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EFFECT OF NASA ADVANCED DESIGNS ON THERMAL BEHAVIOR OF $Ni-H_2$ CELLS

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ABSTRACT

As part of an overall effort to advance the technology of nickel-hydrogen batteries for low earth orbit (LEO) applications, advanced designs for individual pressure vessel (IPV) nickel-hydrogen cells have been conceived. These designs incorporate alternative methods of oxygen recombination which affect the thermal behavior of the cells. The effect of these oxygen recombination methods on the cell temperature profiles will be examined.

INTRODUCTION

There is a need for higher power, lighter and longer-lived flight battery systems. Nickel-hydrogen ($Ni-H_2$) systems can provide significant improvements over nickel-cadmium (Ni-Cd) systems, which have been predominantly used in spacecraft to date. $Ni-H_2$ advantages over Ni-Cd include a greater depth-of-discharge (DOD) capability resulting in a high energy density, longer life and greater tolerance to overcharge and overdischarge. Present individual pressure vessel (IPV) $Ni-H_2$

cell designs are adequate for geosynchronous (GEO) applications, but not for low earth orbit (LEO) applications due to limited cycle life. NASA Lewis has evaluated the standard IPV Ni-H_2 cell design and developed design modifications which should increase the cycle life at deep depths of discharge. Existing technology has been retained where possible.

In order to achieve a substantial energy density advantage, the Ni-H_2 system must be operated at a deeper DOD than Ni-Cd. This creates some difficulties in dealing with thermal and electrolyte management in the cells due to the higher charge and discharge rates and the passive (conductive) rejection of waste heat. Failure to accomplish uniform heat distribution can lead to electrolyte redistribution and evaporation problems, local decreases in efficiency and difficulties with uneven current density. Proper thermal control improves charge/discharge efficiencies and is essential to achieve the necessary long life for LEO.

Electrolyte and thermal management are related to each other because temperature gradients throughout the cell can result in water and/or electrolyte movement from hot to cold locations within the pressure vessel. This will lead to performance differences due to flooding and/or drying which can in turn aggravate the thermal problems. In addition to electrolyte redistribution, high energy releases from oxygen recombination with hydrogen might damage the catalyst in the hydrogen electrode (Ref. 1). Oxygen is present as a product of a side reaction in the nickel electrode during charge. Localized hot spots can result from rapid and uncontrolled oxygen recombination and cause short circuits (Ref. 2). Since the Ni-H_2 cells rely on conductive heat transfer from the stack to the pressure vessel, it is important to examine the actual operating temperature and temperature gradients associated with the several cell design modifications.

In addition to the advanced oxygen recombination techniques, several other design modifications were incorporated into the advanced designs. They will be considered in this paper only as they relate to the thermal response of the cells. The reader is directed to previously published material for a detailed description of the modifications and their effect on life (Ref. 3).

IPV Ni-H_2 DESIGNS

The IPV Ni-H_2 cell consists of sets of parallel-connected positive (Ni) and negative (H_2) electrodes which are physically interleaved in a stack and contained at high pressure in an inconel pressure vessel (Fig. 1). In the cell stack, nickel and hydrogen electrodes are kept apart by separators and gas screens. These provide electrolyte and gas access to the electrodes, respectively. The cell stack is kept under mechanical compression and in contact with the containment vessel, the inner surface of which is coated with zirconium dioxide. The coating forms a wick through which the electrolyte can recirculate to the stack by means of the separators.

The most widely used Ni-H_2 design for LEO applications is the Air Force/Hughes design. Figure 1(a) shows a schematic of this "recirculating" design. In this design the nickel electrode is isolated from the adjacent hydrogen electrodes by a gas screen on one side and by a separator on the other. This allows recombination of oxygen directly at a hydrogen electrode after diffusion through the gas screen. Since the oxygen produced in one pair of electrodes is recombined at the hydrogen electrode of the adjacent pair, this results in a very gradual electrolyte transfer from one end of the cell stack to the other. In the case where a permeable (low bubble pressure) separator is used, concentrated oxygen build up can bridge directly to it's own hydrogen electrode causing "popping", a rapid recombination reaction that can result in sintering of the hydrogen electrode catalyst and excessive heating.

The two designs alternatives differ from each other and the Air Force design in their methods of oxygen recombination. Other design modifications incorporated in the advanced designs are an expandable stack, serrated separators, in some cases a reduced KOH concentration, and a back-to-back design. Both designs rely on the use of a high bubble pressure separator to prevent the oxygen from directly recombining in the hydrogen electrode. Figure 1(b) illustrates the component arrangement of a recombination unit cell. It is considered to be a back-to-back design since electrodes of the same kind face each other across a gas screen. In the case of the nickel electrode this results in the oxygen produced during charge being diverted to an alternative recombination surface rather than to a hydrogen electrode. In this particular design the oxygen is directed to a recombination unit (a catalyzed surface) which is placed between the nickel electrodes. This assures that the oxygen will recombine at the alternative site and not at the working hydrogen electrode. The water produced will return to the nickel electrodes in the form of water vapor and condense there. Even though this design proves effective in reducing the risk of catalyst sintering it also increases cell weight and volume. Since the design is relatively simple to implement, the advantages and disadvantages should be weighed for each particular application.

In the second alternative design studied, the recombination site is situated at the pressure vessel inner wall. This has two advantages: (1) heat is generated directly on the wall from which it is readily removed; and (2) the hydrogen electrode is protected from any possible catalyst sintering. A schematic is shown in Fig. 1(c). In this design, oxygen evolved in the nickel electrode during charge diffuses along the back surface of the electrode to the wall and recombines on the catalyzed surface. As in the previous case a high bubble pressure separator must be used. The water formed by the recombination reaction will return to the stack by means of the wall wick and separators and by vapor transfer due to concentration and thermal gradients.

THERMAL MODEL

Heat is produced in the Ni-H_2 cell both during the charge and discharge portions of the cycle. During the charge portion it is mostly due to the recombination of oxygen gas evolved at the nickel electrode. The reaction of oxygen recombination is highly exothermic. Recombination mainly occurs during the last portion of charge and during overcharge.

The goal of thermal investigations is to compare alternative designs in terms of their ability to prevent harmful increases in cell temperature, localized hot spots, and temperature differentials which contribute to electrolyte maldistribution. In order to analyze transient temperature performance it is first necessary to estimate heat generation rates during a complete cycle or orbit. Since the cell design modifications will most significantly affect the thermal behavior during oxygen evolution, the cells instantaneous heat generation during charge was simulated closely using a modified Budder curve for oxygen generation (Ref. 4). A constant (time-average) heat load was assumed during discharge. A charge/discharge ratio (C/D) of 1.1 was used on a 90 min LEO orbit at 80 percent DOD. The 10 percent additional charge was applied uniformly through the entire charge period. The instantaneous heat generation rate was calculated using Eq. (1), on charge:

$$R = -(I_C - I_e)(E_H - V) + I_eV \tag{1}$$

where

I_C total charge current

I_e current used for oxygen generation
(calculated using the modified Budder curve)

V operating voltage

E_H thermoneutral voltage, 1.51 V.

It was assumed that the rate of heat generation due to oxygen recombination is equivalent to the instantaneous rate of oxygen formation. An electrolyte concentration of 31 percent KOH was assumed and enthalpy changes of the stored hydrogen were disregarded. The voltage values assumed throughout the charge were typical for cells with asbestos separators operating according to the LEO regime. For the discharge part of the cycle an average thermal load was calculated using Eq. 2:

$$R = -I_d \, (E_H - V) \qquad (2)$$

where

I_d discharge current

V operating voltage, $V_{avg} = 1.2$ V

E_H thermoneutral voltage

CELL MODELING

Once the thermal loads were estimated, the actual modeling of the response was performed using a finite element analysis computer code (MARC). The inputs to the program include the model geometry, component material properties and heat loads. The properties for each component were calculated based on their material composition and were assumed to be the same in both the radial and the axial directions. Values for the component properties can be found in the literature (Ref. 2). A sample of the cell node and element representation is shown in Fig. 2 for the Air Force design. The cell components have an annular shape so that the assembled stack has a hollow axial core, through which electrode leads can be drawn. Similar representations were used for the other two designs. A single repeating unit at the center of a stack was used for comparison purposes. The outside of the pressure vessel was assumed to be kept at a constant temperature of 10 °C and all heat transport was by conduction. Although some convection is expected, its effect on the total thermal performance is minimum (Ref. 5) and is therefore not considered in the analysis. Additional thermal dissipation paths such as the power leads and axial conduction were also disregarded; therefore actual cell temperatures are expected to be lower than the calculated values. The heat due to resistive losses was assumed to be generated uniformly through the cell components; the heat of recombination was evolved at the specialized recombination site, or the surface of the hydrogen electrode, depending on the particular design being studied.

DISCUSSION

Figure 3 represents the temperature at the inside diameter of the nickel electrode for each design. Calculations for the Air Force design are consistent with previous data where inside temperatures were reported (Ref. 2). The results showed that the end of charge temperature in the advanced catalyzed wall design remains low while the Air Force design sees a sharp increase in temperature and the recombination unit cell falls in between. The sharpest increase in temperature occurs at the inside diameter of the stack (nickel electrode) and can be as high as 14 °C for the Air Force design and as low as 2 °C for the catalyzed wall design. At the operating conditions of the Ni-H_2 cells, temperature gradients on the order of 6 to 10 °C are sufficient to cause electrolyte redistribution due to vapor pressure effects. Figure 3 also indicates what would be the thermal response of the cells if charge were continued for another 6 min. In applications where overcharging has a high probability of occurring or where prolonged periods of trickle charging are required, the advanced designs will definitely improve both the performance and life of the cells.

Temperature gradients radially across the face of the electrode were also investigated. Figure 4 represents a typical 0.9 hr charge at the LEO rates for the Air Force design, since it experienced the highest temperature gradients. As expected, the highest temperature is located at the inner diameter of the electrode. There is approximately a 10 °C gradient from the inner to the outer diameter of the electrode for this particular design. It can be seen that the cell cools through most of the charge portion of the cycle, since the charge process is endothermic up to 0.6 hr when the oxygen evolution is increased drastically.

Several cycles were also simulated to determine the temperature profiles of the cells for the three designs, after the temperature transient from the start-up at 10 °C. The results are shown in Fig. 5. From this figure it can be seen that the maximum operating temperature in all cell designs occurs at the end of discharge, and not at the end of charge, as long as the cell is not overcharged. Heat is absorbed during the early part of charge. The catalyzed wall cell is the coolest during charge because the heat is evolved directly at the pressure vessel wall. The two advanced design cells always operated from 1 to 5 °C cooler than the Air Force designs. It is also seen that the period of time that the cells spent at the high temperatures is less for the advanced designs, reducing their average operating temperature. This minimizes the risks of electrolyte movement in the cell, increases cell efficiency and should extend cycle life.

CONCLUSIONS

The mathematical analysis would suggest that the new NASA Lewis advanced Ni-H_2 cell designs would be effective in reducing the overall temperature of the cell. The designs also provide protection for the damage that could be caused by overcharge. This is in addition to the accommodation of other failure modes such as nickel electrode expansion, possible catalyst sintering, and cell dry-out. Calculations for the Air Force design agree with previously published data, lending confidence to the calculations and their indication that the advanced designs do improve the cell thermal control. The effect on the performance and the cycle life of the cells will have to be demonstrated by actual cell testing. It is expected that both the performance and life will increase due to increased efficiency and the elimination or alleviation of present failure mechanisms.

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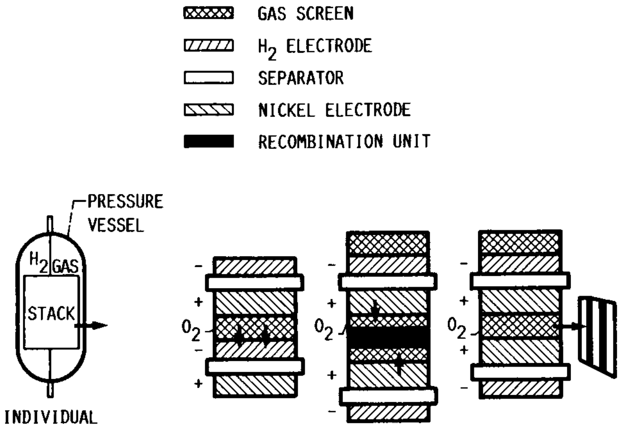

INDIVIDUAL PRESSURE VESSEL CELL

(A) RECIRCULATING AIR FORCE STACK.

(B) RECOMBINATION UNIT.

(C) CATALYZED WALL STACK.

FIGURE 1. - INDIVIDUAL PRESSURE VESSEL STACK DESIGN CONFIGURATIONS.

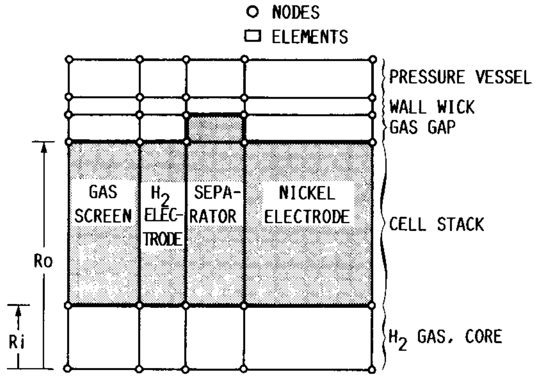

FIGURE 2. - AIR FORCE DESIGN REPEATING UNIT, FINITE ELEMENT MESH. (NOT TO SCALE.)

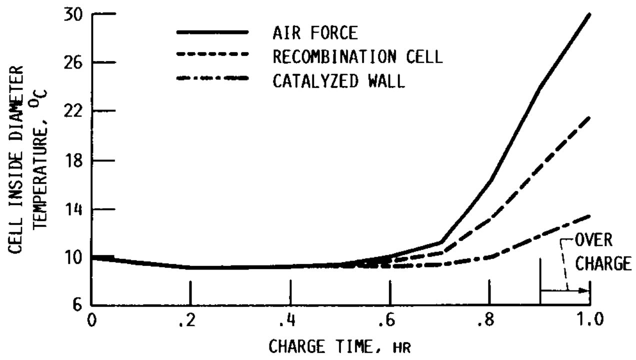

FIGURE 3. - NICKEL ELECTRODE TEMPERATURE FOR A LOW EARTH ORBIT CHARGE RATE AT 80% DEPTH OF DISCHARGE.

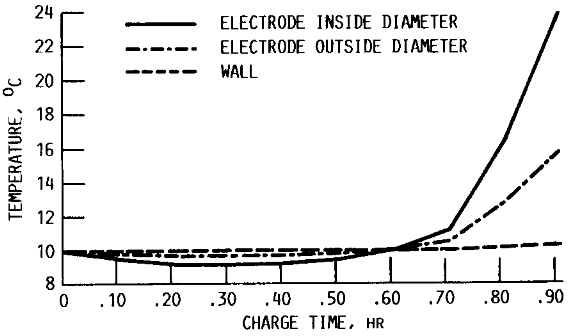

FIGURE 4. - AIR FORCE INDIVIDUAL PRESSURE VESSEL CELL TEMPERATURE PROFILE.

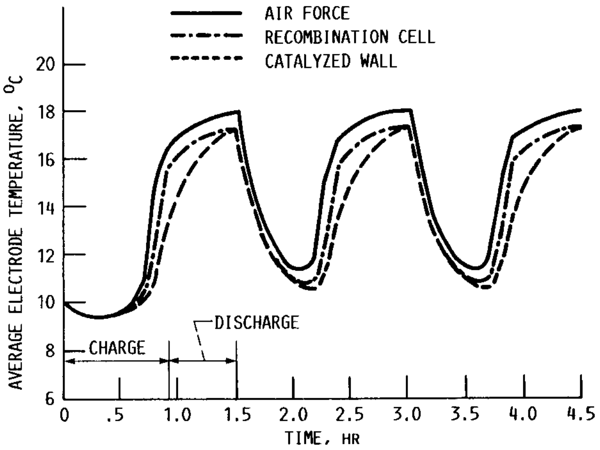

FIGURE 5. - THERMAL PERFORMANCE OF INDIVIDUAL PRESSURE VESSEL NICKEL/HYDROGEN CELLS FOR THE LOW EARTH ORBIT RATE AT 80% DEPTH OF DISCHARGE.

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