

22 pages

NASA TECHNICAL MEMORANDUM

NASA TM- 88471

TM 88471

CURRENT DEVELOPMENTS IN ELECTROCHEMICAL STORAGE SYSTEMS
FOR SATELLITES

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IN - 18368

Translation of "Aktuelle Entwicklungen bei elektro-
chemischen Speichersystemen für Satelliten," Zeitschrift
für Flugwissenschaften und Weltraumforschung, Vol. 9,
July-August 1985, pp. 229-235.

(NASA-TM-88471) CURRENT DEVELOPMENTS IN N86-29412
ELECTROCHEMICAL STORAGE SYSTEMS FOR
SATELLITES (National Aeronautics and Space
Administration) 22 p CSCI 10C Unclas
G3/44 : 43462

1. Report No. NASA TM-88471	2. Government Accession No.	3. Recipient's Catalog No.	
CURRENT DEVELOPMENTS IN ELECTROCHEMICAL STORAGE SYSTEMS FOR SATELLITES		5. Report Date July, 1986	
		6. Performing Organization Code	
Gutmann, G., Deutsche Automobilgesellschaft mbH		8. Performing Organization Report No.	
		10. Work Unit No.	
9. Performing Organization Name and Address Leo Kanner Associates, Redwood City, California, 94063		11. Contract or Grant No. NASW-4005	
		13. Type of Report and Period Covered Translation	
12. National Aeronautics and Space Administration, Washington, D.C. 20546		14. Sponsoring Agency Code	
		15. Supplementary Notes Translation of "Aktuelle Entwicklungen bei elektrochemischen Speichersystemen für Satelliten," Zeitschrift für Flugwissenschaften und Weltraumforschung, Vol. 9, July-August 1985, pp. 229-235. (A86-11760) (ISSN 0342-068X)	
16. Abstract The need for batteries with greater power capacity and service life for power satellites is examined. The Ni/Cd and Ni/H batteries now being used must be upgraded to meet advanced space requirements. Improvements in power capacity, service life, and cycle count for various satellites in LEO and GEO orbits are discussed. The Ni/Cd and Ni/H cell reactions are explained, and the solubility and volume changes for various charged and uncharged masses are described. A chart of the energy content and cycle count for various cell systems is presented, and the factors which cause aging and failure in the Ni/Cd and Ni/H cell systems are discussed. The advantages of the Ni/H battery are given and the need for more developed electrochemical storage systems because of an increase in the mass of satellites is explained. The requirements for space batteries and the work currently done by NASA and West Germany on advanced batteries are discussed.			
17. Key Words (Selected by Author(s))		18. Distribution Statement Unclassified-unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 20	22.

CURRENT DEVELOPMENTS IN ELECTROCHEMICAL STORAGE SYSTEMS
FOR SATELLITES

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Summary

In the near future, satellites will require batteries with an output of 10 kW or more and a lifespan of 10 to 12 years. To satisfy these requirements, previously used nickel/cadmium and nickel/hydrogen batteries must be enlarged and their lifespans improved. Nickel/hydrogen batteries have the more favorable qualifications.

1. Introduction

To supply satellites with energy, a combination of photovoltaic solar cells as energy converters and storage batteries as energy reservoirs has become established. Among currently available systems, it offers good loading performance and the highest energy content per unit mass, for the required lifespan. Solar generators put out up to 32 W/kg and have achieved high reliability. Storage battery systems, which must be sealed and maintenance-free, are selected according to requirements arising from the use of the satellite; this use determines orbit, power

*Numbers in the margin indicate pagination in the foreign text.

consumption, lifespan and load profile as relevant battery criteria. Telecommunications and earth exploration are profitable areas of application for satellites in increasing commercial use. Their economy increases with useful life, which in turn depends on the fuel supply of the position control systems and upon battery lifespan. In addition to low battery volume and weight, therefore, a long lifespan is the most important characteristic, but also the hardest to predict. The factors influencing battery lifespan which arise from the two aforementioned applications are exemplary for satellites. Telecommunications satellites are usually operated at heights of ca. 36,000 km in geostationary (GEO) or high orbits (higher than 833 km); earth exploration satellites are operated rather in high or low orbits (lower than 833 km) (LEO). In LEO, passage through the earth's shadow typically takes 35 minutes; in GEO it takes ca. 1.2 hours. For this period, the satellite must be powered from the batteries. A depth of battery discharge (DOD) of 25-35% is allowed in LEO, and 50-60% in GEO. From this, at one- to two-hour discharge rates, one can calculate corresponding average discharge currents. For recharging, 22.8 hours are available in GEO, but only 55 minutes in LEO. The useful lifespan of a geostationary satellite is ten to twelve years and means some 1000 chargings and dischargings for the battery. In LEO, lifespan is only three to six years because of the greater braking effect of the residual atmosphere, but the battery is loaded with 20,000 to 35,000 charging/discharging cycles. These requirements for cycle count and lifespan can be met by only a few electrochemical storage systems. /230

2. Suitable Battery Systems for Satellites

All storage battery systems used to date had alkaline electrolytes. They combine the following negative catalyst and mass electrodes with positive mass electrodes (Fig. 1):

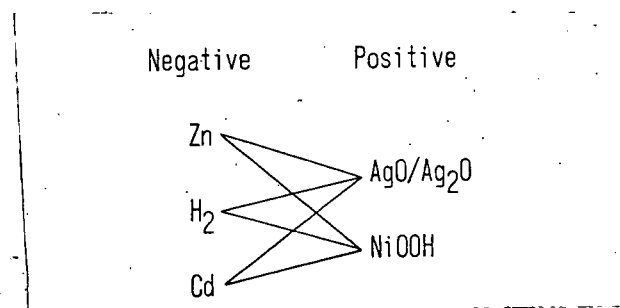


Fig. 1. Anode and cathode combinations in satellite batteries with alkaline electrolytes.

These systems have a low-electrolyte construction in common; the cells contain at most enough electrolyte to fill the pore volume of the electrodes and separators. This is a prerequisite for sealed construction, which is made possible by the so-called "oxygen cycle" in cells with a negative mass electrode. It prevents an uncontrollable pressure buildup during overcharging and pole reversal. The inevitable, though slight, differences in capacity, the different charge acceptances and aging behavior of individual cells in the battery set, as well as the ampere-hour efficiency of less than 100%, increase discrepancies among individual cell capacities at the high required cycle counts, if a certain degree of overcharging is not allowed. Overcharging and pole reversal of individual aging cells must not endanger the

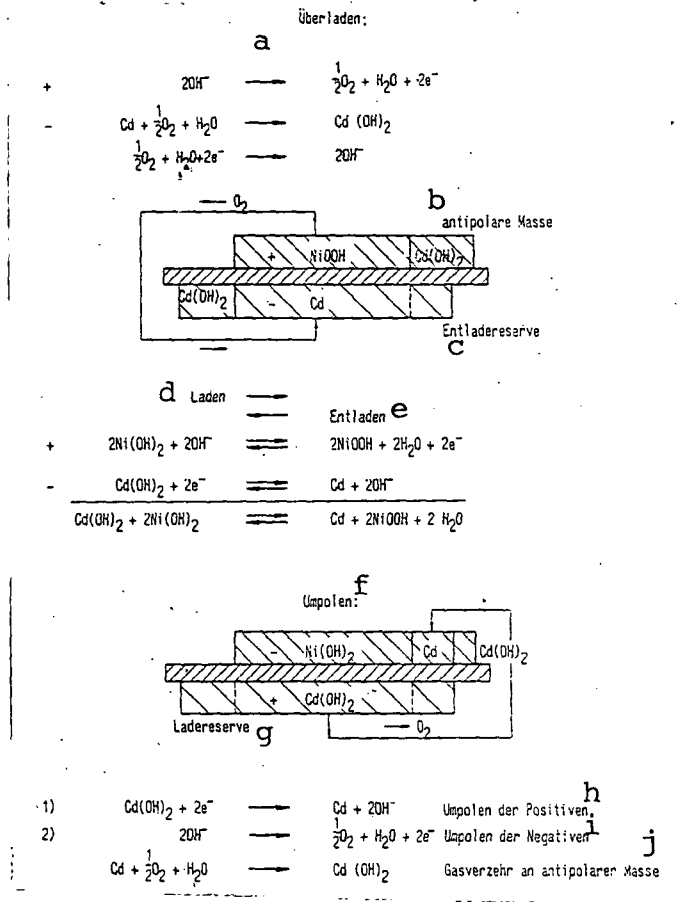


Fig. 2. Reactions in sealed nickel/cadmium cells.

- Key:
- a. overcharging
 - b. antipolar mass
 - c. discharge reserve
 - d. charging
 - e. discharging
 - f. pole reversal
 - g. charge reserve
 - h. reversal of positives
 - i. reversal of negatives
 - j. gas consumption at antipolar mass

entire battery.

The operation of sealed cells will be described from the example of the nickel/cadmium system (Fig. 2).

The charging and discharging process does not differ from

open nickel/cadmium cells, aside from larger changes in electrolyte concentration [1]. Depending on operating temperature and charging current, starting at a charging state of ca. 60%, oxygen is evolved at the nickel oxide electrode, until after charging of the positive electrode is complete the entire charging current produces oxygen according to the top equation in Fig. 2. In sealed cells, the capacity of the negative active mass is greater than that of the positive active mass (indicated in Fig. 2 by bar length). This "charge reserve" of the negative mass continues the charging reaction and prevents evolution of hydrogen, if oxygen is already evolved at the positive electrode after the active mass is completely oxidized. Oxygen diffuses through the precipitator to the negative electrode and there is converted partly chemically (25-30%) and partly electrochemically. The charging state of both electrodes thus no longer changes.

How fast oxygen can be consumed at the negative electrode depends on the electrolyte concentration, the amount of electrolyte, the electrode spacing, the gas permeability of the separators, the surface of the negative electrodes, the temperature and the oxygen pressure. The cell pressure during overcharging at a certain charging rate can thus be influenced by the design of the stated parameters. For larger prismatic cell types, the pressure must be kept lower than for round cells. In space cells, the surface of cadmium electrodes is often hydrophobized with PTFE to make it readily accessible to oxygen.

A certain degree of pole-reversal stability can be achieved by including cadmium hydroxide as an "antipolar mass" in the positive electrode. When the capacity of the positive electrode is exhausted during discharge, it reverses polarity and first partially reduces its antipolar mass into cadmium. The negative electrode first consumes its discharge reserve and then also reverses, evolving oxygen, which is again consumed at the antipolar mass. Thus at least a time-limited pole-reversal

Table I. Nickel/hydrogen cell: Reaction equations

Laden: a, Entladen: b				U_0/V	$V_{gemessen}$
positive Elektrode ^c	$NiOOH + H_2O + e^-$	$\xrightarrow{\text{Entladen}}$	$Ni(OH)_2 + OH^-$	+ 0.490	
		$\xleftarrow{\text{Laden}}$			
negative Elektrode ^d	$1/2 H_2 + OH^-$	$\xrightarrow{\text{Entladen}}$	$H_2O + e^-$	- 0.829	
		$\xleftarrow{\text{Laden}}$			
Gesamtreaktion ^e	$NiOOH + 1/2 H_2$	$\xrightarrow{\text{Entladen}}$	$Ni(OH)_2$	1.319*	1.2
		$\xleftarrow{\text{Laden}}$			1.5
Überladen: f					
positive Elektrode ^c	$2 OH^-$	\longrightarrow	$2 e^- + 1/2 O_2 + H_2O$	+ 0.401	
negative Elektrode ^d	$2 H_2O + 2 e^-$	\longrightarrow	$2 OH^- + H_2$	- 0.829	
Gesamtreaktion ^e	H_2O	\longrightarrow	$H_2 + 1/2 O_2$	1.23	1.52
			g		
			rekombinieren an negativer Elektrode		
Umpolen: h					
positive Elektrode ^c	$H_2O + e^-$	\longrightarrow	$OH^- + 1/2 H_2$	- 0.829	
negative Elektrode ^d	$1/2 H_2 + OH^-$	\longrightarrow	$H_2O + e^-$	- 0.829	
				0.0	- 0.3

* 5 bars H₂ pressure: 1.339 V

Key: a. charging b. discharging
 c. positive electrode d. negative electrode
 e. total reaction f. overcharging
 g. recombination at negative electrode
 h. pole reversal

stability is provided for not-too-large currents.

As can be seen from Fig. 2, this gain in operating reliability is purchased at the cost of increased active mass, which correspondingly reduces the energy content per unit mass of the cells. Hydrogen/metal oxide cells need only a slight excess /231 of the slightly negative mass hydrogen to get the same effect. In the reaction equations in Table I, this is formulated for the nickel-hydrogen cell.

During charging, nickel(II) hydroxide in the positive active mass is oxidized into nickel(III) oxide hydroxide, thus releasing water, which is reduced at the negative electrode. Oxygen,

generated during overcharging of the cell at the positive electrodes, recombines at the negative electrodes with the hydrogen formed there. Upon reversal of the cell, the anodic reaction at the negative electrodes continues because of the excess active mass present, and consumes the hydrogen developed cathodically at the positive electrodes. During overcharging and pole reversal, neither the cell pressure nor the electrolyte concentration changes; the electrolyte concentration, moreover, is also dependent on the charge state. The cell pressure reproduces the charge state of the cell rather exactly. Normally the vessel volume is chosen to develop a pressure of 40 bar in the fully charged state.

The rechargeable batteries listed in Fig. 1 differ in useful lifespan in terms of both cycle count and absolute lifespan. Two important causes for the limitation of lifespan are given in Table II for individual electrodes: solubility of the active masses, and their volume changes during charging and discharging.

Solubility leads to short circuits due to dendrite formation and to migration of ions to the electrode of opposite polarity, producing among other things negative results for self-discharging and charge acceptance. Suitable separators can indeed delay short circuiting at the cost of higher internal resistance, but cannot eliminate it. Volume changes cause material fatigue of the mass supports. These changes are limited in applications/232 requiring high cycle counts (LEO) by restricting the depth of discharge to a low percentage of available capacity. The energy density of the battery system becomes correspondingly unfavorable.

Table III shows the effects of the properties listed in Table II upon cycle counts. Cells with a zinc anode or a silver oxide or silver peroxide cathode only reach relatively low cycle counts because of their high solubility. Nevertheless there are

Table II. Change in volume and solubility of various active masses

Aktive Masse a		d Volumen- änderung bei vollständiger Entladung [%]	Konzentration e Me ⁺ⁿ im Elektrolyten [Mol · l ⁻¹]
geladen b	c entladen		
Ag ₂ O ₂ +Ag ₂ O	Ag	- 37	5 · 10 ⁻⁴
NiOOH	Ni(OH) ₂	+ 19	2,5 · 10 ⁻⁶
Cd	Cd(OH) ₂	+136	1 · 10 ⁻⁴
Zn	ZnO	+ 62	1

Key: a. active mass b. charged c. discharged
 d. change in volume with complete discharge
 e. Me⁺ⁿ concentration in electrolyte

Table III. Energy content and cycle counts of satellite batteries. Single cells with 30- to 50-Ah capacity, 20°C operating temperature.

Zellensystem a	b Energieinhalt (Einzelzelle)		c Zyklenzahl	
	Wh/kg	Wh/l	LEO	GEO
Zn/Ag _x O	80	160	2000/ 6,6 % DOD	200/50% DOD
Zn/NiOOH	60	100	2000/<10 % DOD	400/50% DOD
H ₂ /Ag _x O	80	65	> 3000/ 27 % DOD	> 200/50% DOD
H ₂ /NiOOH	50	60	>30000/ 36 % DOD	> 5000/80% DOD
Cd/Ag _x O	70	140	6000/ 50 % DOD	500/80% DOD
Cd/NiOOH	35	100	25000/ 25 % DOD	1000/50% DOD

Key: a. cell system b. energy content (single cell)
 c. cycle count

applications in which their use makes sense, e.g. where extremely high energy density at low cycle counts, where only non-magnetic components are allowable, or as a reserve battery.

The causes of failure and aging of the relatively long-lived nickel/cadmium and nickel/hydrogen systems are compared in Table IV. Primary causes are emphasized with circles. The most frequent cause of failure in nickel/cadmium cells is short

Table IV. Causes of aging and failure of nickel/cadmium and nickel/hydrogen cells.

	Cd	NiOOH	H ₂	NiOOH
a Verlust aktiver Masse	+	+		+
b Verringerung der arbeitenden Fläche	⊕		+	
c Verringerung der Leitfähigkeit		⊕		⊕
d Verzögerte Einstellung von Phasengleichgewichten, Bildung nichtleitender Phasen, Verringerung der Fehlordnung	+ (Memory) +			(Memory) +
e Kurzschlüsse durch Dendriten	⊕			
f Abbau der Separatoren		+		+
g Undichte Gehäuse und Pole		+		+

- Key: a. loss of active mass
 b. decrease in working area
 c. decrease in conductivity
 d. delayed phase equilibrium adjustment, formation of non-conductive phases, decrease in faulty arrangement
 e. short circuits due to dendrites
 f. breakdown of separators
 g. broken seals in vessel or poles

circuiting by dendrite formation, induced by the noteworthy solubility of cadmium hydroxide in the electrolyte. Depending on the conductivity of the material causing the short (cadmium or cadmium hydroxide), either a "hard" short circuit with immediate failure of the cell, or a "soft" short circuit first notable as increased self-discharging, will occur. The latter is the usual case in satellite applications [2 - 4]. Reconditioning techniques can eliminate soft shorts for a limited time [5]. The recrystallization rate is also a consequence of solubility. It causes a reduction of the surface and thus of loadability and mass utilization. The "memory effect" is ascribed in the literature sometimes to the negative [6, 7] and sometimes the

positive electrode [8, 9]. It appears after several partial chargings and dischargings as a lowered mean discharge voltage of the discharge curve of the first complete discharge following the partial cycles. The first part of the discharge curve corresponds exactly to the curve of the partial discharges. The mean discharge voltage is reduced 40 to 120 mV. In cadmium sintered electrodes, after a long storage time, especially at high temperatures, the alloy Ni_5Cd_{21} forms, whose potential is some 120 mV more positive than that of the cadmium electrode. As Fig. 3 shows, a memory effect can also be observed in nickel/hydrogen cells. Here it is caused by the positive electrode. The reason is hypothesized as the formation of poorly conductive regions in the active mass [9]. The reduction of discharge voltage, in properly functioning electrodes, disappears already after the next full charging.

In summary, it can be ascertained that the qualifications for a long lifespan are better in nickel/hydrogen cells than in nickel/cadmium cells because independently of the employed catalyst (platinum or Raney nickel) the negative catalyst electrode is considerably more stable in the electrolyte than the cadmium electrode, and is not exposed to mechanical stresses during changes in charge state; the cyclical mechanical stress for this is borne by the duly designed pressure vessel. In the nickel/hydrogen cell, the nickel oxide electrode becomes the component that limits lifespan.

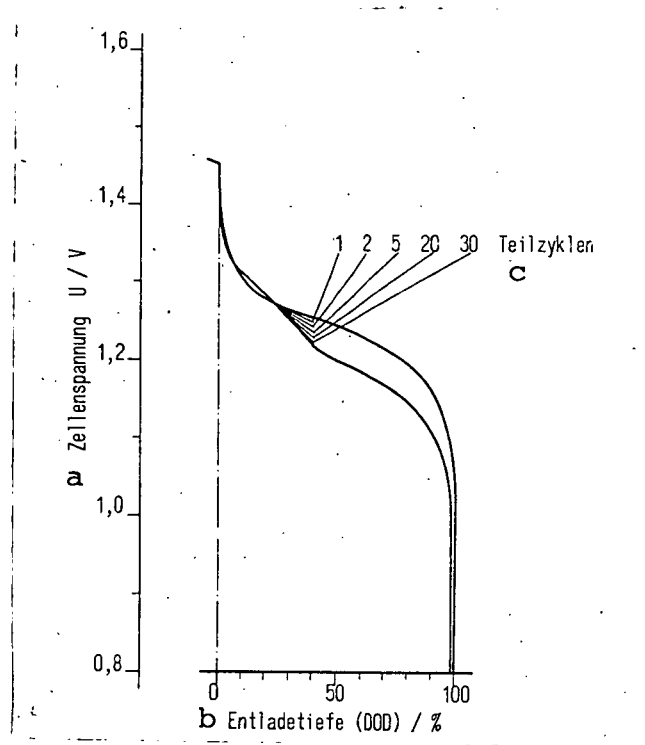
3. Requirements for Batteries in Future Satellites

The communications satellites considered here because of their economic significance are often categorized by generations according to their state of technical development; they differ in mass and electric output [10]. The first generation includes satellites up to 800 kg in mass and 0.8 kW output; the second, those up to 2300 kg mass and under 6 kW output (e.g. Intelsat V);

Fig. 3. Development of memory effect in a nickel/hydrogen cell

Key:

- a. cell voltage
- b. depth of discharge
- c. partial cycles



the third generation will include satellites with over 3000 kg ^{/233} mass and over 4 kW output. The mass is limited by the power of the carrier rockets. Thus Ariane 3, as a currently available carrier system, can put 2350 kg in a geostationary transfer orbit or 1350 kg directly into geostationary orbit. As early as 1986, Ariane 4 should be able to put 4300 kg into transfer or 2500 kg into geostationary orbit. The batteries for the third-generation satellites thus positioned must put out ca. 10 kW, approximately the battery output of an electric automobile. Corresponding to the energy efficiency, a heat quantity must be dissipated which amounts to 15 to 25% of the drawn power, depending on the battery design. At the same time, the lifespan should be extended from ca. 8 years to 10-12 years. Nickel/hydrogen batteries are favored for this demanding task.

The nickel/hydrogen battery of Intelsat V [11, 12] is

exemplary of the state of development of electrochemical storage systems of a second-generation satellite. 27 30-Ah single cells with individual pressure vessels by Eagle-Picher are combined in series into a 34-V battery. A cylindrical vessel shape was chosen, sealed by hemispherical caps, each carrying a pole. The single cells make up 80% of the battery weight. Aluminum tubes fitting against the cell walls, simultaneously serving for cell support, conduct heat to the base plate, from which it is dissipated. At a total mass of 30 kg, the energy content is 1.17 kWh. At 100% DOD this yields an energy content per unit mass of 39 Wh/kg; but since only a 50% DOD is required, the practical energy density is 19 Wh/kg. Compared to an equivalent nickel/cadmium battery, 6.3 kg is saved [12].

The batteries of the next satellite generation must have roughly ten times the power and ten times the energy content of the Intelsat V battery. A simple increase in cell count is unattractive because of the high volume requirements. The diameter of the individual cells cannot be increased beyond the present 90 mm if passive cooling is retained at the required loads, because otherwise the electrodes in the center of the cell become too hot. 50 to 60 Ah can hardly be exceeded under these conditions as an individual cell size.

At the expense of a higher operating pressure, volume savings can be achieved by housing several stacks of cells in series in a shared, elongated pressure vessel [13]. Because of the cell voltage, which exceeds the decomposition voltage of water even when two cell stacks are connected one after the other, and because of the risk of discharging via electrolyte short circuits, electrolyte bridges to the shared pressure vessel must absolutely be prevented. Another problem is the formation of electrolyte films between cell stacks by the known creepage of electrolyte at the negative cell connectors [14]. Finally, uniform temperature of all cell stacks in the shared vessel must

be maintained, to prevent uneven distribution of electrolyte and variable charge acceptance of the positive electrodes. This can probably only be achieved by forced cooling of the vessel. Despite these difficulties, a battery with several cell stacks in shared pressure vessels seems attractive up to the required size of ca. 10 kWh.

NASA has proposed a bipolar construction for nickel/hydrogen batteries up to an output of 35 kW [15, 16]; here the arrangement of electrodes in the cell stack resembles that of fuel cells. It offers the advantage of uniform current distribution over large-area electrodes and simple adaptation to the required voltages by the number of stacked electrode units. The compact cell stack must be actively cooled, either by recirculating hydrogen (see Fig. 4 [15]) as a coolant or by a liquid coolant. Energy density per unit mass and volume can be improved ca. 10 to 20% over a battery of cells with individual pressure vessels. In addition to the greater risk of leakage currents (at the edges of the bipolar partitions) and the problems of oxygen recombination and electrolyte distribution, the dependency of functioning on a subordinate component subject to mechanical wear, the blower, seems especially questionable.

The largest reserves with regard to useful energy content are doubtless to be found by increasing the depth of discharge, if this can be done without reducing lifespan.

Fuel cell electrodes as catalyst electrodes are not stressed mechanically; their volume depends on their charge state. As a long-lived system, therefore, a regenerative hydrogen/oxygen /235 fuel cell has been proposed, whose electrodes can function both as gas-evolution and gas-consumption electrodes. In the charged state, hydrogen and oxygen are stored in the shared pressure vessel, separated from one another by the separators impregnated with alkaline electrolytes [17]. In practice these cells failed

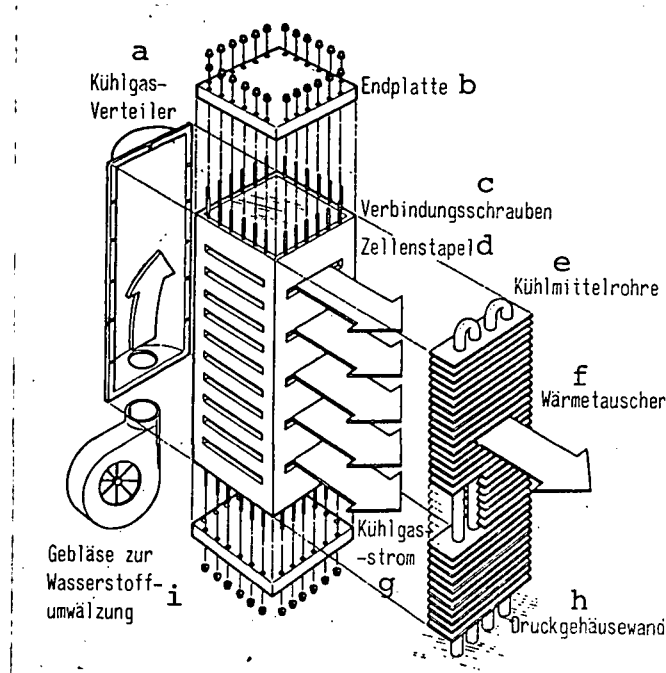


Fig. 4. Diagram of a bipolar nickel/hydrogen battery with hydrogen circulation and cooler (after Thaller [15]).

Key: a. coolant gas distributor b. end plate
 c. fastening screws d. cell stack
 e. coolant tubes f. heat exchanger
 g. coolant gas stream h. pressure vessel wall
 i. blower for hydrogen circulation

due to insufficient separation of the reaction gases and low lifespan of the oxygen electrodes; even platinum metal catalysts could not withstand the attack of oxidation. The combination of stable electrodes from these fuel cells and the nickel/cadmium cell, the hydrogen catalyst electrode and the nickel oxide electrode, led to the development of the nickel/hydrogen cell [18, 19]. If reaction gas development and conversion are divided between different reaction sites -- electrolyzer and fuel cell -- then by interposing a hydrogen and an oxygen compressed gas reservoir one can likewise obtain a long-lived electrochemical storage system, which NASA considers a competitor of the nickel/hydrogen battery, and which should present a comparable energy content per unit mass and volume [20]. A drawback is doubtless

the complex structure, which requires extensive, uninterrupted regulation.

For these storage aggregates now under development, useful energy contents per unit mass of 40-45 Wh/kg are expected for one-hour discharges. Higher energy densities are expected from cells with alkaline metal anodes, non-aqueous electrolytes, electrolyte melts or solid electrolytes and transitional metal oxide, sulfide or halogenide cathodes. But they will hardly be available for use as secondary batteries before 1990.

Finally, we should briefly discuss the state of battery technology for satellites in the Federal Republic of Germany. For the time-limited tasks in the context of the Spacelab program, silver/zinc batteries were successfully used by Silberkraft in the MAUS project (material-science autonomic experiments under weightlessness). In the uniformly structured MAUS containers, completely autonomous experiments were conducted. The power supply battery, with an energy content of > 1.8 kWh, consisted of four times twenty 15-Ah cells, was discharged with a current of ca. 1 hour, and including vessel weighs 30 kg; thus it achieves over 60 Wh/kg at 64 W/kg. It satisfies NASA safety requirements. Still somewhat more favorable in energy content per unit mass (nearly 66 Wh/kg) is the 2.3 kWh battery designed for low discharge rates, used in the SPAS-01 satellite, which was released and recovered by the Space Shuttle. The first silver/zinc battery by Silberkraft was used successfully as early as 1973 in the Aeros satellite [21], and others were used in Helios probes; they are also planned for the German plasma cloud satellites in the Ampte project [22].

Among long-lived systems, a 15-Ah nickel/cadmium cell was developed for space purposes by the Varta AG company [23], together with a charge regulator for temperature-controlled constant-current charging (TGI), to provide optimum conditions

for a long lifespan. A battery module was built of these cells, in collaboration with the AEG company [24]. It contains 24 cells; the energy content is 0.58 kWh, mass is 20.4 kg, volume is 11.34 l. From this, an energy content per unit mass of 28 Wh/kg and an energy content per unit volume of 50 Wh/l can be calculated, of which however at most 60% is used during geostationary missions. The module satisfies the requirements for missions with the Ariane carrier rocket. Three modules can be combined into a 28-V, 50-Ah battery.

Developmental work on nickel/hydrogen cells in the Federal Republic of Germany is limited to making their good system properties usable for terrestrial applications [25]. By using improved nickel oxide electrodes with fiber structure frameworks, Raney nickel/hydrogen electrodes and steel vessels, it was possible to reduce production costs without significant reductions in cell properties. It cannot yet be predicted with certainty whether the stability of Raney nickel/hydrogen electrodes suffices for a lifespan of ten years under the load demands of geostationary operation. For positive electrodes, the elasticity of the frameworks [26] allows the hope that volume movements of the active mass can be handled better than with sintered framework electrodes, which have a lower mass charge for long-lived cells [27]. But a possible greater depth of discharge allowable for fiber framework electrodes might itself lead to an effective reduction of battery mass.

Nickel/hydrogen cells are presently offered in conservative construction with individual pressure vessels by the Eagle Picher Industries company; Hughes Aircraft Company also has production capacities [28]. In Europe, nickel/hydrogen (and silver/hydrogen) cells are only produced experimentally by the SAFT company [29, 30]. For commercial telecommunications satellites, therefore, there is a heavy dependency on American suppliers. Costs for developing reliable, long-lived batteries seem well situated

in view of the costs of launching and satellite [31].

Hearty thanks here to Drs. E.A. Häusler (Silberkraft Leichtakkumulatoren GmbH) and L.H. Thaller (NASA Lewis Research Center) for information and documentation.

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