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Efficiency of an AMTEC Recirculating Test Cell, Experiments and Projections

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ABSTRACT

The alkali metal thermal to electric converter (AMTEC) is an electrochemical device for the direct conversion of heat to electrical energy with efficiencies potentially near Carnot. The future usefulness of AMTEC for space power conversion depends on the efficiency of the devices. Systems studies have projected from 15% to 35% thermal to electric conversion efficiencies, and one experiment has demonstrated 19% efficiency for a short period of time. Recent experiments in a recirculating test cell (RTC) have demonstrated sustained conversion efficiencies as high as 10.2% early in cell life and 9.7% after maturity. Extensive thermal and electrochemical analysis of the cell during several experiments demonstrated that the efficiency could be improved in two ways. First, the electrode performance could be improved. The electrode for these tests operated at about one third the power density of state of the art electrodes. The low power density was caused by a combination of high series resistance and high mass flow resistance. Reducing these resistances could improve the efficiency to greater than 10%. Second, the cell thermal performance could be improved. Efficiencies greater than 14% could be realized through reducing the radiative thermal loss. Further improvements to the efficiency range predicted by systems studies can be accomplished through the development and use of an advanced condenser with improved reflectivity, close to that of a smooth sodium film, and the series connecting of individual cells to further reduce thermal losses.

INTRODUCTION

The alkali metal thermal to electric converter (AMTEC) is being developed at JPL primarily to provide electrical power for robotic spacecraft. In off-planet applications, component mass is a key driver in design. One way to reduce the mass of a power supply for a specified need is to improve the conversion efficiency. AMTEC systems studies have projected thermal to electric conversion efficiencies of 15% to 35%.(1,2) These efficiencies, if achieved in a practical device, would be 3 to 5 times the efficiencies of state of the art static conversion devices currently used on spacecraft such as Voyager and Galileo.(3)

Significant progress has been made in understanding the fundamental processes and performance of AMTEC electrodes. The electrical and electrochemical processes of electrodes with several different compositions are now well known.(4-7) These processes were evaluated in experiments using small electrodes (up to 10 cm^2) in a cell not intended to operate at high efficiency. Recently, we have begun to incorporate this electrode performance understanding into the operation and evaluation of a Recirculating Test Cell (RTC) designed for high efficiency and long life and using a single large area electrode (up to 120 cm^2). In addition to the required electrode performance, the RTC must have good thermal performance in order to achieve high efficiency. This paper describes the results of several RTC experiments and details the electrode and thermal performance of the cell. The experiments have built our knowledge in an evolutionary fashion so that later experiments have performed better than earlier ones. This improvement process still continues, and the paper concludes with projections as to what additional improvements will be required to reach the practical limits of this cell design.

BACKGROUND

The AMTEC is a thermally regenerative electrochemical device for the direct conversion of heat to electrical energy. As shown in Figure 1, AMTEC uses ß" alumina solid electrolyte (BASE) as a separator between liquid sodium (Na$_L$) at 900–1300 K and a low pressure region in which the sodium activity is controlled by a condenser at 400–700 K.(8,9) A sodium activity difference resulting from the pressure difference results in an open circuit voltage of up to 1.5 V between the Na$_L$ and a porous metal electrode (PME) on the low pressure side of the BASE. When current flows, metallic

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sodium is oxidized at the Na_L / BASE interface allowing Na^+ to enter the BASE. Electrons pass through the external load performing work and then recombine with Na^+ at the porous electrode. The Na then vaporizes from the electrode, traverses the vapor space, and condenses at the low temperature region. The Na_L from the condenser is recycled to the hot Na reservoir by an electromagnetic pump or other appropriate method. Through this cycle, the AMTEC essentially converts the work of isothermal expansion of Na vapor directly to electric power with efficiencies potentially near Carnot.[10] AMTEC has many advantages for terrestrial and space power applications including no moving parts with the resulting potential for low maintenance and high durability, efficiency that is substantially higher than other static power systems, modular construction, and the ability to use high-temperature combustion, nuclear, or solar heat sources.

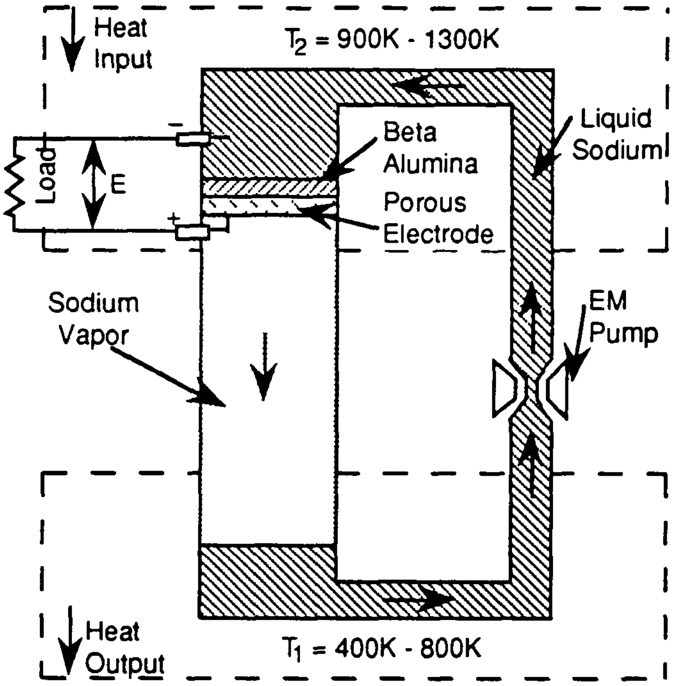

Figure 1: AMTEC Cycle Schematic

High efficiency and high power production from AMTEC cells has been achieved with some success primarily through the AMTEC effort at Ford Motor Company where the AMTEC was also called the Sodium Heat Engine. A short term conversion efficiency of 19% has been demonstrated with a single cell,[11] and in a separate system, a total power of 550 W was drawn from a system with 36 BASE tubes.[12] The Ford effort has now moved to the Environmental Research Institute of Michigan (ERIM). At JPL, we initially focused our effort on characterizing and modeling the electrochemical performance of the cells. About two years ago we began to develop operating cells for long life and high conversion efficiency. Preliminary tests and design details of the RTC have been reported previously;[1,13] the first results from large area electrodes are reported in this paper.

EXPERIMENTAL

The RTC design is similar in geometry to single cells of proposed AMTEC power systems.[2] In particular, the RTC utilizes a cylindrical electrolyte with Na liquid on the interior and a PME on the outside, has a small condenser to BASE diameter ratio, has a high temperature BASE to metal seal, and incorporates an electromagnetic pump for recycling the sodium. The RTC differs from the space systems designs particularly through the use of an electrical resistance heater that is immersed in the Na pool. Using an immersed heater allows simple control of a known heat input.

The PME's on the exterior of the BASE tube are thin films (0.5 to 2 μm thick) of porous RhW or PtW alloys or Mo. A current collecting mesh is tied around the electrodes and attached to electrically isolated feed throughs. An optional heat shield and Cu condenser liner can be used to help reduce thermal losses. The exterior of the condenser is wrapped with a heating tape to allow independent control of condenser temperature.

The RTC has been operated six times with full tube electrodes. The experiments are identified chronologically as FT1 through FT6. The experimental conditions are listed in Table 1. For each experiment, the thermal performance and electrode performance were characterized. Conversion efficiency was calculated as the power output divided by the total power input. Output power was determined by measuring cell voltage and current. The voltage was determined in a three probe configuration using a separate, non current carrying lead to sense the PME potential. Thus, the resistance of the positive lead was bypassed in the power calculation. As is well known from small electrode experiments, the initial performance of the electrodes is better than the mature performance after about 24 hours at high temperature. All reported values are for mature electrodes unless indicated by the phrase "early in life."

Several evolutionary changes were made in the cell with successive experiments. FT4 and later experiments used a new, smaller tube support to minimize conductive losses. This support promoted the development of a more uniform temperature over the length of the electrode which permitted the confident evaluation of electrode performance parameters. The support was further modified for FT5 and later by including a low resistance lead to contact the Na pool. All the experiments used a heat shield. For FT1 to FT3 the shield was a single layer of Mo foil. FT4 and FT5 used a

Table 1: Summary of RTC full tube electrode experimental conditions.

Exp.	Electrode Material	Electrode Area, cm^2	Temp, K	E_{oc}, V
FT1	Rh_3W	118.4	1117	1.066
FT2	Rh_3W	102.2	1071	0.835
FT3	Mo	120.2	1021	0.897
FT4	Mo	86.24	1079	1.400
FT5	Pt_2W	105.0	1097	1.163
FT6	$Pt_{2.4}W$	109.9	1059	0.887

mesh with alternating axial strips of Mo foil. The purpose of this design was to have the advantages of a heat shield (reduced radiation loss) but also to allow Na vapor to pass to the condenser. FT6 abandoned this approach in favor of a multifoil heat shield composed of a 6 layer coil of Mo foil. The layers were separated by strips of W mesh. FT6 also used a new current collector arrangement. Earlier experiments collected current axially along the tube then connected the bus bars together at the top of the electrode. For FT6 the current was collected from the electrode extremities and drawn from the electrode at the center. Additionally, in FT6 twice as many bus bars were used to collect the current, and the Mo mesh current collector and the top electrode surface were coated with a 10 nm layer of Pt to reduce contact resistance.

RESULTS

Table 2 compiles the thermal efficiency and electrode performance results for the six experiments. The experiments typically lasted 200 to 300 hours except for FT4 which operated 851 hours and FT6 which operated only 33 hours. All experiments ended due to BASE tube failure caused at least in part by internal electrical short circuits. These short circuits developed when Na_L bridged a gap between a bus bar and the condenser wall.

Table 2: Summary of RTC full tube electrode experimental efficiencies and electrode parameters.

Exp.	Q_{loss} W/cm^2	η_{max} %	J_c at η_{max} A/cm^2	R_s Ω-cm^2	G
FT1	1.61	7.1	0.279	N/A^c	N/A
FT2	1.61	1.6	0.153	N/A	N/A
FT3	1.26	7.0	0.358	N/A	N/A
FT4	1.74	7.2	0.340	0.62	200
		8.6^a	0.464		
FT5	1.59	6.7	0.286	0.67	100
FT6	0.942	9.5	0.326	0.33	660
		10.2^a	0.197		
		9.7^b	0.344		

a) Early in life, 1031 K for FT4, 1056 K for FT6.

b) FT6 at 1091 K, mature electrode.

c) N/A: Reliable data not are available.

Q_{loss} is the parasitic heat loss in the cell as determined from the power input required to keep the cell at temperature when at open circuit (E_{oc}). Q_{loss} is composed of both the conductive loss and the radiative loss. The conductive loss is estimated from materials properties to be about 30W in the early experiments and 18W in the later ones. The largest portion of Q_{loss} is due to radiation loss.(13)

The maximum efficiency was found experimentally by increasing the current and keeping the cell at constant temperature. Keeping a constant temperature required increasing the heat input (Q_{in}) according to

$$Q_{in} = Q_{loss} + (C_p \Delta T + L_v)\, J_c/F + J_c V_c \qquad (1)$$

where C_p = Na heat capacity, $\approx$28.86 J/mol K

ΔT = Temperature difference between condenser and Na Pool, K

L_v = Na Heat of Vaporization, $\approx$89.07 kJ/mol

J_c = Current Density, A/cm^2

F = Faraday, 96485 C/mol

V_c = Cell Potential, V

Then, the efficiency (η) at any point is determined by $\eta = J_c V_c / Q_{in}$. η_{max} is the maximum efficiency point which occurs at the current density listed in Table 2. Also listed in the table are measurements of η_{max} for two cells during the first few hours at high temperature. This efficiency is higher than the cell efficiency with mature electrodes due to the higher electrode performance typically observed early in life. As the electrode matures over the first 24 hours at high temperature, the performance reaches a steady value.

The cell power requirement usually followed Equ. 1. However, in FT4 subsequent to a vacuum leak, the Q_{loss} apparently increased with current. During current flow in the hours after the leak (and repair) the total thermal loss at 1073 K increased by 80 W as the current was increased from 0 to 30 A (Q_{loss} from 1.8 to 2.7 W/cm^2). Several days later, the increase was not as dramatic; the total thermal loss at 1123 K increased by 32 W as the current was increased from 0 to 35 A (Q_{loss} from 2.24 to 2.61 W/cm^2). An possible explanation for these observations is that the leak resulted in an oxide film on the condenser surface that prevented the condensation of the Na vapor. With few places to condense, the Na pressure increased to a pressure where thermal conduction in the vapor became an important loss. Conduction in the vapor had been ignored because the Na pressures in the vapor region is typically low. However, for higher pressures, the vapor phase conductive loss for the RTC geometry is conservatively estimated to be about 15 W, within the range to account for most of the increased Q_{loss}. At E_{oc} the Na pressure dropped low enough that this conduction mechanism 'turns off.' This conduction mechanism became less important as the oxide was slowly cleaned off of the metal surfaces by the action of the Na; thus, the increase in Q_{loss} decreased with time. The data in Table 2 for FT4 are from before the vacuum leak.

The most efficient RTC operated was FT6. This cell performed well primarily because Q_{loss} was reduced by the multifoil heat shield. The thermal radiation portion of Q_{loss} (Q_{rad}) is ruled by the Stephan-Boltzman equation:

$$Q_{rad} = \frac{\sigma}{Z}\left(T_2^4 - T_c^4\right) \qquad (2)$$

where σ = Stephan-Boltzman constant, 5.67X10^{-12} W/cm^2 K^4

T_2 = Electrode Temperature, K

T_c = Condenser Temperature, K

Z = Radiation Reduction Factor

The Z is a function of geometry and materials emissivities. For FT4 and FT5 with the louvered heat shields, Z was about 7. For FT6 with a 6 layer heat shield, the Z was expected to increase to greater than 30 with emissivities estimated from previous experiments. However, the experimental Z was only 13; the heat shield acted more like a single layer than a multi-layer shield. Two possible explanations for the low Z are being investigated. First, the layers may not have been thermally isolated. The layers may have been touching at enough locations or the Na vapor pressure may have been high enough to make the several layers act like a single layer. Alternatively, a build up of Na-Mo oxides on the inner shield surface may have reduced the reflectivity of this surface and thus the effectiveness of the entire heat shield. A combination of these two effects may also have been present. Still, the heat shield for FT6 was the most effective heat shield used. Future experiments will build on this success and try to improve the heat shield performance.

Of secondary importance to the efficiency of FT6 was the change in electrode performance. Until this cell, no significant changes in electrode performance had been achieved, except for FT2 which performed very poorly due to a too thin electrode over most of the surface. Relative to FT4 and FT5, FT6 had a reduced series resistance (R_s) and an elevated mass transport impedance as monitored by the parameter G. These performance parameters have been described elsewhere.(5,6) In addition to these two parameters, the electrodes from FT4 to FT6 were evaluated to determine exchange current density which fell within accepted values determined from small electrode experiments. Electrode parameters for FT1 to FT3 were not reliably evaluated due to large temperature gradients over the electrode length.

The reduced R_s for FT6 resulted from several evolutionary improvements. R_s is composed of the BASE resistance (R_b), a lead resistance mostly from the negative lead (R_l), the bus bar resistance (R_{bb}), and the contact resistance (R_c). From literature values, R_b is ~0.2 Ω-cm² at these temperatures.(14) R_l and R_{bb} are determined from both materials properties calculations and room temperature measurements scaled to operating the temperature. R_l for FT6 was ~0.22 mΩ X 110 cm² = .024 Ω-cm² which is smaller than R_l for FT5 (~0.34 mΩ X 105 cm² = .036 Ω-cm²).

Since the current is distributed over the electrode surface, R_{bb} is not the total resistance of the bus as determined by cross-sectional area and length. A finite element calculation shows R_{bb} is ~0.011 Ω-cm² near maximum efficiency for FT6. In changing the bus bar arrangement from FT5 to FT6, R_{bb} was reduced by a factor of 8. Doubling the number of bus bar wires reduced R_{bb} by 2, and halving the distance over which current is collected reduced R_{bb} by an additional factor of 4. Thus, in FT5 and earlier, R_{bb} was ~0.09 Ω-cm² or more than 10% of the observed R_s. R_c is the resistance of the electrode/mesh and mesh/bus bar contacts. R_c cannot be determined from materials properties, and room temperature measurements are probably not indicative of high temperature values. For FT6 R_c is estimated to be ~0.1 Ω-cm² by subtracting the known elements from the observed R_s. For FT4 and FT5, R_c is 0.31 to 0.36 Ω-cm². The reduction in R_c was made by using a Pt coating on the electrode and mesh surfaces. Future experiments will investigate this result further.

As large as the reduction in R_s was for FT6, most of the efficiency improvement was washed out by a very large G. G is a dimensionless measure of the mass transport impedance for Na flow through and away from the electrode. State of the art, small area electrodes have G values from 10 to 50.(5,6) Since G values are intensive and the electrodes were identical in composition and structure to small electrodes, the additional magnitude of G is probably due to the presence of the heat shield. Comparing FT4 and FT5 with FT6, the mesh heat shield (used in FT4 & FT5) successfully permitted Na vapor flow to the condenser. When this pathway was blocked by the solid shield in FT6, G increased dramatically. A G of 660 corresponds to a pressure drop of 96 Pa which is about the pressure drop expected for continuum flow in a channel the size of the Na vapor flow path to the condenser.(15) The multifoil heat shield is apparently necessary in this RTC for good thermal performance. Future experiments will use a larger gap between the electrode and heat shield to try to achieve a smaller G.

PERFORMANCE PROJECTIONS

None of the full tube electrode RTC experiments to date have combined both good electrode performance and good thermal performance. Table 3 lists the performance possible with the improved (or new) conditions listed under the same operating conditions listed in Table 1. The parameters are those thought possible for the experimental conditions. For FT6 which already had a very low R_s, an improved G alone would increase the efficiency to greater than 12%. Additional efficiency improvement to almost 14% would be possible with a Q_{loss} reduction to 0.8 W/cm².

Table 3: Summary of projected RTC performance with improved electrode and thermal performance under the same operating conditions listed in Table 1.

Exp.	New R_s Ω-cm²	New G	Calc η_{max}^a %	New Q_{loss} W/cm²	Calc η_{max}^b %
FT4	0.35	48	10.4	1.00	14.0
FT5	0.58	50	7.7	0.77	12.5
FT6	0.33^c	50	12.4	0.80	13.7

a) With improved electrode performance only.

b) With both improved electrode and thermal performance.

c) No change from experimental value.

An efficiency of 14% is probably the practical limit for the current RTC design when operated in the temperature range of these experiments. Current state of the art electrodes, if they can be operated in large areas, appear to be sufficiently powerful and durable to produce even greater efficiencies. The limit appears to be the thermal performance. Conductive losses have been minimized in the design, but radiation losses still dominate. In order to further reduce Q_{loss} and not suffer the electrode performance degradation associated with heat shield and remote condensing, a much more reflective condenser must be developed. Creare has proposed such a condenser design.(16) If successful, this condenser will maintain a smooth, 98% reflective Na film on the condenser surface. A 98% reflective surface, even without a heat shield, would reduce the radiation loss by a factor of 2 below the best achieved with a heat shield. This would allow a further increase in the cell efficiency. Once radiation losses have been minimized, conduction losses (Q_{cond}) can be further reduced to improve efficiency. One obvious method to reduce Q_{cond} is to use a hot feed through. Most systems designs require a hot feed through to reduce losses, but a hot feed through is not currently available.

As seen from the evaluation of the experimental cells, the three critical parameters for cell efficiency are R_s, G, and Q_{loss}. Figures 2 to 4 plot the calculated efficiency change with the independent variation of each of these parameters. The measured performance of the experimental cells is also plotted. The calculated lines are not intended to model the experimental values but are estimates of the best practical conditions for RTC operation.

The common parameters used for the calculation of RTC performance are:

Electrode area:	100	cm^2
Electrode Temperature:	1100	K
Exchange Current Density:	21.7	A/cm^2
Condenser Temperature:	535	K
Open Circuit Voltage:	1.1	V
BASE Thickness:	1.2	mm

Figures 2 to 4 show that if two of the three parameters are near optimum values, then the efficiencies greater than 10% can be achieved. FT6 is a demonstration of this result. Efficiencies greater than 15 % and as high as 20% can be achieved if Q_{loss} is reduced to less than 0.7 W/cm^2 including a conductive loss of 0.18 W/cm^2.

CONCLUSIONS

The JPL AMTEC Recirculating Test Cell has been operated using full tube electrodes with a goal of high efficiency, long life operation. One cell ran for 850 hours and another cell demonstrated 10.2% thermal to electric conversion efficiency early in life and 9.7 % after maturity. Evolutionary design changes have allowed lifetime and efficiency increases to be demonstrated. We anticipate further lifetime and efficiency improvements as our understanding and capabilities are refined. Modeling based on actual performance shows that efficiencies as high as 14% can be achieved in this cell with good electrode and thermal performance. With significantly improved condenser reflectivity, efficiencies as high as 20% may be achieved. In addition to demonstrating AMTEC performance capabilities, RTC operation is

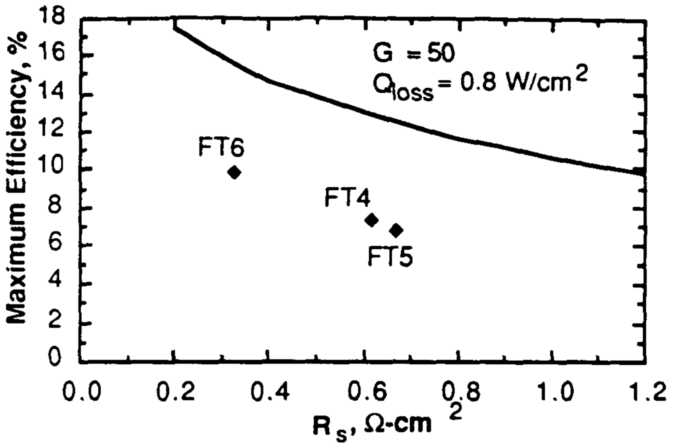

Figure 2: Variation of cell conversion efficiency with series resistance while holding G and Q_{loss} constant. Experimental data points are also included. The curve does not model of the experimental results but an example of the possible improvements.

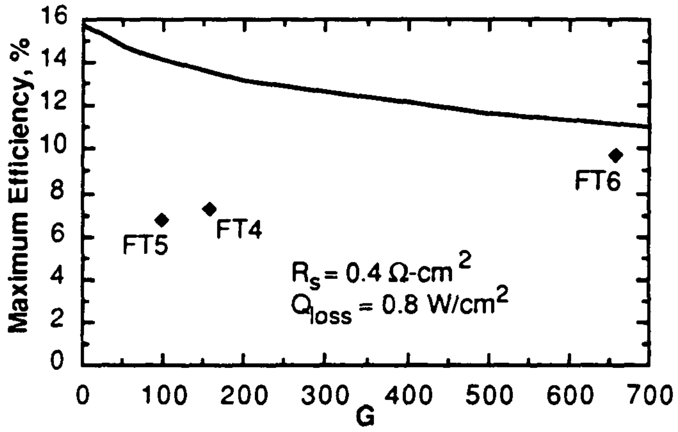

Figure 3: Variation of cell conversion efficiency with mass transfer parameter G while holding with R_s and Q_{loss} constant. Experimental data points are also included. The curve does not model of the experimental results but an example of the possible improvements.

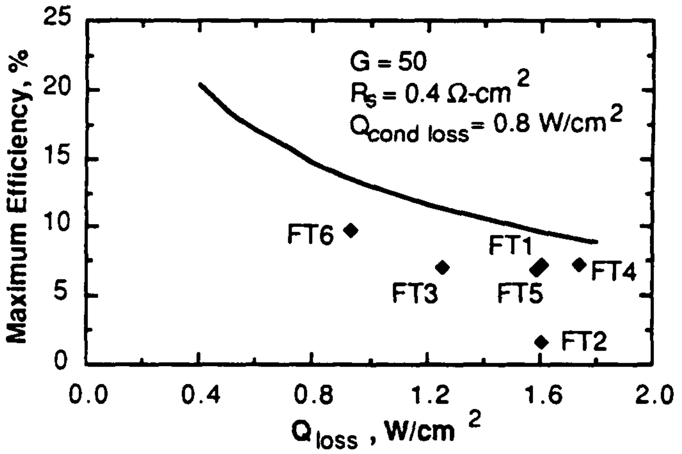

Figure 4: Variation of cell conversion efficiency with total thermal loss while holding with R_s and Q_{loss} constant. Experimental data points are also included. The curve does not model of the experimental results but an example of the possible improvements.

providing insight and a data base for design and modeling of advanced cells that will meet the needs of future spacecraft.

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