POWER SYSTEMS STUDY FOR TWO VARIABLE SPECIFIC IMPULSE MAGNETOPLASMA ROCKET APPLICATIONS

By:

E. Meintanis
R.D. Bengtson
R.E. Hebner

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Center for Electromechanics
The University of Texas at Austin
PRC, Mail Code R7000
Austin, TX 78712
(512) 471-4496

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Power Systems Study for Two Variable Specific Impulse Magnetoplasma Rocket Applications

E. Meintanis¹, R.D. Bengtson², and R.E. Hebner³

Abstract

In this study, we analyze the power storage systems needed for operational tests of a Variable Specific Impulse Magnetoplasma Rocket (VASIMR) on the International Space Station (ISS). Two tests are considered: a short-term test of VASIMR operation in a space environment and long term drag compensation operation. Energy storage possibilities examined include nickel hydrogen, nickel cadmium, and lithium-ion batteries and flywheels. For the near-term planned tests, all approaches are technically feasible with Ni-Cd batteries likely least expensive. For use in drag compensation, ten-year operation is beyond the capability of any battery system without battery replacement. For this long-term multi-cycle application the flywheel energy storage costs can be significantly lower.

1. Motivation

With the International Space Station (ISS) orbiting at a nearly circular, Low Earth Orbit (LEO), the atmospheric drag causes an altitude loss of ~ 0.2 km/day. To compensate, a bi-propellant reboost is carried out every 10 to 45 days. Electric thrusters could provide a cheaper alternative for reboost. They also provide the option for a low thrust, steady state drag compensation to improve the ISS microgravity environment and make the current, reboost burns infrequent or even unnecessary. Within this framework, various approaches to powering a novel electric propulsion thruster, the Variable Specific Impulse Magnetoplasma Rocket (VASIMR), have been explored.

2. VASIMR

The variable specific-impulse magnetoplasma rocket [1] is a plasma thruster that uses RF electromagnetic fields to create and accelerate a plasma with minimal plas-

1 Physics Department, The University of Texas at Austin, MC C1600, Austin, TX 78712

2 Professor, Physics Department, The University of Texas at Austin, MC C1600, Austin, TX 78712, (512) 471-3943, bengtson@physics.utexas.edu

3 Director, Center for Electromechanics, The University of Texas at Austin, MC R7000, Austin, TX 78712, (512) 471-4496, r.hebner@mail.utexas.edu

ma surface interaction. The engine (fig. 1) consists of three sections. In the first two, superconducting solenoids create a longitudinal magnetic field to confine the charged particles. These charged particles come from the ionization of neutral gas by electromagnetic waves, in the first section of the engine. The plasma flows to the Ion Cyclotron Resonance Heating (ICRH) section, where the transverse velocity of the ions is increased. The last section, the magnetic nozzle, controls the expansion of magnetic field lines outside the engine. As the magnetic field weakens, the adiabatic invariance of the magnetic moment of the particles causes their transverse (rotational) velocity to decrease and the velocity parallel to magnetic field to increase.

There are two proposed applications of the VASIMR on the ISS. Both involve a 24 kW VASIMR engine, with an operating specific impulse range of 4,500-10,000 s and corresponding thrust limits of 0.5-0.2 N. The 24 kW of power would drive RF generators, which operate at 50 V dc and 480 A. The first application is a short-term experiment that would activate the thruster for 10 min every 24 hours. The device would have enough fuel to perform 200 runs without refueling. For this analysis, it is assumed that the experiment will operate for less than a year. The second application is a propulsion module to provide drag compensation for the ISS, operating continuously, usually at the full thrust level of 0.5 N. Since the atmospheric drag on the space station varies in the range of 0.4-1.5 N the thruster would not be a stand-alone solution and periodic boosts would be necessary to keep the station in orbit.

Because operation of a 24 kW device from station power system would upset its power balance, alternatives are needed for both VASIMR applications. The short-term experiment requires only a rechargeable energy storage system, which would charge at a slow rate between the daily firings of the rocket. The need, therefore, is for a 4

Figure 1. Conceptual drawing of VASIMR

kWhr unit. The continuously operating propulsion module would have to be autonomous in terms of power. A dedicated solar panel array is envisioned for that module but an energy storage system would be necessary to provide power during the eclipse portion of the orbit. The typical ISS orbit has a period of 96 min with an eclipse portion as long as 36 min. The system should have a lifetime equal to the 10 year projected lifetime of the module, which translates into ~58,000 cycles of operation. This system must have a capacity of approximately 15 kWhr.

3. Energy Storage System Options

A wide range of energy storage systems is available today. The primary technologies that operate reversibly include secondary batteries, flywheel energy storage systems (FESS), superconducting magnetic energy storage (SMES) systems, inductors, capacitors and supercapacitors. For this application, the last three need not be considered, due to their fast self-discharge. SMES operate by converting electric energy into magnetic field energy in a coil of superconducting wire. They can achieve high energy and power with slow self-discharge in optimized designs. Due to the size and weight of a SMES unit, the present applications have been concentrated on high power stationary uses in terrestrial power systems. Flywheels store electric energy as mechanical energy of a rotor. FESS are characterized by long lifetimes and they can be designed to provide large power densities. They are being developed for both fixed and mobile applications. Chemical batteries and flywheel energy storage are technologies that are analyzed in this paper.

3.1 Secondary batteries

Secondary (rechargeable) batteries are electrochemical energy storage systems. They consist of galvanic cells, connected in series or in parallel to yield the necessary electrical properties. In the following paragraphs, three battery chemistries [2] will be examined; Ni-H₂, Ni-Cd and Li-ion.

3.1.1 Ni-H₂

Nickel hydrogen batteries are used on most satellites and the space station. Their operation is based on the following half reactions:

where the discharge direction is left to right. The net reaction is:

The functional unit of a Ni-H₂ cell consists of a catalytic, hydrogen anode, a nickel (Ni(OH)₂) anode, and a separator between the two. These units are stacked with gas screens between them to allow the flow of hydrogen. In the most popular current design, the Individual Pressure Vessel (IPV) cell, the assembly is enclosed in a pressure vessel with a wick on the wall to allow the recirculation of electrolyte, an aqueous solution of KOH.

There are advantages to the Ni-H₂ chemistry. Cells are tolerant of overcharge and overdischarge since the H₂ that is being produced recombines with O₂ and OH⁻ respectively with heat the only byproduct. Moreover, the amount of H₂ in the cell is proportional to the available electrons; therefore its pressure is a state of charge (SOC) indicator. These cells have the best demonstrated, lifetime performance.

A shortcoming is that the performance of Ni-H₂ batteries depends on the depth and rate of discharge. A second challenge is cost. There has been limited use outside the space industry and Ni-H₂ batteries have not been mass-produced. A third challenging attribute of this technology is that the free flow of H₂ in the cell allows the discharge reaction to proceed spontaneously, giving rise to a self-discharge of the cell. The ISS batteries lose about 20% of their charge after 72 hours.

The cell aging mechanisms are not well documented. Failure is typically associated with a significant decrease of the end-of-discharge voltage rather than an electrical short between the electrodes [2]. Experiments have shown the life of these cells is dependent on the electrolyte concentration, with optimum concentration of 26%.

3.1.2 Ni-Cd

A Ni-Cd cell consists of an anode and a cathode with Cd(OH)₂ and Ni(OH)₂ as their active materials respectively. Between the electrodes there is a separator (usually polyamide), wetted with KOH electrolyte solution. Cell operation is based on the following half reactions:

where the discharge direction is left to right. The net reaction is:

The cathode reaction shown is a simplified version of the actual complex reaction.

Sealed Ni-Cd cells are a mature technology, mass produced at low prices. Their operating temperature range is typically 0-50°C. They can withstand deep discharge and produce high currents without affecting performance. Ni-Cd cells achieve better volumetric and gravimetric energy densities than Ni-H₂ and they also compare favorably with Ni-H₂ in terms of charge retention (~90% after 3 days).

A disadvantage of Ni-Cd cells for this application is their short cycle life, which depends exponentially on the depth of discharge (DOD). Typical cells perform satisfactorily for 300-5000 cycles. The capacity of these cells can be reduced prematurely, due to the memory effect and the formation of Cd alloys on the anode. Periodic cell conditioning with a slow cycle of full charge and discharge to minimize these effects. Additionally, sealed Ni-Cd cells offer no SOC indicator.

Ni-Cd cells degrade mainly through dendrite generation on the Cd electrode during charge. These dendrites can short the electrodes, decreasing the cell voltage and accelerating its self-discharge. An additional degradation mechanism is present

because the polyamide separator is sensitive to the increased temperatures and oxidation that occurs during overcharge and can be carbonated. This reduces the electrolyte conductivity and increases the internal resistance of the cell.

3.1.3 Li-ion

The high electrochemical potential of a Li electrode was recognized early in this century. The advantage of such a cell is its increased energy storage capacity, compared with cells of the same charge capacity. The operation of the Li-ion cell is based on the extraction of Li^+ ions from the anode and their intercalation into the cathode active material crystals and vice versa, during discharge and charge respectively. Intercalation refers to the insertion of ions in a crystal, without significantly altering its structure. In terms of chemical half-reactions, the operation of these cells can be described by:

where M is a metal, the oxide of which intercalates Li (most commonly Co, Ni, Mn or an alloy), and x depends on the chemistry of the cell and is usually ≤ 0.5 . The discharge direction is left to right and the net reaction is:

The Li-ion cell consists of an anode and a cathode, with carbon and a lithiated metal oxide respectively as active ingredients. The cathode material is a subject of ongoing research. Most mass produced cells rely on cobalt dioxide, while for special, high-energy applications, nickel dioxide or a mixture of the two oxides is preferred. A separator is used between the electrodes, wetted by an electrolyte of lithium salts (LiPF_6 , LiAsF_6 , LiClO_4 , etc) dissolved in stable carbonate-based solvents (ethylene carbonate, propylene carbonate, dimethyl carbonate, etc).

Li-ion cells enjoy an advantage, over all studied chemistries, in terms of their volumetric and gravimetric energy densities. The cycle life performance of Li-ion cells seems to be better than that of at least the Ni-Cd and Ni-MH competition. Further, no conditioning is needed for these cells, as there is no memory effect. Since the potential of the lithiated metal oxide electrode is a function of the Li^+ concentration, the voltage of the cell provides a SOC indicator.

The main disadvantage of Li-ion cells has to do with safety. Each cell must operate within defined voltage, current and temperature ranges. If these limitations are not observed, adverse consequences range from degradation of cell performance to electrolyte venting or even cell ignition. Integrated into every Li-ion battery therefore, are cell monitoring and protection electronics. Another result of the limitations is the complex charging scheme that has to be employed for Li-ion cells, which involves constant current and constant voltage phases.

There is limited data published on the aging of Li-ion cells. Electrolyte decomposition [3] and buildup of a passivation layer onto the electrodes are possible explanations for the increasing internal impedance as the cells age. In addition, the layered cobalt oxide material tends to lose oxygen if the lithium content falls below 50% of the stoichiometric quantity in the fully charged electrode (LiCoO_2), due to overcharge of the cell. An exponential dependence of cycle life on depth of discharge seems to be confirmed by both real-time and accelerated experiments, with current cycle numbers in the range of 1,000 to >200,000 for large to small DOD.

3.2 Flywheel energy storage systems

The FESS is an electromechanical approach to store energy. The concept is that an alternator converts the electrical energy of an external circuit into the rotational energy of a flywheel and vice versa. An FESS consists of a rotating mass (the flywheel), an alternator, power electronics and a monitoring electronics package. Currently, flywheels are made of either metal or composites. For a cylinder (the typical shape of a flywheel) of mass density ρ , inner and outer diameters r_i and r_o respectively, rotating with angular velocity ω , the stored mechanical energy is:

$$E = \frac{1}{2} \rho \omega^2 \frac{r_o^4 - r_i^4}{4}$$

The radial (σ_r) and hoop (σ_θ) stresses at a given radius are also both proportional to $\rho\omega^2$. Composite flywheels spin at high speed, taking advantage of their high strength, to store significant energy in a relatively light package.

During the discharge of a FESS, the alternator produces a variable frequency current. To make this output consistent with that of a battery, power electronics rectify the current. During charge, the available dc current is modulated to accelerate the flywheel with minimum heat generation. This bi-directional ac/dc conversion is performed by a power electronics package, which becomes a part of the FESS system, along with the flywheel and/or magnetic bearing monitoring and control systems.

Among the advantages of the FESS technology is the fact that typical lifetimes for modern flywheel systems exceed 90,000 cycles at 90% DOD. Further, since a flywheel doesn't depend on temperature sensitive chemical reactions, neither its output power nor capacity depends on temperature.

Like chemical batteries, these systems do provide some challenges. First, their operation involves a change in the speed of a rotating mass which is a change in angular momentum. The resulting torque can be compensated using a counter-rotating device or used for attitude correction. Second, their operation is always accompanied with power consumption. Systems designed for the ISS have an efficiency of more than 90% for the full charge-discharge cycle.

4. Systems Comparison

Basic data on all electrochemical systems discussed are shown in Table 1. In this table, ORU and BCDU stand for orbital replacement unit and battery charge/discharge unit. The flywheel-based system is a modification of a design that is being qualified

to replace the ISS batteries [4]. The main parts affected would be the alternator and power electronics, which would have to handle larger current and power in the VASIMR applications. The relevant data are provided in Table 2. In this table, FESU, FM and FESE stand for flywheel energy storage unit, flywheel module and flywheel energy storage electronics respectively. A FESS would pair two FESU with counter-rotating flywheels that would yield a zero total angular momentum.

Table 1. Electrochemical systems

	Ni-H ₂	Ni-Cd	Li-ion	
Cell	Eagle Picher 89 Ah	Sanyo CP2400SCR	SAFT VES 140 O	SAFT HP 30
ORU	38S/ORU	50S18P/ORU	15S24P/ORU	16S6P/ORU
Battery	2 ORUs in parallel	2 ORUs in parallel	1 ORU	1 ORU
Cost	\$4M/battery	~\$0.9M/battery	TBD	TBD
Operation	35% DOD, LEO cycling	50% DOD, 3.1 C discharge	35% DOD, LEO cycling	50% DOD, 2.8 C discharge
Voltage (/ORU)	<V>=45.5 V	<V>≥58.4 V	<V>≥54 V	<V>≥54 V
Usable capacity (/ORU)	28 Ah, ~1.3 kWh	~19 Ah, ~1.1 kWh	~16 kWh	~4.7 kWh
Cell life (in cycles)	>42,000	>1,500	10 ⁵ (30% proj.)	>20,000 (proj.)
Operating temperature	0-10°C	0-40°C	0-40°C	0-40°C
Energy densities (batt.)	Volumetric	~3.1 Wh/l	~24 Wh/l	~51 Wh/l
	Gravimetric	~7.6 Wh/kg	~14 Wh/kg	~40 Wh/kg
Energy densities (system)	Volumetric	~2.7 Wh/l	TBD	TBD
	Gravimetric	~5.8 Wh/kg	~8 Wh/kg	TBD

Table 2. FESS

System	Each FESS is two FESUs in parallel, Each FESU contains a FM and a FESE package	
Cost	\$1.6M per unmodified FESS	
Operation	90% DOD, LEO cycling	
Opp. Voltage (/FESU)	43-58 V	
Usable Capacity (/FM)	~3 kWh	
Design life	92,000 cycles (15.75yr) design life	
Operating temperature	Composite range for full speed operation is 23°C to 82°C (72°F to 180°F)	
Energy densities (FESU)	Volumetric	~5.2 Wh/l
	Gravimetric	~12 Wh/kg

5. Conclusions

For a short duration experiment on the ISS, the Ni-Cd batteries appear to be the most likely candidate. These batteries are available, relatively inexpensive, and should satisfy the life cycle requirements. The continuous duty application, however, does not offer as clear an option as none of the most attractive contenders have a track record in space. The flywheel approach is promising in that material properties are consistent with long life and independent of depth of discharge. Researchers are

also working to advance competitive Li-ion batteries. The appropriate near term strategy is to assume a flywheel source for the boost operation, but monitor advances in the Li-ion. It appears that both may provide a suitable alternative, providing the security of redundant, but independent, solutions.

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