

## SYSTEM LEVEL ELECTROCHEMICAL PRINCIPLES

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### INTRODUCTION

The high power applications that are appearing on the horizon will require a considerable change in the approach taken in spacecraft design. This is particularly true in the area of energy storage. These projected applications are not only seen to require higher voltages and powers but coincidentally will require higher heat rejection rates. For many years the function of energy storage was to make up for the dark portion of the orbit when the solar array could not supply the required power. This meant that a few hundred watts were required for periods of time up to 1.2 hours at a voltage level of about 28 volts. In the past few years the power requirements have increased to where several kilowatts are now required during the dark portion. Some of the projected applications will not only require significant increases in the power but the energy storage function may be used to supply peaking power during light as well as dark portions of the orbit. Copper loss considerations will dictate the use of significantly higher operating voltages; possibly in the range of 100 to 200 volts as the output of the energy storage device. As the power requirements are increased, the heat rejection requirement will also increase.

Traditionally, batteries are made up of series connected strings of individual elements called cells. These cells are usually individually monitored and may be individually controlled. Heat may be rejected passively by judicious placement in selected locations within the spacecraft or semiactively by being placed upon a cold plate. The heat rejection requirements limit the peak power outputs of traditional batteries to a greater degree than the actual electrochemistry. The adverse effects on cell life caused by operation at elevated temperatures has the effect of restricting the maximum rates of power output to rather modest levels. Aside from the limitations related to rates of power that can be withdrawn, the energy density of the more traditional batteries based on nickel-cadmium or IPV nickel-hydrogen cells place an upper limit on the size of the energy storage system. This is a consequence of total launch capability of the current or future space transportation system. To meet this challenge presented by high power application, several alternative energy storage concepts are being considered. Figure 1 depicts a generic overall system for such an application. The size of the solar array and the radiator are functions of the operating characteristics of the energy storage and power conditioner characteristics. Since this short paper is to consider the energy storage portion of the overall system, the power management and distribution portion with its own temperature and efficiency characteristics will not be considered.

The size of the solar array (per unit of power out of the storage subsystem) will depend upon the round-trip efficiency of the storage portion of the power system. In like manner the size (weight) of the radiator will be very much a function of the operating temperature of the storage device. The usual figure of merit of a storage device is its energy density (Whr/Kg). Another very important characteristic of a storage device is its power density (W/Kg). These numbers can be misleading when comparing one device against another. The most meaningful number is related to the entire system. It is only as the power system is considered as a whole can different devices and technologies be properly compared. Overall system weights would be favored by a high round trip efficiency device to reduce the solar array areas as well as by a high heat rejection temperature to reduce the weight associated with the radiator.

It is only fair to point out that storage systems based on non-electrochemical devices are currently being considered for these more advanced, higher powered missions. The major problems associated with traditional battery concepts that are based on the connecting together of series strings of individual cells are related to difficulties in maintaining intercell and/or intracell balance of the state of charge of the active materials within the cells. The challenges are being presented by concepts based on flywheels, solar dynamic systems, as well as newer electrochemical concepts. So besides abandoning electrochemical concepts entirely, there are several suggested solutions to this problem that are being investigated. Electronic sensing and control of the grouping of cells is a very attractive approach that has reached a high degree of sophistication. Cell sensing, control and switching; charge protocols; reconditioning techniques; etc. might be viewed as an electrical engineer's approach to the problem. This paper will confine itself to electrochemical concepts and principles, and within that framework, suggest ways of addressing the problem. Electrochemical approaches to this problem have addressed the use of active materials that are more amenable to electrochemical rebalancing techniques (sometimes called reconditioning) as well as the more recent approach of using electrochemistries that lend themselves to the common storage of reactants as fluids. These fluids are common to all the cells of a separate power producing assembly of electrochemical cells. The regenerative fuel cell (RFC, Ref. 1) is an example of this type of storage system which might truly be called an electrochemical system.

#### BATTERY PACK APPROACHES

Table 1 represents one way of classifying the single cell electrochemistries that have found various degrees of acceptance for aerospace applications. Also noted in this table is a nonexhaustive list of difficulties that have been associated with batteries made from groupings of these cells or simply cells by themselves. Common to all but sodium sulfur batteries is the problem of the gradual dispersion of the intercell and intracell electrochemical capacities of the individual cells caused by a certain degree of randomness associated with the charge and discharge efficiencies among the cells. Sodium

sulfur cells experience their own type of capacity dispersion resulting from the stochastic nature of the individual cell resistance. One of the apparent attractive features of the nickel hydrogen electrochemistry is the ability to safely overdischarge the cells. By comparison, nickel cadmium cells can not tolerate a very high rate of overdischarge (possibly  $c/20$ ), Ref. 2. Antipolar mass, signal electrodes, reconditioning cycles are all words associated with the art of keeping a multi-cell battery in proper balance and to correct for the cumulative effects of very minor differences among cells within a battery pack. An alternative approach to keeping all of the cells in balance is to use fluids as the reactive materials and have these fluids be common to all the cells of the battery. These devices tend to be somewhat more complicated than traditional battery packs. They will be referred to as electrochemical systems.

### ELECTROCHEMICAL SYSTEMS

As a point of clarification, Figure 2 describes very briefly three different classes of batteries. On the top is illustrated the traditional type of battery where a cell string is placed in contact with a cold plate. In the center of that figure is illustrated a fully contained battery where an actively cooled stack of cells is employed. At the lower part of the figure a battery is illustrated where the actively cooled cell stack and the storage portions of the complete system may be treated somewhat independently. The stack of cells, complete with internal cooling passages, can be sized in terms of cell area and number of series connected cells to best meet the load requirements. In like manner, storage tanks for the electrochemical reactants are sized according to the requirements of the particular mission.

The use of active cooling is new to the more traditional battery industry but let the electrochemical aspects of these latter two battery concepts be described in more detail before that aspect is covered. Figure 3 is a simplified schematic of an RFC. It is seen that in reality it consists of a water electrolysis section and a fuel cell section along with the water storage and gas storage portions of the system. In principle, one cell (or stack of cells) could be used for both the charging portion (electrolysis of water) and discharging portion (consumption of hydrogen and oxygen) of the cycle. Then it would more closely resemble the type of cell it is meant to replace; namely, the more traditional type of cell wherein the active materials are contained in a completely sealed container. The containment of the reactive materials is a significant difference between the more traditional electrochemical cell and the RFC. It should be obvious that they both perform the function of a rechargeable electrochemical cell. This difference becomes more evident when one makes the transition between thinking about a single cell and thinking about a multicell battery. With the more usual battery, it is made up of a number of individual units each containing a sealed set of active materials. The fuel cell battery is also made up of a number of individual cells. The reactants however, being fluids, are stored in a common set of tanks; one containing all the hydrogen and the other all the oxygen. Storage of reactants in this manner permits all of the cells to always be at the same state of charge.

Another significant difference exists between RFC and traditional batteries. This is related to the method that groups of cells are assembled together to form the battery. Traditional cells being completely independent entities are wired together electrically, binding post to binding post. Fuel cells and water electrolysis stacks are grouped together in a more or less integral manner with appropriate manifolds for the distribution or collection of the gases and liquids. Since the reactant gases are stored outside of the stack of cells, the cells themselves are rather thin. This facilitates the interleaving of coolant plates in among the electrochemical cells. Usually a dielectric material serves as the heat transfer medium. It is hard to say whether the use of active cooling techniques or the commonality of reactants are the most significant difference between the RFC concept and the traditional battery pack.

Although a hydrogen oxygen RFC was used as an example in describing a large actively cooled bipolar battery, there is ongoing research and development being carried out on other electrochemical systems as well. Hydrogen bromine and hydrogen chlorine are examples of concepts where the storage portion of the system and the power producing portion of the overall system can be independently sized. Bipolar nickel hydrogen battery systems (Ref. 3) represent an example of a fully contained actively cooled electrochemical system. In this case the hydrogen is common to all the cells whereas the nickel oxide cathode material is unique to each individual cell. The special attributes of these actively cooled bipolar batteries can be summarized as follows: 1) In the case of the fully decoupled power section and storage section ( $H_2-O_2$ ,  $H_2-Br_2$ ,  $H_2-Cl_2$ ) cell to cell capacity dispersion can be eliminated, 2) active cooling permits scaling up or down in cell size without undesirable consequences upon the thermal characteristics of the basic electrochemical cell, 3) active cooling permits a very wide range of peak and base power output, 4) the cell-to-cell stochastic characteristics that result in capacity dispersion and performance decay can be designed for as part of the battery design process. It is probably this last point that may be the one that is most difficult to understand, comprehend, and internalize, yet at the same time, it may well be the most significant.

Capacity dispersion usually stems from competing electrochemical reactions that take place on recharge. The nickel electrode, for example, evolves oxygen during recharge at a rate that depends on the type of additive in the nickel electrode, the state of charge, the temperature, the current density and possibly other factors. During any one recharge, the oxygen evolved will most likely be a random variable that causes the individual cell capacities to diverge. This divergence can be corrected for by using a reconditioning cycle in the case of traditional IPV nickel hydrogen cells or nickel cadmium cells. In the case of the electrolysis of alkaline (KOH) or hydrobromic acid (HBr) solutions, the contribution from spurious side reactions is all but nonexistent. In the case of large bipolar nickel hydrogen devices techniques as described in reference 4 address that system. In brief, cell designs are described that render the battery less susceptible to minor cell to cell

variations. The design of the cell and battery components in regard to pore size, pore size distribution, chemical compatibility, compression strength, etc. is very important to minimize the performance decay phenomenon that take place during operation. By more fully understanding these processes, certain design modifications can be made.

#### SUMMARY

In summary, it can be stated that the traditional electrochemical storage concepts are difficult to translate into high power, high voltage multikilowatt storage systems. The increased use of electronics, as well as the use of electrochemical couples that minimize the difficulties associated with the corrective measures to reduce the cell to cell capacity dispersion, have already been adopted by battery technologists. However, these concepts can become quite complicated and heavy. Actively cooled bipolar concepts are described which represent some attractive alternative system concepts. In general, they are projected to have higher energy densities lower volumes than current concepts. Furthermore, they should be easier to scale from one capacity to another and most definitely will have a closer cell-to-cell capacity balance. These newer storage system concepts will be easier to manage since they are designed from the start to be a fully integrated battery. Grouped together, these ideas are simply referred to as system level electrochemistry. The hydrogen-oxygen RFC is probably the best example of the integrated use of these principles. These principles in part should be recognized to be to a certain degree ex post factor from the perspective of people familiar with fuel cell technology while at the same time they may appear to be somewhat avant-garde from the point of view of one steeped in the details of single cell electrochemical technology.

#### REFERENCES

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Table 1

DIFFICULTIES WITH SPECIFIC ELECTROCHEMISTRIES AS THEY RELATE TO MULTICELL BATTERY PACKS

	NICKEL HYDROGEN	NICKEL CADMIUM	SILVER HYDROGEN	SILVER CADMIUM	SILVER ZINC	SODIUM SULFUR (350° C)	LITHIUM IRON SULFIDE (450° C)
CELL TO CELL CAPACITY DISPERSION	×	×	×	×	×		×
POOR OVERDISCHARGE CHARACTERISTICS		×		×	×	×	×
POOR OVERCHARGE CHARACTERISTICS					×	×	×
INDIVIDUAL CELL CONTROL REQUIRED					×		×
CADMIUM MIGRATION		×		×			
SILVER SOLUBILITY			×	×	×		
SHAPE CHANGE					×		
RANDOM SOFT SHORTS						×	×

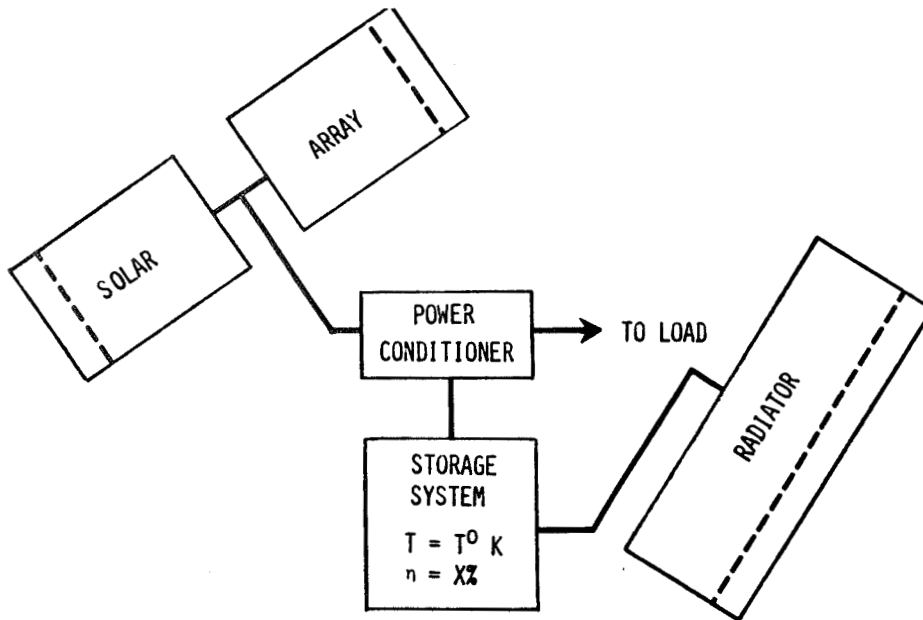


Figure 1. Components of a Large Space Power System

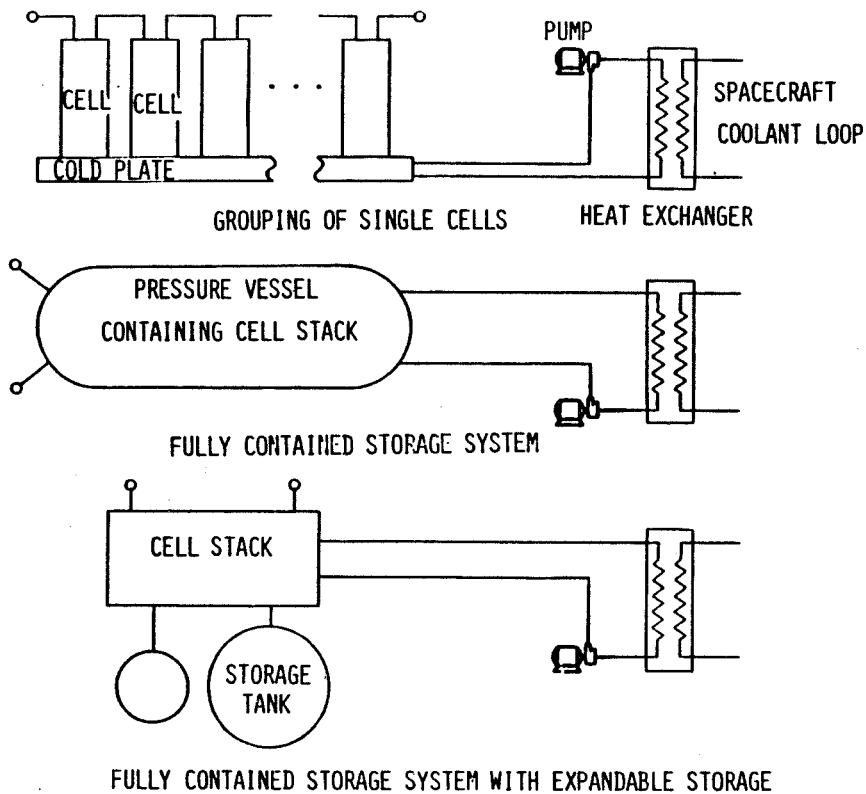


Figure 2. Three Different Classes of Electrochemical Storage Systems

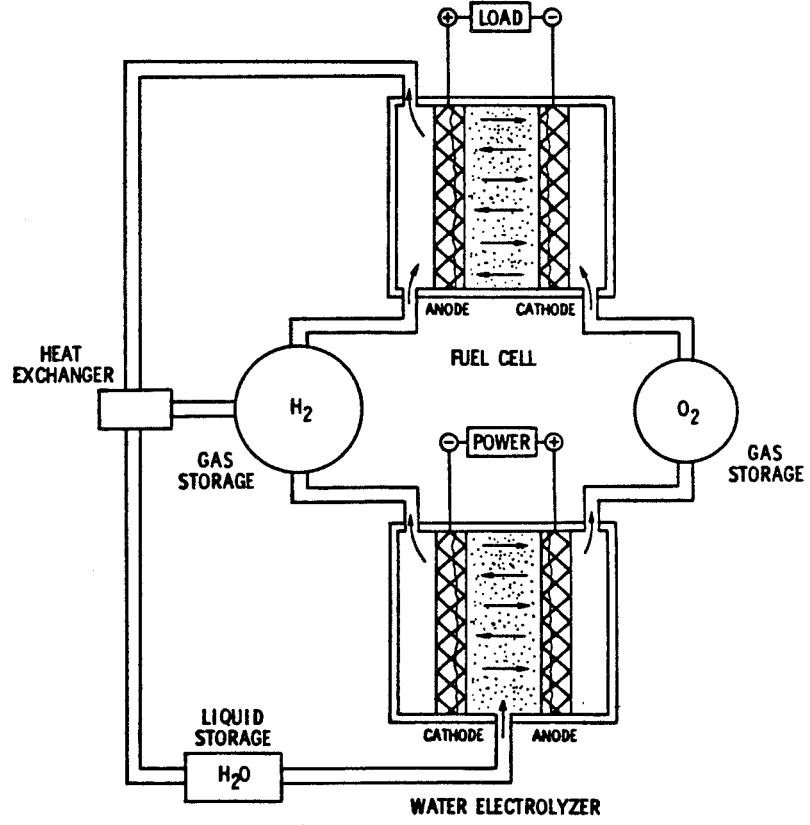


Figure 3. Schematic Diagram of a Hydrogen Oxygen Regenerative Fuel Cell