N90-20458

A SURVEY OF ADVANCED BATTERY SYSTEMS FOR SPACE APPLICATIONS

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The results of a survey on advanced secondary battery systems for space applications are presented. Fifty-five battery experts from government, industry and universities participated in the survey by providing their opinions on the use of several battery types for six space missions, and their predictions of likely technological advances that would impact the development of these batteries. The results of the survey predict that only four battery types are likely to exceed a specific energy of 150 Wh/kg and meet the safety and reliability requirements for space applications within the next 15 years.

1.0 INTRODUCTION

The Jet Propulsion Laboratory, under the NASA Headquarters sponsorship of the Advanced Battery Concepts Task, recently completed an evaluation of various advanced battery concepts to replace the current Ni-H_2 and Ni-Cd space qualified batteries. The goals were: 1) to identify advanced battery systems capable of outperforming present day batteries by a significant margin; 2) to obtain an accurate estimate of the anticipated improvements afforded by some technologies; and 3) to obtain a consensus as to which of the large number of possible systems are likely to yield the desired improvements with the highest likelihood of success by the year 2005, if properly funded.

2.0 APPROACH

Following an initial analysis by JPL of various electrochemical energy storage devices, the opinion of battery experts was solicited through a 5-part questionnaire. A brief description of each battery system considered by JPL was included with the questionnaire as background information, together with estimates of theoretical and practical energy densities derived from our initial analysis. Participants were asked to submit comments and answer the questions only within their areas of expertise.

3.0 APPLICATIONS REQUIREMENTS

A long shelf life, from 3 to 7 years, is a firm requirement in most space applications; however, capacity, cycle life and rate requirements tend to vary depending on the specific application. The energy storage requirements of six anticipated space missions are shown in Table 1. The requirements vary widely within the following limits: (a) charge time of 2 hours to 22 days; (b) discharge time of 0.6 hour to 17 days; (c) cycle life from 80 to 50,000 cycles; and peak power from 0.5 kW to 100 kW.

3.1 Currently Available and Near-Term Systems

The systems currently in use for space applications include the Ni-Cd, Ni-H_2 and Ag-Zn batteries. Near-term advanced systems include the advanced Ni-Cd battery and the bipolar or common pressure vessel Ni-H_2 batteries. JPL estimates of the characteristics of the space qualified and the near-term advanced systems are summarized in Table 2. As is immediately noticed, substantial reductions in the overall weight of the battery system would result from a battery capable of a specific energy in excess of 200 Wh/kg. However, the importance of long cycle life, safety, and reliability cannot be overemphasized; and high energy density alone cannot be the only factor to be taken into consideration when assessing the potential of a specific technology for space applications.

4.0 RESULTS OF OPINION SURVEY

4.1 Respondents Profile

The questionnaire together with background information was sent to 205 specialists selected from all sectors of industry, government, the universities and research institutes. Fifty-five respondents returned the questionnaire, including a low percentage of responses from universities. Table 3 shows a summary of the make-up of the respondents group.

4.2 Energy Density Critique

As a starting point for the survey, we had identified a total 23 advanced power sources capable of significant improvements over present day technology. Six types of power systems were represented: aqueous, molten salt, solid electrolytes, lithium-halogens, lithium-intercalation systems, and regenerative fuel cells. The participants were asked to evaluate the accuracy of our estimates of achievable specific energies for the proposed systems and to comment in general on the various systems presented to them for consideration.

Their responses are summarized in Table 4. On average, the respondents' estimates were slightly more conservative than JPL's estimates, but the range of estimates is much wider for systems still in their early stage of development. For example, the respondents estimate for the advanced nickel-hydrogen system is 75 ± 6 Wh/kg vs JPL's estimate of 76 Wh/kg. For the solid electrolyte Li/S system the respondent's estimate is 335 ± 179 compared to JPl's value of 500 Wh/kg.

4.3 Risk to Develop Successful Aerospace Batteries

The respondents were asked to give their best estimates of the likelihood of developing the proposed battery systems by the years 1995, 2000 and 2005 and to list the main obstacles to be overcome for each system. The estimates of these probabilities are summarized in Table 5. The systems with an acceptable risk for development are marked with an asterisk. Although the ranges of the estimates are fairly wide, certain trends are clearly evident.

The standard deviations for the estimates are lower for systems under active and well funded development; the likelihood of their development by the year 2005 is also high. Regenerative fuel cells, Advanced Nickel-Hydrogen and Sodium-Sulfur are typical examples and are all rated high.

Solid electrolyte systems based on Beta" Alumina and metal chloride cathodes are rated somewhat lower than Na/S but with acceptable development risks. The same is true for $LiAl/FeS_2$, lithium-intercalation systems (including those with polymer electrolytes,) and solid electrolyte fuel cells. Here again the intermediate rating seems to reflect the lower degree of funding for those systems.

A few systems are consistently rated "high risk", the lithium-halogens, the solid electrolyte Na/Cl_2 and Li/S, and the molten salt Be/NiF_2.

A list of the most frequently mentioned comments and perceived main obstacles on the most promising candidates is presented in Table 6. Li/S and Li/halogens are included in the list although these two systems were judged poor prospects for development.

4.4 Worthwhile Systems Omitted from JPL List

The respondents were also asked to identify other advanced battery candidates omitted or overlooked by JPL, and to give their best estimate of the realizable specific energy for each system.

Within five of the six categories of systems identified as potential candidates in our questionnaire, the following additional systems were suggested as having potential for achieving specific energies approaching 200 Wh/kg:

(a) Molten Salts:

At 240 Wh/kg, the bipolar "Upper Plateau" $LiAl/FeS_2$ battery offers outstanding peak power, in excess of 500 W/kg throughout its discharge period, over a wide range of states of charge.

(b) Solid Electrolytes:

Li/O_2 and Ca/O_2 are being explored in conjunction with a solid oxide ionic conductor operating at high temperatures (>700 C). Practical energy densities in excess of 200 Wh/kg are conceivable.

(c) Lithium-Halogens:

Systems of the type Lithium/SO_2 inorganic electrolyte/Metal Halides are considered by some as safer and more practical alternatives to the lithium-halogens systems. These systems are capable of achieving 200 Wh/kg at high rates of discharge, but safety is a concern.

(d) Li/Intercalation Cathodes:

Several systems with metal oxide cathodes, not mentioned in our original list of potential candidates, were considered capable of achieving high specific energy. Li/CoO_2 (150 Wh/kg) is one such candidate but requires a suitable electrolyte to achieve long cycle life. Li/MnO_2 (currently at 125 Wh/kg) is another and could reach a substantially greater specific energy in bigger cells, due to the improved packaging factor in large cells. The cell voltage of 2.8 V for Li/MnO_2 is inside the electrochemical window of the current most promising organic electrolytes.

As a whole the class of Lithium/Intercalation Cathodes offers specific energies from 100 to 200 Wh/kg, and presents opportunities for both solid polymer electrolytes as well as ambient temperature conventional electrolytes.

(e) Regenerative Fuel Cells:

The solid polymer electrolyte (SPE) H_2/O_2 fuel cell is a major candidate for the space station. A breadboard system successfully operated for more than 1000 cycles at NASA/JSC. NASA is currently funding a study to conduct a flight experiment on a reversible regenerative SPE fuel cell with all passive fluid and thermal controls. For large systems a specific energy in excess of 200 Wh/kg appears quite feasible. In many respects this system is very similar to the alkaline RFC and could be considered as a direct replacement for it.

(f) Supercapacitors:

A most interesting development which may impact energy storage technology in the future is the supercapacitor. To date devices with specific energies approaching 5 Wh/kg have been successfully demonstrated. These devices offer the additional advantages of ruggedness, high power density (up to 200 W/cc) and potentially unlimited cycle life.

4.5 Suitability of Systems for Space Applications

The fourth question set required the survey participants to estimate the degree of suitability of the proposed systems for several space applications. The panelists were requested to rate each battery system as highly suitable (H), moderately suitable (M) or not suitable (L) for each of six types of space missions. The responses are tabulated in Table 7 for each of the most promising systems. Based on those estimates, the development priorities are shown in Table 8.

For the six missions listed, the Beta" solid electrolyte (BASE) systems, Na/BASE/S and Na/BASE/metal chlorides battery are considered best for four missions; the H_2/O_2 alkaline RFC is ranked best for two missions. The U.P. $LiAl/FeS_2$ system was found worthwhile in 3 missions, whereas the Li/TiS_2, as a representative of a lithium/intercalation cathode system, was deemed useful in three applications. The Ni/H_2 was also highly rated for nearly all applications but was not considered an advanced battery candidate because of its lower specific energy and advanced stage of development. Some of the matches are quite evident, as discussed below.

(a) Lithium-Intercalation Batteries for the Planetary Rover:

The planetary rover has requirements that are well suited to ambient temperature lithium-intercalation batteries, both in terms of cycle life and rate. The fact that these batteries have no special temperature control requirements, and can be packaged and temperature controlled like the rest of the vehicle equipment is an important plus. The fact that they do not require a close temperature control is an advantage also. Several chemistries are available, including polymeric electrolytes, giving flexibility in a final choice.

(b) Regenerative Fuel Cell for Lunar Base:

The lunar mission is unique in that it requires very long operating times (days vs hours). In such applications the dominant weight of the energy storage system is in the reactants. The regenerative H_2/O_2 fuel cell has a very high specific energy for this application, approaching 500 Wh/kg, as most of its weight would be in the light weight reactants and their required tankage.

(c) Upper Plateau (U.P.) $LiAl/FeS_2$ for GEO:

The basis for recommending this system for development is its high energy density capability and its very high expectations of success. Recent results obtained at Argonne National Laboratory have shown that the system is capable of a cycle life in excess of 1000 cycles and a specific energy approaching 200 Wh/kg. The only other candidate system for GEO, aside from the Ni/H_2 system, would be the Na/S system. Although significantly more dollars were spent on Na/S, the U.P. $LiAl/FeS_2$ system shows expectations of having a greater energy density, lower risk of catastrophic failure, less risk of premature shorting, better high rate and peak power capability, less temperature variation during cycling, and less safety concerns for manned Shuttle launches. In addition, the U.P. $LiAl/FeS_2$ system can be activated prior to launch.

(d) Na/BASE/S or $FeCl_2$ or $NiCl_2$ for LEO and Planetary Orbiters:

The requirements for LEO are very strenuous with respect to cycle life and can only be met by very few systems (Ni-Cd or Ni-H_2). Currently the Na/S system is being developed for LEO but is still considered a high risk due to its high operating temperature. The Na/Metal Chlorides are attractive alternatives for this application because of their lower operating temperature and lower current density, hence lower risk of premature failure.

4.6 Technological Breakthroughs

Finally an estimate of the likelihood of occurrence of several new technological breakthroughs by the years 1995, 2000 and 2005 was requested from the participants. Only those estimates which show a reasonable degree of certainty are included in Table 9.

5.0 CONCLUSIONS AND FUTURE WORK

The results appear to support the following conclusions:

a) Most experts believe that the technical problems of the sodium-solid electrolyte systems, if continued to be funded at their current level, will be resolved by 2005. This type of system will provide an intermediate specific energy storage device (130 Wh/kg).

b) Key requirements for the development of lithium-intercalation systems appear well underway to being resolved by 2005, the main obstacle at this time being the plating efficiency of the lithium electrode.

c) The molten salt U.P. $LiAl/FeS_2$ system will be a serious high specific energy (180 Wh/kg) contender by 2005.

d) The development of a passive regenerative fuel cell is very likely by 2005. However, the parallel development of a bifunctional oxygen electrode is far from being certain.

e) The halogen-based systems, whether with lithium or sodium, are unlikely to be developed by the year 2005.

f) In general, the survey results are conservative. Participants in the survey are pessimistic about the chances of success of high risk developments with high potential payoffs, such as the lithium/solid ion conductor/sulfur or lithium-halogen battery, maybe due to the current low level of funding for their development.

As a follow up to this survey, the participants will be given a chance to comment on the results and conclusions.

TABLE 1

ENERGY STORAGE REQUIREMENTS OF SIX ANTICIPATED SPACE MISSIONS

PRIORITY	CHARGE/ DISCHARGE DURATIONS	TYPICAL OPERATIONAL CYCLES REQUIRED			TYPICAL PEAK POWER AND ENERGY STORAGE REQUIRED
		ACTUAL	QUAL*	DESIRED	
#1 Outer Planetary Orbit	C - 2 hr D - 0.7 hr	500	1,000	2,000	0.5 C (1 KWH)
#2 Inner Planetary Orbit	C - 2 hr D - 0.7 hr	3,000	6,000	10,000	1.5 C (2 KWH)
#3 GEO	C - 22.8 hr D - 1.2 hr	1,000	1,500	4,000	1.5 C (5 KWH)
#4 Planetary Rover	C - 12 hr D - 3 hr	300	600	800	1.3 C (3 KWH)
#5 Lunar Base	C - 11 Days D - 17 Days	80	160	350	0.02 C (5 MWH)
#6 LEO	C - 1 hr D - 0.6 hr	30,000	35,000	50,000	1.1 C (25 KWH)

GEO = Geosynchronous Orbit
LEO = Low Earth Orbit
*QUAL = Minimum number of cycles needed to qualify for application

TABLE 2

SECONDARY BATTERIES FOR SPACE APPLICATIONS

SYSTEMS CURRENTLY IN USE

SYSTEM	SPECIFIC ENERGY (Wh/kg)	ENERGY DENSITY (Wh/l)	CYCLE LIFE (40% DOD)	OPERATING TEMPERATURE (°C)
Ni-Cd	34*	70	20,000**	10 - 20
$Ni-H_2$ (IPV)$	45	25	25,000	10 - 20
Ag-Zn	90	80	50	10 - 20
ADVANCES IN STATE-OF-THE-ART				
Advanced Ni-Cd	36	110	35,000	10 - 20
$Ni-H_2$ (CPV)#	60	70	15,000	10 - 20

* NASA standard, 50 Ah battery
** Standard Cell Qualification Test
$ IPV = Individual Pressure Vessel
\# CPV = Common Pressure Vessel

TABLE 3

PROFILE OF CONTRIBUTORS TO SURVEY
ON ADVANCED BATTERIES

Occupation	Number of Respondents
Aerospace Industry	6
Battery Manufacturers	15
Other Manufacturers	8
Government	14
Universities	3
Institutes	9
TOTAL	55

TABLE 4

ESTIMATES OF ACHIEVABLE SPECIFIC ENERGY FOR ADVANCED BATTERIES (Wh/kg)

System	JPL Estimate	Panel's Estimate	Range	Number of Responses
AgO/Fe	90	85 +/-13	60-110	18
Advanced Ni/H_2	76	75 +/-6	60-80	25
U.P.LiAl-FeS_2	180	154 +/-33	75-188	31
Be-NiF_2	185	156 +/-43	95-185	9
LiAl-NiS_2	180	155 +/-35	75-184	19
Na/BASE/S	130	132 +/-26	80-220	29
Na/BASE/Cl_2	200	197 +/-70	100-350	9
Na/BASE/TCNE	100	95 +/-12	70-100	10
Na/BASE/$CuCl_2$	160	132 +/-30	80-160	11
Na/BASE/$FeCl_2$	150	130 +/-20	80-150	19
Na/BASE/$NiCl_2$	160	137 +/-24	80-160	17
Li/Solid Ion Conductor/S	500	335 +/-179	100-510	14
Lithium/Polymer electrolyte	250	183 +/-67	50-250	28
Li/Cl_2	500	375 +/-173	80-500	15
Li/Br_2	200	170 +/-56	70-250	14
Li/TiS_2	90	95 +/-13	73-130	28
Li/$NbSe_3$	100	105 +/-15	80-150	25
Li/Mo_6S_8	140	126 +/-28	50-180	22
Li/V_2O_5	150	143 +/-27	75-200	24
Li/a-Cr_3O_8	200	176 +/-37	75-200	22
Zn/O_2	100	99 +/-15	60-140	17
Alkaline RFC	100	152 +/-113	100-500	14
Solid Oxide H_2/O_2	200	252 +/-180	120-750	10

BASE = Beta" alumina solid electrolyte

TABLE 5

LIKELIHOOD OF DEVELOPMENT OF ADVANCED BATTERY SYSTEMS

System	Estimates of Probability of Development by 1995	2000	2005
AgO/Fe	37 +/- 32	47 +/- 33	54 +/- 38
Advanced Ni/H_2*	56 +/- 25	71 +/- 19	81 +/- 17
U.P.$LiAl-FeS_2$*	36 +/- 26	52 +/- 31	60 +/- 30
$Be-NiF_2$	12 +/- 16	25 +/- 24	35 +/- 35
$LiAl-NiS_2$	28 +/- 25	41 +/- 28	46 +/- 31
Na/BASE/S*	56 +/- 28	72 +/- 25	80 +/- 22
$Na/BASE/Cl_2$	17 +/- 18	31 +/- 25	29 +/- 29
Na/BASE/TCNE	23 +/- 20	33 +/- 28	42 +/- 33
$Na/BASE/CuCl_2$*	27 +/- 19	47 +/- 26	60 +/- 29
$Na/BASE/FeCl_2$*	36 +/- 23	53 +/- 28	66 +/- 29
$Na/BASE/NiCl_2$*	35 +/- 21	54 +/- 25	66 +/- 27
Li/Solid Ion Conductor/S	18 +/- 19	29 +/- 25	39 +/- 28
Lithium/Polymer electrolyte*	33 +/- 29	45 +/- 31	55 +/- 30
Li/Cl_2	10 +/- 14	19 +/- 18	32 +/- 25
Li/Br_2	12 +/- 13	21 +/- 18	33 +/- 26
Li/TiS_2*	44 +/- 26	57 +/- 29	66 +/- 31
$Li/NbSe_3$*	42 +/- 27	57 +/- 31	66 +/- 30
Li/Mo_6S_8	34 +/- 28	50 +/- 31	58 +/- 34
Li/V_2O_5*	34 +/- 23	48 +/- 28	58 +/- 32
$Li/a-Cr_3O_8$*	27 +/- 18	43 +/- 24	55 +/- 28
Zn/O_2	33 +/- 23	44 +/- 25	58 +/- 24
Alkaline RFC*	49 +/- 30	63 +/- 28	77 +/- 26
Solid Oxide H_2/O_2*	30 +/- 24	47 +/- 27	59 +/- 30

* These systems present acceptable development risks

TABLE 6

OBSTACLES TOWARD THE DEVELOPMENT OF ADVANCED BATTERIES

System	Obstacle
Advanced Ni/H2:	2-electron nickel electrode is unlikely No obstacle to improved Ni/H2 (CPV and/or Bipolar)
U.P. LiAl FeS2:	Corrosion and materials compatibility
Na/Beta"/S or Metal Chlorides:	Reliability of ceramic electrolyte and seals
Lithium-Sulfur:	Development of lithium ion conducting electrolyte
Thin Film lithium/ polymer electrolyte:	Need for higher ionic conductivity in polymer Low cycle life
Lithium-Halogens:	Material compatibility and corrosion
Lithium-Intercalation Cathodes:	Lithium cyclability Poor electrolyte stability
Alkaline RFC:	Development of the oxygen bifunctional electrode
Solid Oxide Fuel Cell:	Materials compatibility

TABLE 7

SUITABILITY OF ADVANCED BATTERY SYSTEMS FOR SPACE APPLICATIONS
(L= Not Suitable; M= Moderately Suitable; H= Highly Suitable)

SYSTEM	PLANETARY INNER ORBIT	PLANETARY OUTER ORBIT	GEO	ROVER	LUNAR BASE	LEO
Advanced Ni/H_2	L=5	L=7	L=2	L=10	L=14	L=3
	M=9	M=5	M=6	M=9	M=8	M=7
	H=13	H=14	H=20	H=9	H=7	H=20
U.P.LiAl-FeS_2	L=7	L=7	L=8	L=8	L=8	L=18
	M=13	M=11	M=7	M=5	M=12	M=7
	H=6	H=8	H=11	H=14	H=6	H=2
Na/BASE/S	L=5	L=3	L=2	L=3	L=5	L=13
	M=15	M=15	M=13	M=16	L=11	L=12
	H=10	H=12	H=15	H=11	H=16	H=6
Na/BASE/$FeCl_2$	L=5	L=3	L=2	L=4	L=6	L=10
	M=11	M=12	M=12	M=13	M=8	M=8
	H=6	H=6	H=6	H=4	H=9	H=4
Na/BASE/$NiCl_2$	L=5	L=3	L=2	L=3	L=6	L=9
	M=10	M=10	M=10	M=11	M=7	M=8
	H=7	H=8	H=8	H=6	H=9	H=5
Lithium/Polymer electrolyte	L=18	L=11	L=10	L=9	L=12	L=23
	M=5	M=9	M=10	M=10	M=6	M=1
	H=4	H=6	H=6	H=8	H=9	H=3
Li/TiS_2	L=21	L=11	L=11	L=10	L=16	L=28
	M=8	M=15	M=13	M=13	M=8	M=5
	H=4	H=7	H=8	H=10	H=6	H=1
Li/V_2O_5	L=24	L=15	L=13	L=12	L=16	L=30
	M=8	M=14	M=12	M=11	M=11	M=5
	H=1	H=3	H=8	H=9	H=6	H=0
Li/a-Cr_3O_8	L=21	L=12	L=11	L=9	L=13	L=26
	M=8	M=14	M=14	M=11	M=11	M=5
	H=1	H=4	H=5	H=9	H=6	H=0
Alkaline RFC	L=9	L=8	L=6	L=6	L=1	L=9
	M=11	M=12	M=13	M=16	M=8	M=9
	H=3	H=3	H=5	H=2	H=16	H=6
Solid Oxide H_2/O_2	L=10	L=9	L=7	L=8	L=1	L=9
	M=7	M=7	M=8	M=9	M=5	M=7
	H=3	H=4	H=6	H=4	H=17	H=6

TABLE 8

RANKING OF ADVANCED BATTERY SYSTEMS

Mission	Recommended Systems (Ranking)
Planetary Inner Orbit	Na/BASE/S or $FeCl_2$ or $NiCl_2$ (1) U.P. LiAl-FeS_2 (2) H_2/O_2 Alkaline RFC (3)
Planetary Outer Orbit	Na/BASE/S or $FeCl_2$ or $NiCl_2$ (1) U.P. LiAl/FeS_2 (2) Li/TiS_2 (3)
GEO	Na/BASE/S or $FeCl_2$ or $NiCl_2$ (1) H_2/O_2 Alkaline RFC or U. P. LiAl/FeS_2 (2) Li/TiS2 (3)
Planetary Rover	Na/BASE/S or $FeCl_2$ or $NiCl_2$ (1) U.P. LiAl/FeS_2 (2) Li/TiS_2 or Alkaline RFC (3)
Lunar Base	H_2/O_2 Alkaline RFC or Solid Oxide (1) Na/BASE/S or $FeCl_2$ or $NiCl_2$ (2) U.P.LiAl/FeS_2 (3)
LEO	H_2/O_2 Alkaline RFC or Solid Oxide (1) Na/BASE/S or $NiCl_2$ or $FeCl_2$ (2)

The advanced Ni-H_2 system was not included in the rankings as this system is much further ahead in its development stage.

TABLE 9

PROJECTED PROSPECTS FOR TECHNOLOGICAL BREAKTHROUGHS

Future Event	% Probability 1995	2000	2005
Improved Beta" alumina suitable for prismatic cells	39+/-26	53+/-27	66+/-27
Improved ceramic seals for Beta" Alumina	57+/-27	71+/-27	82+/-24
Hermetic seals for high temperature molten salt lithium batteries	29+/-32	61+/-31	71+/-28
A metal oxide intercalation electrode for lithium batteries with cycle life of 100	44+/-26	60+/-25	73+/-30
A reversible lithium electrode capable of 1000 cycles in organic electrolyte at 25C (e.g., Li/TiS_2 or Li/Metal Oxide)			
a) Medium voltage cells (~2 V.)	42+/-28	57+/-28	66+/-29
b) High voltage cells (~3V.)	33+/-24	47+/-25	59+/-28
Chemical overcharge protection for Li-Al/FeS_2 molten salt system	46+/-26	59+/-25	69+/-26
The development of very thin, suitable polymer electrolytes for thin Li cells	41+/-29	52+/-28	66+/-28
Development of hot-launch, ready to use, high temperature rechargeable batteries			
a) Na/Beta" Alumina/S	50+/-29	59+/-29	70+/-29
b) Li-Al/FeS_2	44+/-30	54+/-29	69+/-31
Development of practical rechargeable designs for			
a) Li/Cl_2	11+/-13	24+/-18	33+/-22
b) Li/Br_2	16+/-17	28+/-20	37+/-23
High rate (100mA/cm^2), reversible, long life, oxygen electrode for alkaline fuel cells	36+/-21	48+/-27	61+/-29