronous satellite as an example to show the weight reductions which have taken place in solar arrays (from rigid panel arrays to flexible roll-up structures), as well as in storage batteries, during the past eight years. Finally, it should be possible to realize, by using "second generation" secondary cells, the values which are given in Tables 2 and 3.

R and D programs have also emphasized the use of heat pipes for cooling, bypass circuits to prevent cell reversal, and control units (charge/

TABLE 1

Solar array/battery advancement
5 year life synchronous satellite of 1 500 kg mass [4]

| Year | Spacecraft mass fraction (complete power source) (%) | Specific mass (complete power source) (kg/kW) | Specific mass (storage battery) (kg/kW) |
|---|---|---|---|
| 1968 | 35 - 40 | ~320 | ~180 |
| 1976 | 20 - 25 | 115 - 125 | 80 - 85 |
| 1980 | 15 - 18 | 65 - 70 | 25 - 35 |

discharge, temperature) built into the battery. This paper does not discuss these "auxiliary systems". The battery structure is often of light metal, *e.g.*, aluminium.

In Table 2 are shown the specific mass and the net electrochemical reaction of interesting secondary battery systems. The specific mass of advanced storage batteries ranges from 2 to 10 kg/kW.

Table 3 shows the specific energy, the expected cycle life and the expected introduction date.

In general, those batteries which have reached a relatively advanced state of development (and already have matching manufacturing capacity or will have it in the near future) fall into the low range of specific energy.

The NiOOH/Cd battery is the only rechargeable system carried on present spacecraft for use with solar cells in missions requiring long life (5 - 10 years). The use of NiOOH/Cd cells in a fully packaged battery at about the 1 kW power level should provide up to 9 W h/kg for 3 - 5 years life in low earth orbit, and as high as 20 W h/kg in synchronous orbit for 5 to 10 years.

According to test results, discharge up to 90% seems to be possible if a narrow working temperature range (*e.g.*, 10 - 20 °C) can be guaranteed. In principle, the classical alkaline batteries work within the temperature range −20 to 50 °C, but in normal spacecraft practice the range is −10 to 30 °C.

Automatic charge control is essential. The trend in R and D for spacecraft batteries is increasingly towards the development of integrated storage systems. This especially involves pressure control, series cell redundancy, and discharge boost regulators.

TABLE 2

Secondary batteries

| Generation/ systems | Specific mass 1/4 h-discharge (kg/kW) | Net electrochemical reaction ⟶ discharge ⟵ charge |
|---|---|---|
| First | | |
| NiOOH/Cd | 10 - 15 | $Cd + 2NiOOH + 2H_2O \rightleftharpoons Cd(OH)_2 + 2Ni(OH)_2$ |
| AgO/Cd | 3 - 5 | $Cd + AgO + H_2O \rightleftharpoons Ag + Cd(OH)_2$ |
| AgO/Zn | 2 - 4 | $Zn + AgO + H_2O \rightleftharpoons Ag + Zn(OH)_2$ |
| Second | | |
| $NiOOH/H_2$ | 3 - 4 | $H_2 + 2NiOOH \rightleftharpoons 2Ni(OH)_2$ |
| $AgO/H_2$ | 2 - 3 | $H_2 + AgO \rightleftharpoons Ag + H_2O$ |
| $H_2/O_2$ | 10 | $2H_2 + O_2 \rightleftharpoons 2H_2O$ |
| $Zn/O_2$ | 5 - 10 | $2Zn + O_2 \rightleftharpoons 2ZnO$ |
| Third | | |
| Na/S | 10 | $x Na + yS \rightleftharpoons Na_xS_y$ |
| Li/X | 10 | $x Li + X \rightleftharpoons Li_xX$ (X = halogen-, sulfide-, oxygen-compounds) |

(→ discharge, ← charge)

TABLE 3

Expected specific energies, cycle lives, and date of introduction of first, second and third generation spacecraft batteries

| GENERATION | SPECIFIC ENERGY Wh/kg | EXPECTED CYCLE LIFE (at 50% Discharge) | ANTICIPATED TIME FOR INTRODUCTION |
|---|---|---|---|
| FIRST (METALOXIDE – METAL) | Ni/Cd 55; Ni/Zn 70; Ag/Cd 80; Ag/Zn 150 | Ag/Zn ≤500; Ni/Zn ≥1500; Ag/Cd ≥3000; Ni/Cd ≥10 000 | already used |
| SECOND (METALOXIDE–GAS GAS – GAS) | $Ni/H_2$ ≥55; $H_2/O_2$ 55-80; $Ag/H_2$ ≥90; $Zn/O_2$ ≤160 | $Zn/O_2$ ≤1000; $Ag/H_2$ ≤600; $H_2O_2$ open; $Ni/H_2$ ≥10000 | about 1980 |
| THIRD (EXOTIC NON AQUEOUS) | $Zn/Cl_2$ ≤150; $Li/Cl_2$ ≤200; Li/S ≤250; Na/S ≤300 | too soon to predict | not before 1985 |

Because of the mass required for the electrolyte, container, connecting parts, incomplete utilization of the electrodes, separator, etc., we can estimate that the practical specific energy density will not be higher than about 35% of the theoretical.

A general problem concerns the reliable prediction of the attainment of the required lifetime and the cycle life.

Among the new systems the metal–hydrogen batteries offer attractive alternatives to the classical batteries. The best chance for broad, practical use appears to be the hermetically sealed NiOOH–hydrogen battery.

Since hydrogen is consumed on discharge and formed on charge the state of charge can be determined by measuring the gas pressure in the cell.

Nickel oxide–hydrogen batteries involve no complex moving parts (no pumps, no valves etc.), and show a high discharge rate capability which is needed, for example, for operation in synchronous orbit satellites. A battery specific energy of 60 - 65 W h/kg, with 15% of total mass for structure, mounts, electronics and connectors, and operating at 85% of capacity to 1.0 V should be possible in the future for large units. High self-discharge rate, pressure containment, oxygen transport to the $H_2$ electrode, separator burn-up, thermal control, and electrolyte entrainment represent current problems.

The $H_2/O_2$ battery is also a potential replacement for NiOOH/Cd batteries in long-term, high power applications, *e.g.*, 20 kW for several years.

All of the non-aqueous lithium and sodium storage systems are still under development in laboratory prototype or single cell stages. The working temperatures range between 300 (*e.g.*, $Li/Cl_2$) and 350 °C (*e.g.*, Na/S).

The main problems with these types of third generation batteries involve corrosion hazards of liquid alkali metals, battery start-up time, and the initial heat source.

## 4. Fuel cells

Since 1965 when the flight of Gemini 5 took place, manned NASA spaceships have been fitted with electrochemical fuel cells for the power supply to the whole electrical system. The Apollo–Soyuz project used the Apollo Service Module with three Bacon-type fuel cells. For manned space-flights in connection with the next generation of transport vehicles into low orbit, fuel cells will continue to be used.

A considerable number of fuel cell systems have been worked on in the past, and a classification of fuel cells is given in Table 4. Our analysis showed that in the near future only the direct hydrogen–oxygen system will continue to have wide practical use for the power supply for manned space projects.

The $H_2/O_2$ fuel cell power-plant subsystems are shown in Fig. 3 [5]. The reactants must be brought to suitable temperature and pressure using a conditioning subsystem, which implies a requirement for an automatic regulator with temperature and pressure controllers. The operating temperature of the battery with changing load is mainly regulated by the cooling subsystem. The best possible operational behavior requires regulation of the

TABLE 4

Classification of fuel cells

| Fuel cells | | |
|---|---|---|
| Direct | Indirect | Regenerative |
| Low temperature<br>Intermediate temperature<br>High temperature | Reformer<br>Biochemical | Electrical<br>Thermal<br>Chemical<br>Photochemical<br>Radiochemical |

| Direct fuel cells | | |
|---|---|---|
| Low temperature (<100 °C) | Intermediate temperature (100 - 350 °C) | High temperature (>500 °C) |
| Hydrogen/oxygen<br>Organic compounds/oxygen<br>Nitrogenous compounds/ oxygen<br>Hydrogen/halogen<br>Metal/oxygen | Hydrogen/oxygen<br>Organic compounds/oxygen<br>Ammonia/oxygen | Hydrogen/oxygen<br>Carbon monoxide/ oxygen |

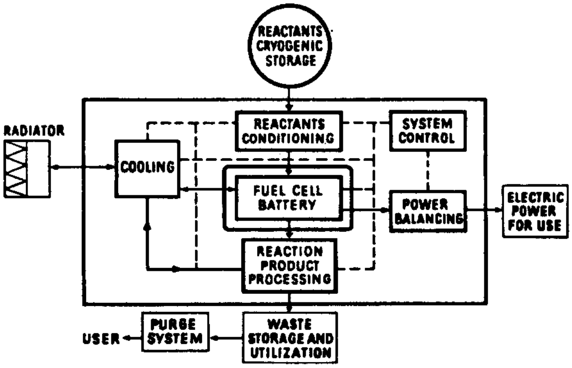


Fig. 3. Subsystems for an $H_2-O_2$ fuel cell power plant.

TABLE 5

Characteristics of advanced $H_2/O_2$ systems
Net reaction: $H_2 + 1/2\ O_2 \rightleftharpoons H_2O + Q$

| Time | Specific mass (kg/kW) | Life time (maintenance free) (h) |
|---|---|---|
| 1965 - 1975 | 40 - 80 | 2 000 |
| Present | 15 - 20 | 2 000 - 3 000 |
| Expected | 7.5 - 10 | 5 000 - 10 000 |

electrolyte concentration. By using a reaction-product-processing subsystem the reaction water is removed by condensation. The overall fuel cell plant efficiency ranges from 60 to 70%.

Further fuel cell data are given in Table 5. The reduction of the specific mass shows a significant improvement, as does the increase in lifetime (reliability without maintenance), which confirm earlier estimations [5]. Considerable further development of acid $H_2/O_2$ systems will probably provide competition in the near future.

Generally, the use of fuel cell power plants is limited to short-term missions because the mass of reactants and tanks determines the weight of the whole system. Figure 4 provides an example for two different specific masses and power demands [5]. The space program will continue with the use of fuel cells for missions requiring about 2 to 20 days. The realization of systems with a specific mass of $<2$ kg/kW, and repeatedly generating megawatts for minutes using evaporative cooling, would be an interesting variant for special unmanned spaceflights.

It can definitely be predicted that the future development of fuel cells will be directed towards finding simplified systems and more stable materials.

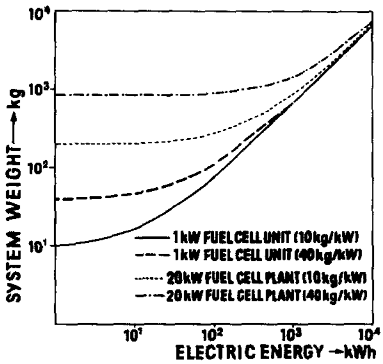


Fig. 4. System weight and electric energy for a complete $H_2$–$O_2$ fuel cell power plant with reactants stored as liquids.

## 5. Conclusions

Non-rechargeable, non-aqueous lithium batteries have emerged as a potential competitor to silver–zinc primary batteries.

The new nickel–hydrogen battery could displace the Nicad storage systems.

$H_2/O_2$ fuel cell systems which use alkaline or acid electrolyte are projected for short-term, high-power demand missions in the future.

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