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SODIUM-SULFUR BATTERY FLIGHT EXPERIMENT DEFINITION STUDY*

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The need for high power space systems is anticipated within the next 10 to 20 years. Examples are the Space Station, co-orbiting platforms, geostationary orbit (GEO) platforms, and space based radar satellites and some classified high power missions. Sodium sulfur (NaS) batteries have been identified as the most likely successor to nickel hydrogen ($Ni-H_2$) batteries for space applications. One advantage of the NaS battery system is that the useable specific energy is two to three times that of $Ni-H_2$ batteries. This represents a significant launch cost savings or increased payload mass capabilities. NaS batteries support NASA OAST's proposed Civil Space Technology Initiative goal of a factor of two improvement in spacecraft power system performance, as well as the proposed Spacecraft 2000 initiative.

The NaS battery operates at between 300 and 400°C, using liquid sodium and sulfur/polysulfide electrodes and solid ceramic electrolyte[1,2,3]. The transport of the electrode materials to the surface of the electrolyte is through wicking/capillary forces. These critical transport functions must be demonstrated under actual microgravity conditions before NaS batteries can be confidently utilized in space.

Ford Aerospace Corporation, under contract to NASA Lewis Research Center, is currently working on the NaS battery space flight experiment definition study. The objective is to design the experiment that will demonstrate operation of the NaS battery/cell in the space environment with particular emphasis on evaluation of microgravity effects. Experimental payload definitions have been completed and preliminary designs of the experiment have been defined.

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INTRODUCTION

The NaS battery cell, pioneered by Ford Motor Co., is seen as one of the most attractive battery systems for spacecraft power systems. The primary advantage of this system is its high energy density, which can reach 150 WH/kg at C-rate discharge at the cell level. The NaS battery offers a combination of system level advantages:

- Mass and volume effectiveness
- High round-trip efficiency
- Heat rejection at high temperature
- Simplicity of battery integration
- Competitive acquisition costs

Nominal NaS cell operating parameters are shown and compared with typical Ni-Cd and $Ni-H_2$ cell data in Table 1. Unusual performance features for the NaS cells are the high cell operating voltages, high roundtrip efficiency and high operating temperature which minimizes the radiator area and cost. Potential cost savings are illustrated in Table 2. It is obvious that the battery mass savings are translated into spacecraft launch cost savings or payload capability increase. Using $Ni-H_2$ systems as a reference, it can save in launch cost from 1.1 to 1.7M$/KW for the GEO missions and 0.2 to 0.4M$/KW for the LEO missions. For example, a 2.5 KW aerospace NaS battery concept design which weighs 31.8Kg while a 0.5 KW $Ni-H_2$ battery weighs 30.5 Kg.

The NaS battery is a particularly good energy storage system for high power satellite missions. A parametric study comparing the operational storage candidates for a 75 KW satellite mission has been performed by Ford Aerospace and the results are shown in Table 3[4]. The NaS battery looks the most favorable with respect to the other storage systems.

The NaS battery cells operate at between 300 and 400° C. The liquid electrode materials rely on the wicking actions for transport to and from the electrolyte interface to support routine cyclic operation. Current developmental space cells have been designed to have adequate wicking, but this critical function must be demonstrated under actual orbital microgravity conditions before NaS batteries can be confidently applied in space. The primary objective of the Ford Aerospace study is to define the specific experimental design required for successful demonstration of NaS battery/cells under space environments.

CELL OPERATIONS AND SELECTIONS

NaS cells as shown in Figure 1 utilize a solid ceramic electrolyte known as β''-alumina to separate anode (sodium) and cathode (sulfur/sodium polysulfide) reactants and to provide a conductive path for sodium ions during operation. The transport of the electrode materials to the surface of the electrolyte is through wicking/capillary forces. A metal protection tube limits the flow of sodium into the reaction zone, thus providing for safe operation of the cell. Since only small amounts of the sodium are available for reaction, a quick, explosive reaction is not possible to occur even in the case of a broken electrolyte tube. The sulfur is contained in the outer part of the cell, imbedded in a carbon fiber mat. The carbon fiber mat improves the electrical conduction path for the sulfur electrode.

At the cell operating temperature, the reactants are at liquid state. During discharge of the cell, the sodium splits into positive ions, which are transported across the electrolyte, and negative electrons, which are carried up by the current collector to the external circuit. Once the sodium ions are transported across the ceramic electrolyte, they join with the sulfur to form a sodium-polysulfide (Na_2S_5). As the cell is further discharged, the Na_2S_5 reacts with sodium to form other sodium polysulfides such as Na_2S_4 and Na_2S_3. Charging the cell results in the opposite reactions taking place with the sodium-polysulfides being dismantled into sodium ions and sulfur. The sodium ions are then transported back across the electrolyte to the sodium electrode.

The proposed flight experiment cells which are rated 40AH are derived from the Ford Aerospace baseline SATBAT-2 cells. The physical characteristics of the cells are summarized as follows and typical 40AH cells are shown in Figure 2.

Cell Capacity (Ah):	40.0
Outer diameter (cm):	3.6
Cell length (cm):	23.0
Cell Mass (g):	519.0

FLIGHT EXPERIMENT JUSTIFICATIONS AND OBJECTIVES

NaS cells differ from most batteries in that they contain molten anodic and cathodic reactants. Ability of the NaS cells to efficiently charge and discharge is critically dependent upon the favorable spatial distribution of the fluid reactants with respect to their interface with the solid beta"-alumina ceramic electrolyte. Fluid motion and reactant morphology are particularly critical for NaS cell operation since the sulfur/sodium-polysulfide catholyte reactants form three immiscible phases during recharge, two of which are non-conductive: molten sulfur, void volume, and Na_2S_5. Should an unfavorable distribution occur, a blocking layer could develop and restrict cell operation.

Terrestrial cell designs incorporate preferential wetting, capillarity and/or graded resistance within the sulfur electrode to maintain efficient operation. Such cells have been developed to operate effectively at high rate and to yield high specific energy and specific power. However, the characteristics of NaS cells under microgravity conditions are unknown because of the uncertain role of gravity in controlling the distribution and consolidation of the separate reactant phases. These effects can only be determined by testing in orbit with 3-axis stabilized spacecraft because it is not possible to simulate low gravity conditions for sufficiently long times to represent cycling or the large equilibration time constraints associated with the sluggish fluids.

The main purpose of the NaS battery/cell flight experiment is to validate the application of NaS battery technology to space power applications. The principal objective of the flight experiment definition study is to design an experiment that will demonstrate operation of the battery/cells under space environments with particular emphasis on evaluation of microgravity effects which are specially critical for 3-axis stabilized spacecrafts. These can be categorized in the followings:

I. To evaluate cell charge and discharge characteristics as affected by the fluid reactant distributions.
II. To determine reactant distributions under microgravity conditions.
III. To understand current and thermal distributions within the cells.
IV. To evaluate freeze/thaw effects.
V. To evaluate multi-cell early LEO (Low Earth Orbit) cycle life.

The approach is to select only those tests that are critical and expected to differ under microgravity conditions. Spin stabilized satellite batteries can be tested on the ground, thus a test to simulate this application in space is not needed. Warm launch has an advantage that the cells in space will require less energy and time to heat up from the warm launch temperature to its final operating temperature. However, the demonstration of the cell survivability to the launch environments can be confirmed on the ground by test followed by electrical cyclic testings. Therefore, the warm launch test need not be included in the experiment.

DESCRIPTION OF PROPOSED EXPERIMENTS

Five tests have been identified in the NaS battery flight experiment definition study to meet the above objectives. Each of these tests will be summarized in the following sections.

I. CELL CHARACTERIZATION TEST
II. REACTANT DISTRIBUTION TEST
III. CURRENT/TEMPERATURE DISTRIBUTION TEST
IV. FREEZE/THAW TEST
V. MULTI-CELL LEO CYCLE TEST

The test cells will be Ford Aerospace baseline 40AH cells except Test III cells which will be specially instrumented with extra thermocouples and voltage probes.

Our general testing philosophy is to have most of the space cells evaluated under various conditions on the ground prior to launch, in the space, and after cells are brought back to earth to provide before-during-after data comparison. Additional control cells will be assigned to an identical ground test to provide additional comparative data base.

I. CELL CHARACTERIZATION TEST

NaS cells will be evaluated under various test conditions in space under two temperature ranges, 275°C and 350°C. Once orbit has been stabilized, the cells will be heated to operating temperatures and the test sequence performed. The charge/discharge cycle variables have been established to cover a sufficiently wide range of parameters to address a majority of anticipated space applications. Pulse loads will be imposed during the discharge. Each cell will be instrumented with power leads, voltage sense leads and a thermocouple pair, all which will penetrate the thermal insulation barrier for connection to ambient temperature connector panels. During the charge/discharge cycle, each cell voltage will be periodically measured.

II. REACTANT DISTRIBUTION TEST

After completion of Test I, the cells will be discharged into their 1-phase region and placed on open circuit to accurately determine their state-of-charge. Each state of charge of the cell will be adjusted to a composition ranging from Na_2S_3 to Na_2S_5.

III. CURRENT/TEMPERATURE DISTRIBUTION TEST

This test will determine the spatial variations of electrode reactions and current densities within the sulfur electrode continuously throughout the electrical cycles while being operated under microgravity conditions. This information will support analysis and assessment of test results of Test I and II, and will provide direction of possible modification of the sulfur electrode design should that prove necessary.

The distribution of internal current densities and electrode reactions will be measured continuously during the electrical cycles by measuring its small ohmic losses. Specially instrumented cells will be fabricated to incorporate a multitude of voltage probes on the positive current collector. In addition to the external thermocouples located at the top, middle, and bottom of the cell container, internal thermocouples on the inside electrolyte tube wall will also be installed at respective locations to measure the temperature gradients. Three sets of voltage probes shall be used to provide information about circumferential uniformity.

IV. FREEZE/THAW TEST

Cells will be evaluated for the freeze/thaw cycles. Cells will be initially heated up to operating temperature and evaluated electrically, followed by several freeze/thaw cycles. On the last day of the flight experiment, cells will be again evaluated electrically to determine the effects of the freeze/thaw under microgravity conditions. The cells will be cooled for reentry.

V. MULTI-CELL LEO CYCLE TEST

NaS cells will be series connected and evaluated in the 90 minute orbit regime. Cells will be cycled at a high rate discharge for 36 minutes and followed by a charge for 54 minutes. It is almost impossible to evaluate the life cycle of the NaS cells in such short experiment duration. However, the proposed LEO cycle will provide an early life real time LEO operational experience and demonstrate the multi-cell operation. Information obtained will be definitely valuable for full size battery scaling-up.

SYSTEM IMPLEMENTATION AND CARRIER OPTIONS

A variety of payload carriers, shown in Figure 3, including Middeck Modular Locker, Get Away Special, Hitchhiker G, and Hitchhiker M have been reviewed[5]. Concerns such as electrical power, mass load/structure, and mounting orientation have been considered as factors for carrier selections. From the preliminary design of the five tests, the total weight of the enclosures, batteries, and support equipments is estimated to be a total of less than 100 lbs. The experiment will occupy a space approximately 3.0'x3.0'x1.5'.

SUMMARY AND CONCLUSION

NaS batteries have been identified as the most likely successor to space $Ni-H_2$ or Ni-Cd batteries, primarily due to a mass reduction by a factor 2-3 over $Ni-H_2$ and by a factor of 4 over Ni-Cd. This yields major launch cost reductions or payload mass improvements. NaS batteries support NASA OAST's proposed Civil Space Technology Initiative goal of a factor of two improvement in spacecraft 2000 initiative. Since $Ni-H_2$ and Ni-Cd batteries have been space flight proven, it is essential to have the flight experiment to establish a national space technology base to demonstrate the operation of the NaS battery for space applications.

ACKNOWLEDGEMENT

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Table 1. SPACE BATTERY OPERATING PARAMETER COMPARISON

Battery System	Condition	Average Cell Voltage (V) Charge	Discharge	Roundtrip Efficiency (%)	Discharge Dissipation (kWt/kWe)	Operating Temperature (C)	Typical DOD (%)
Ni/Cd	GEO	1.43	1.22	80	0.18	0-20	45-60
	LEO	1.45	1.23	80	0.17	0-20	15-22
Ni/H_2 (IPV)	GEO	1.45	1.25	80	0.20	0-20	68-80
	LEO	1.47	1.27	80	0.18	0-20	28-40
Ni/H_2 (bipolar)	GEO	1.45	1.26	82	0.19	0-20	68-80
	LEO	1.46	1.28	82	0.27	0-20	28-40
Na/S	GEO	2.10	1.83	87	0.18	300-400	50-80
	LEO	2.15	1.80	84	0.21	300-400	35-50

Table 2. Sodium/Sulfur Batteries Offer Spacecraft Mass Savings

Battery System	Condition	Mass Performance	Volume Performance	Cost vs Ni/H2 Prod	Cost vs Ni/H2 Launch	Life Years
Ni/Cd	GEO	55-90 kg/kW	30-55 l/kW	1.1	+ 1.0-1.5 M$/kW	5-7
	LEO	70-140 kg/kW	40-85 l/kW	1.6	+ 0.3-0.5 M$/kW	5-5
Ni/H_2 (IPV)	GEO	35-60 kg/kW	60-120 l/kW	1	0	10-15+
	LEO	35-70 kg/kW	60-150 l/kW	1	0	5-8
Ni/H_2 (Bipolar)	GEO	35-60 kg/kW	25-45 l/kW	1.2	0	10-15+
	LEO	35-70 kg/kW	25-55 l/kW	1.2	0	5-8
Na/S	GEO	13-25 kg/kW	40-120 l/kW	1.2	- 1.1-1.7 M$/kW	5-(a)
	LEO	11-20 kg/kW	30-85 l/kW	1.2	- 0.2-0.4 M$/kW	1-(a)

a) requires demonstration

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TABLE 3. ENERGY STORAGE SYSTEM OPTIONS COMPARISON

	ENERGY STORAGE SUBSYSTEM OPTIONS						
PARAMETER	RFC H_2-O_2	RFC H_2-O_2	BIPOL Ni-H_2	IPV Ni-H_2	Ni-Cd	Na-S	FLY-WHEEL
ROUND TRIP EFFICIENCY (%)	55	60	77	75	75	82	82
DEPTH-OF-DISCHARGE (%)[a]	38	38	38	38	20	38	38
MASS (kg)	2100	2500	3300	4100	9500	1500	4200[b]
VOLUME (m^3)	9.3	9.9	2.5	6.6	5.2	1.9	4.0[b]
WASTE HEAT/CYCLE (kW·h)	42	34	15	17	17	11	11
ECLIPSE HEAT REJECTION (kW)	57	55	17	18	17	17	9
TEMPERATURE (°C)	80	80	10	10	10	350	35
CHARGE POWER REQUIREMENT (kW)	98	90	74	76	76	66	66

[a]IN ALL CASES, EXCEPT Ni-Cd CONTROLLED BY ONE ORBIT HALF POWER REQUIREMENT FOLLOWING A FULL POWER ECLIPSE
[b]EXCLUSIVE OF CONTAINMENT

FIGURE 1. SCHEMATIC OF NaS CELL

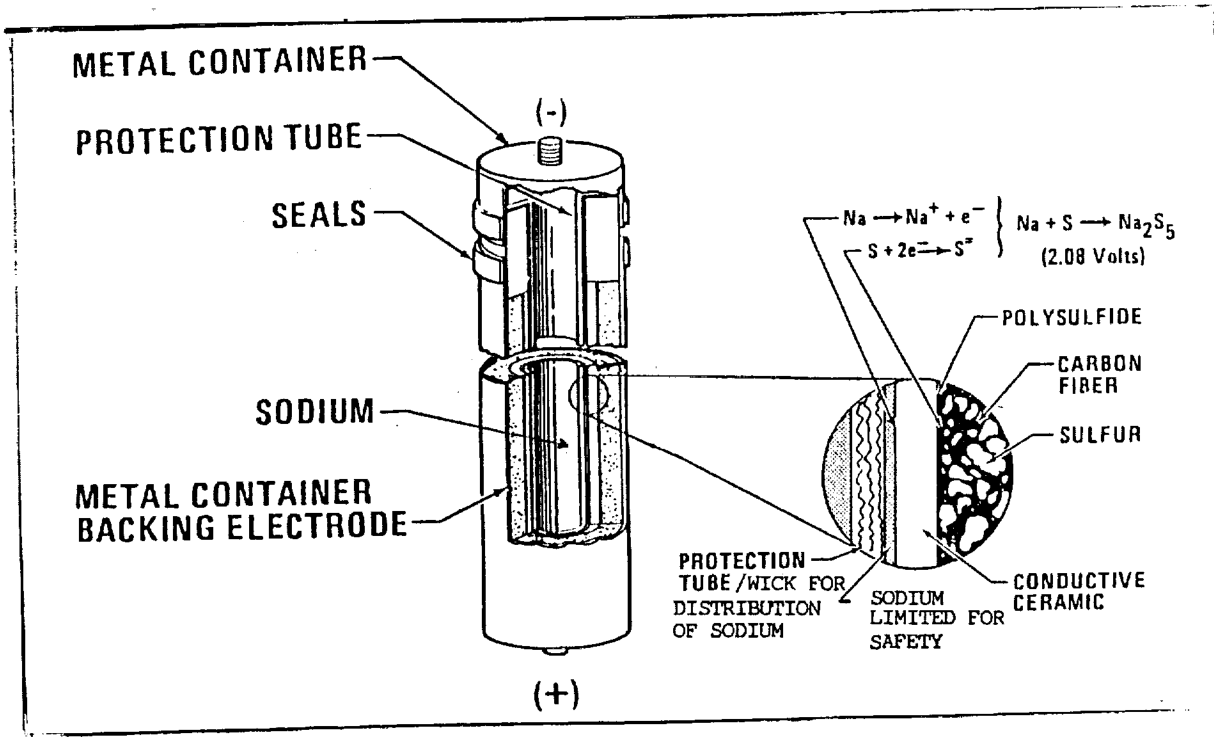

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FIGURE 2. FORD AEROSPACE NaS CELLS

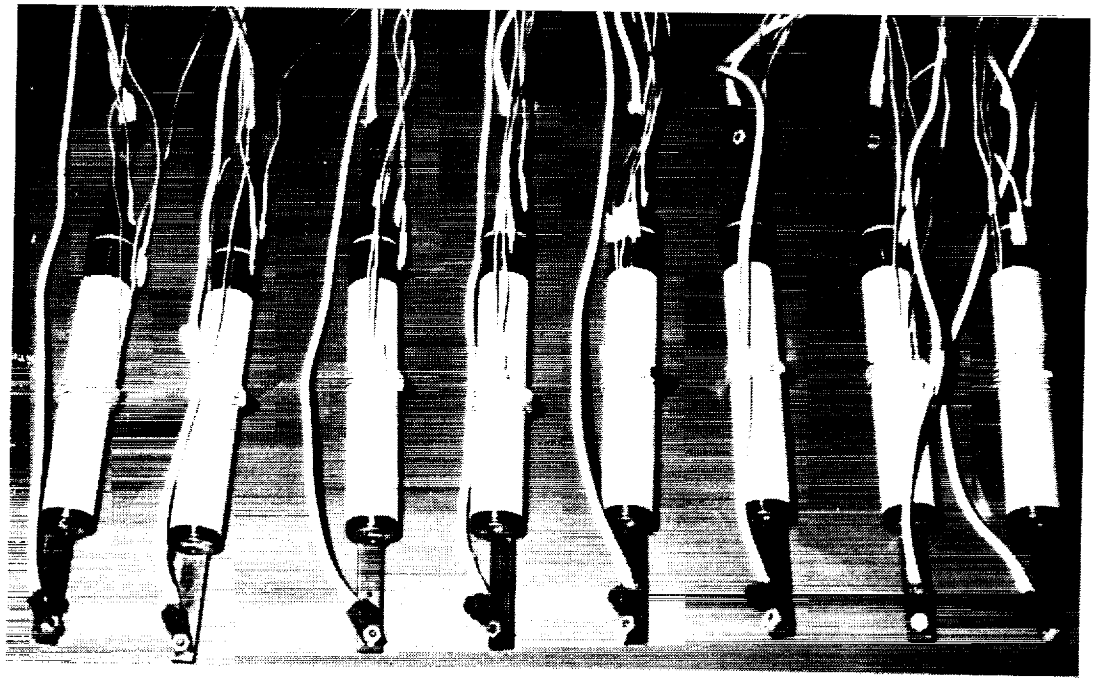

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FIGURE 3. PAYLOAD CARRIER OPTIONS