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Nickel-Hydrogen Battery Fault Clearing at Low State of Charge

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BACKGROUND

- **Battery fault clearing requires high rate, short duration discharges.**
- **Spacecraft batteries may be at low state of charge when a fault occurs, e.g., during reconditioning discharge to 1.0 volt per cell in a single battery power subsystem architecture.**
- **There is little relevant data available for this operating mode.**
- **Accordingly fault clearing data was obtained experimentally.**
- **The scope of the effort reported here includes determination of nickel-hydrogen battery fault clearing capability at low state of charge and comparison with capability at high state of charge.**

Battery fault clearing requires high rate discharges for a short periods of time. Fault clearing events are assumed to consist of fuse blowing and durations are typically a few milliseconds. Faults can occur at any time and battery state of charge can vary from full to very low state of charge. For example, a fault occurring at the end of a reconditioning discharge, to 1.0 volt per cell, in a single battery system, could require the fault to be cleared with little faradaic capacity in the battery.

Battery operating data describing short duration high rate discharge at low state of charge is not available. Accordingly a relevant data base was determined experimentally. Fault clearing data was obtained at high and low states of charge.

APPROACH

- Fault clearing events are simulated by 3-millisecond discharges into resistive loads.
- The resistive loads are sized to provide data in the range C/2 to 3C.
- All testing is performed at 10° C.

The experimental approach includes several assumptions and constraints.

Fault clearing events are simulated by 3-millisecond discharges into resistive loads. Fuse blowing generally occurs in less than 3 milliseconds and the load presented to the battery is closely approximated by a constant resistance.

The resistive loads are sized to provide data in the range C/2 to 3C (75 to 450 amperes with the 150 ampere-hour nickel-hydrogen cells used). This range provides a broad and conservative data base.

All testing is performed at 10°C. This is a "typical" battery operating temperature. A single temperature was considered adequate because fault clearing capability is a weak function of temperature over the usual spacecraft operating temperature range.

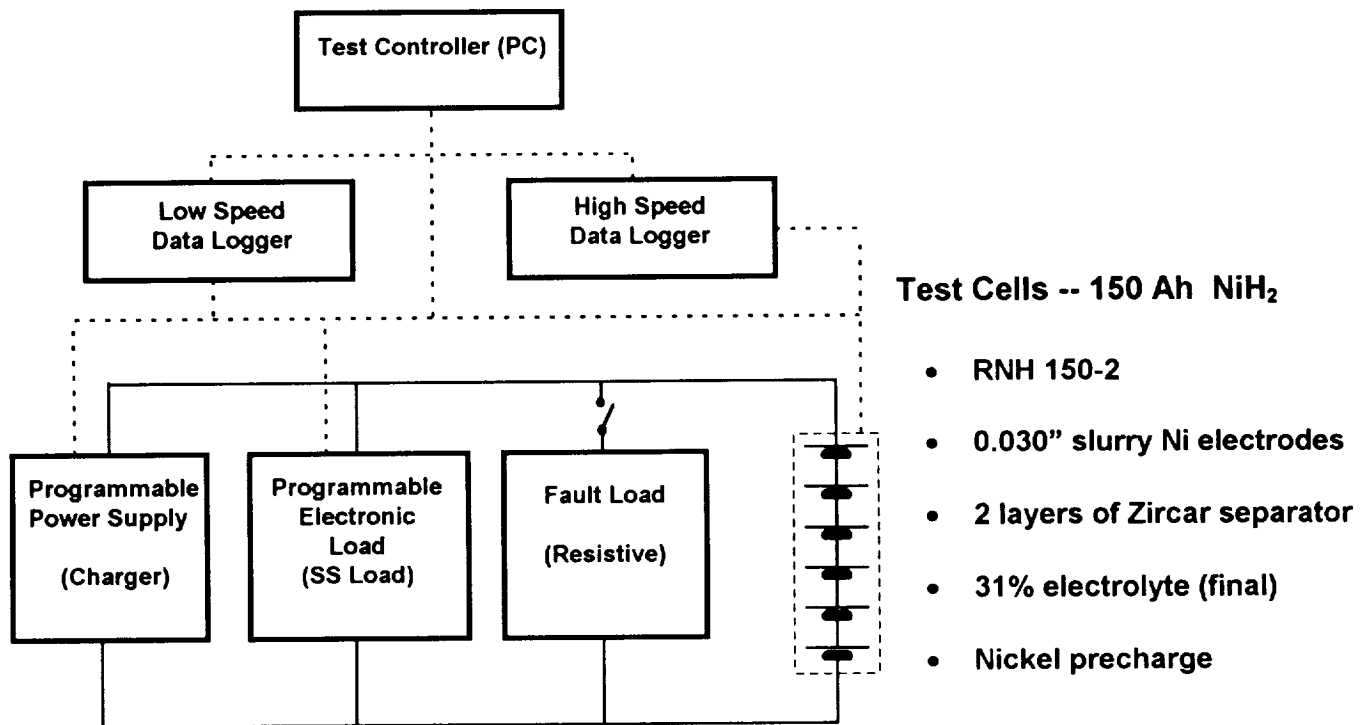
PLAN

- **Fault clearing discharges are performed at high and low states of charge.**
- **Test Sequence**
 - **Charge at the C/10 rate for 14 hours.**
 - **Discharge at the C/20 rate.**
 - **Add the fault clearing load, for 3 milliseconds, at 3 hours into the C/20 discharge. (*High state of charge event SOC = 85%*)**
 - **Continue the C/20 rate discharge**
 - **Add the fault clearing load, for 3 milliseconds, at end of discharge. Three end of discharge voltages were considered: 0.9, 1.0, and 1.1 volts. (*Low state of charge event*)**

Comparison of data obtained at low and high states of charge provides additional insight into the cell level processes taking place during the fault clearing events.

The test sequence is designed to provide data at a high state of charge defined by C/20 rate discharge to 85% state of charge and at three low state of charge conditions defined as C/20 rate discharge to 0.9, 1.0, and 1.1 volts per cell. The difference in capacity at 0.9, 1.0 and 1.1 volts per cell is small, but, as will be seen from the data, the difference in fault clearing parametric performance is significant.

Test Set Up

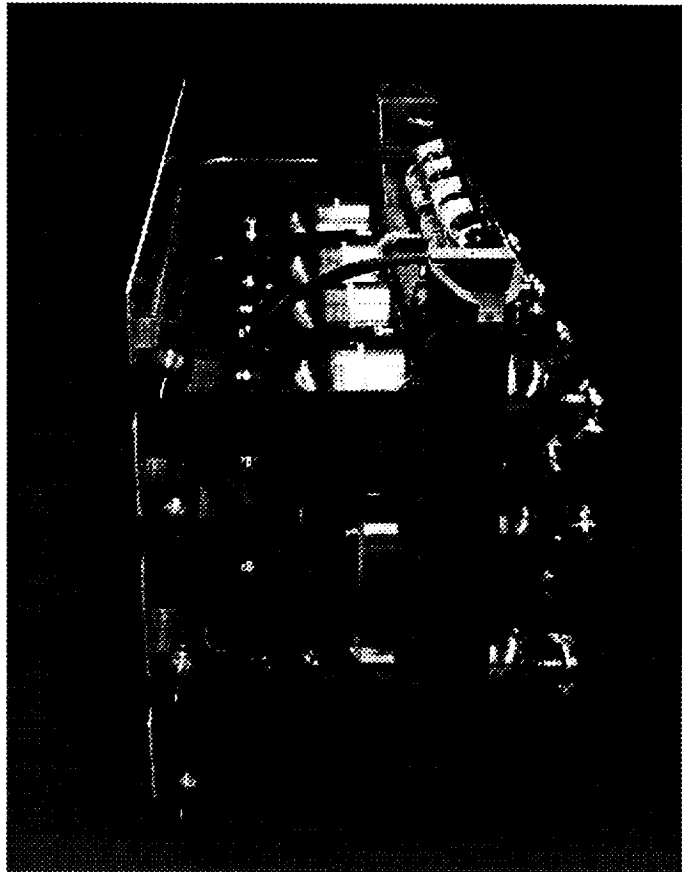


The test equipment was designed to control all aspects of charge, discharge, thermal management, and data logging, automatically, with a PC as the primary test controller. Separate data logging was provided for the low speed requirement to provide continuous overall charge/discharge data, and the high speed requirement to provide adequate data during the millisecond fault clearing discharge pulses. The fault loads were superimposed on the C/20 steady state discharge loads at the appropriate times.

The test cells were Eagle Picher (Joplin) RNH 150-2 150 ampere-hour nickel-hydrogen cells packaged in a battery module shown on the next chart.

12-Cell 150-Ah Battery Module

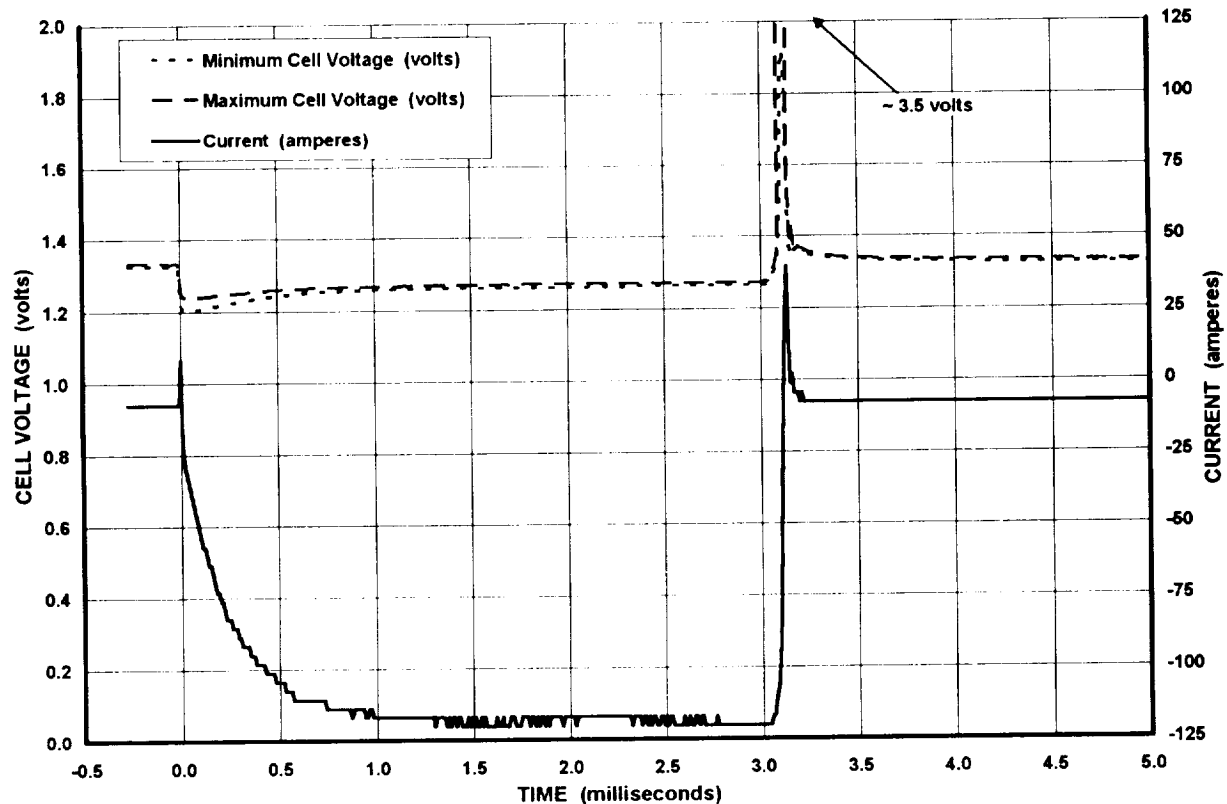
- RNH 150-2 cells
- Cooling via VCHP to secondary mirror
- Fluid loop cooling capability
- Individual cell bypass
- Modular design
 - 11 or 12 cells per module
 - 110 to 210 Ah



The test cells were packaged in the 150 ampere-hour battery module shown above. The packaging is modular in design and can accommodate 11 or 12 cells with capacities from 110 to 210 ampere-hours. Each cell is protected against cell open failures by individual cell bypass switches. Thermal management capabilities include cooling by moving heat from the cells to center-of-gravity mount thermal sleeves and, using variable conductance heat pipes (VCHP), to a secondary mirror for radiation to space. Fluid loop cooling capability is also provided for thermal management where active control is desired. The fluid loop cooling was utilized during the testing reported here.

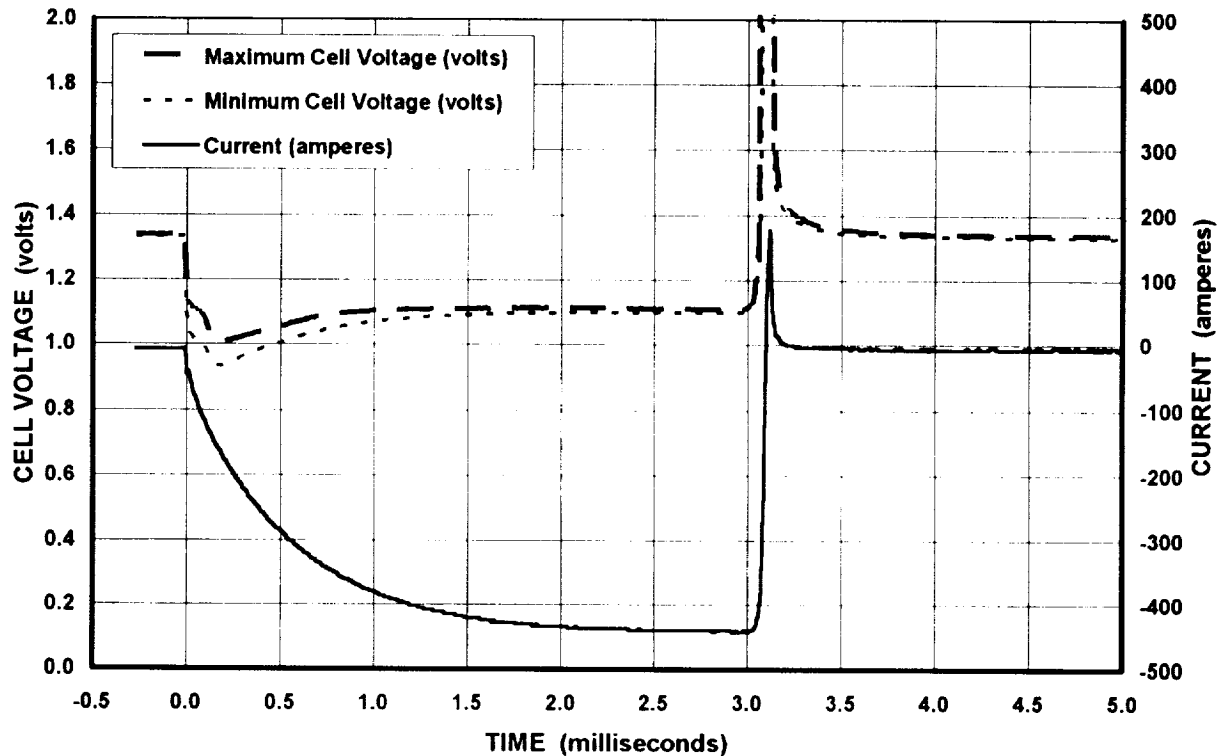
120-AMPERE 3-MILLISECOND PULSE

AT HIGH STATE OF CHARGE



The 120-ampere discharge curve shows a typical fault clearing discharge at high state of charge. Only maximum and minimum cell voltages are plotted because the cells are well matched and the range of cell voltages is small. As can be seen from the curves the voltage is very stable during the discharge period. The dip in cell voltage at the leading edge of the pulse, as well as the "rounding" at the front end of the current trace, are due to the non-linear (inductance and capacitance) elements in the battery and test equipment. The large voltage excursion at the pulse turn-off is due, primarily, to cell inductance.

450-AMPERE 3-MILLISECOND PULSE AT HIGH STATE OF CHARGE

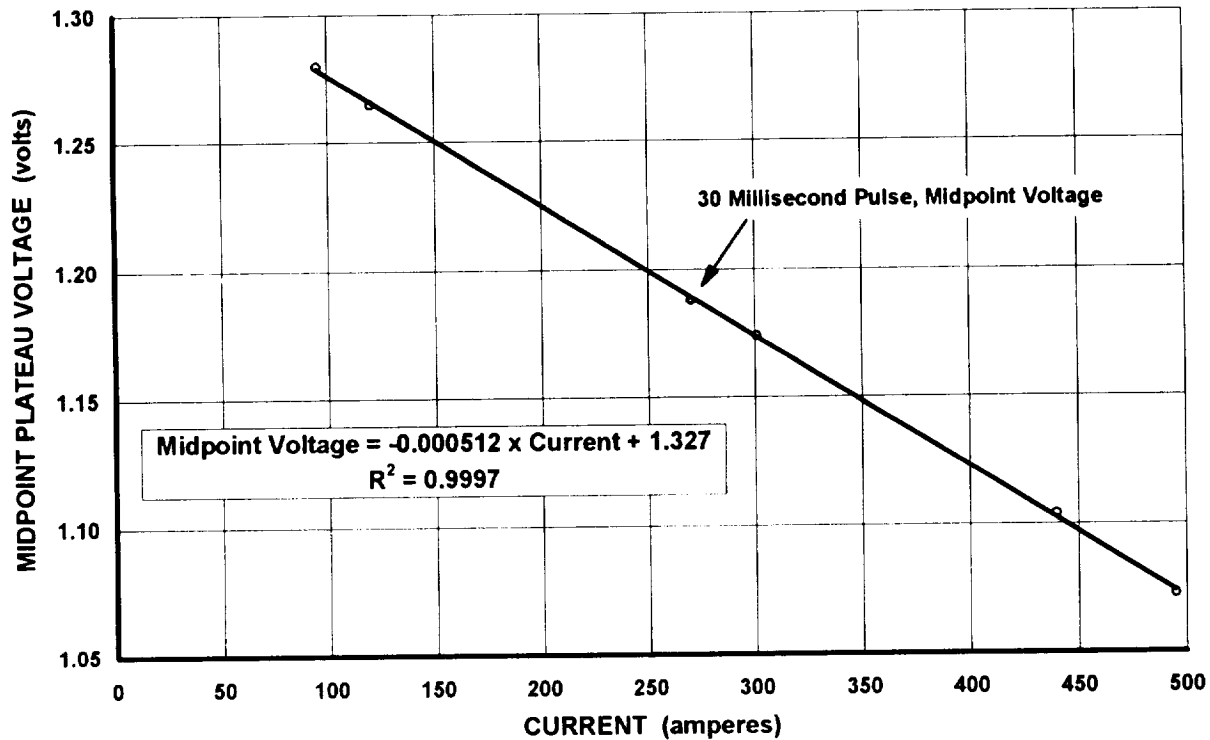


The 450-ampere discharge also shows excellent voltage "stiffness" during the fault clearing discharge. The difference between the starting voltage, e.g., the voltage prior to the fault clearing event, and the plateau voltage is greater than observed with the 150 ampere discharge. As will be seen in the succeeding charts the relationship between the initial and plateau voltages is a function of cell impedance and follows Ohms Law.

This relationship suggests that the energy expended during the fault clearing event comes from cell capacitance and that mass transfer processes do not occur to any appreciable extent.

AVERAGE PLATEAU VOLTAGE

3-MILLISECOND PULSES AT HIGH STATE OF CHARGE

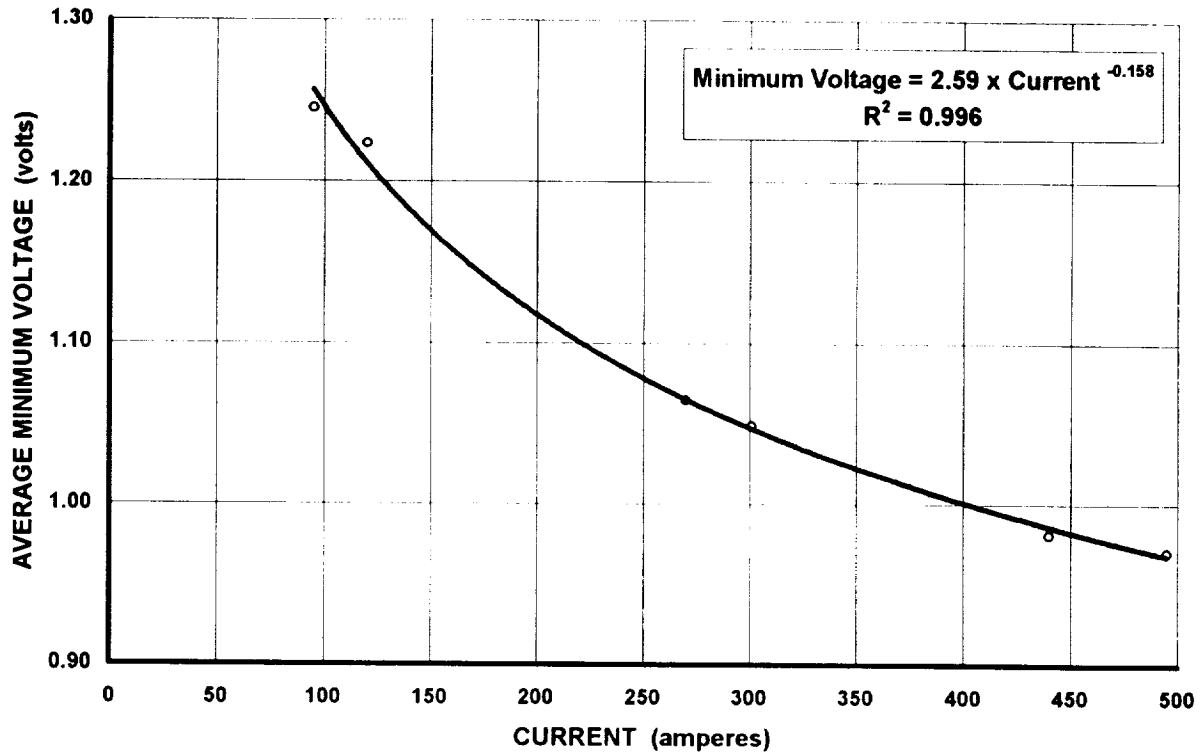


Midpoint plateau voltage data obtained at high states of charge are summarized in the plateau voltage *versus* pulse current chart. The slope of the voltage *versus* current plot is the cell resistance; the linear relationship is an expression of Ohms Law.

The 30-millisecond data point is included to demonstrate the stability of the plateau voltage. Stability in this time domain indicates that voltage decay due to faradaic and mass transfer effects require longer discharge durations at these conditions.

AVERAGE MINIMUM VOLTAGE

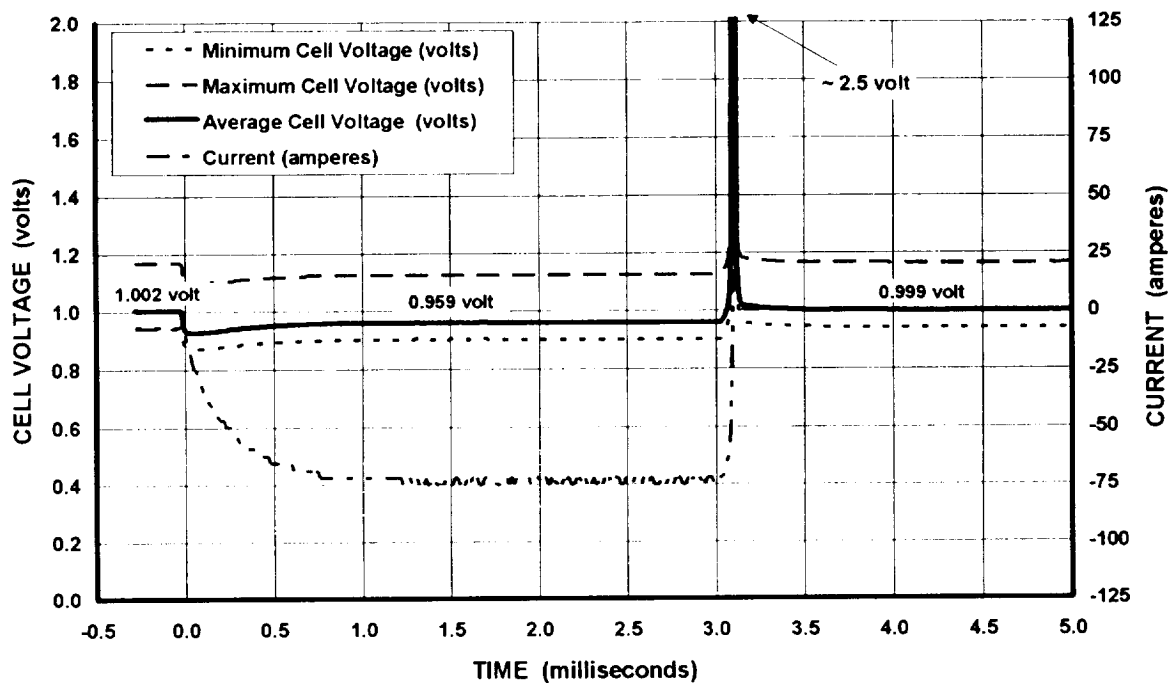
3-MILLISECOND PULSES AT HIGH STATE OF CHARGE



The minimum voltage observed during the fault clearing event may be of interest in terms of spacecraft bus voltage regulation. This chart shows the relationship between the average minimum voltage and the pulse current for the fault clearing data obtained at high state of charge.

It is interesting to note that an excellent fit is obtained with a power curve. If the voltage dip were due to cell inductance only the best fit would be provided by an exponential model.

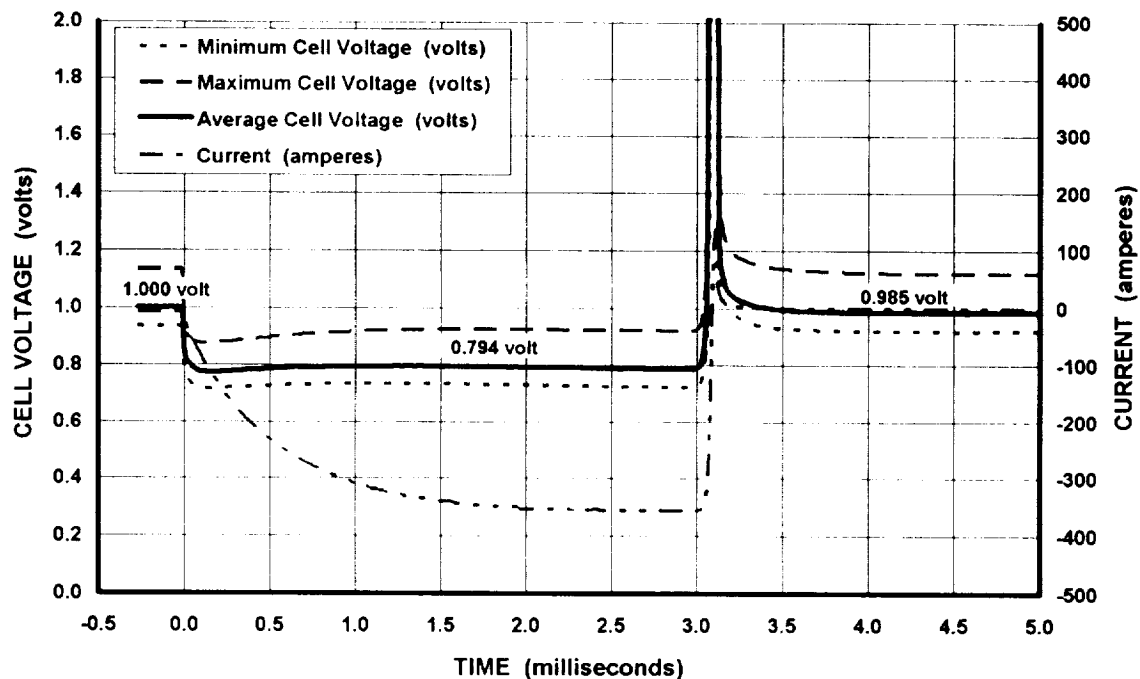
75-AMPERE 3-MILLISECOND PULSE AT LOW STATE OF CHARGE



The next series of charts shows similar plateau voltage *versus* pulse current relationships obtained at low states of charge.

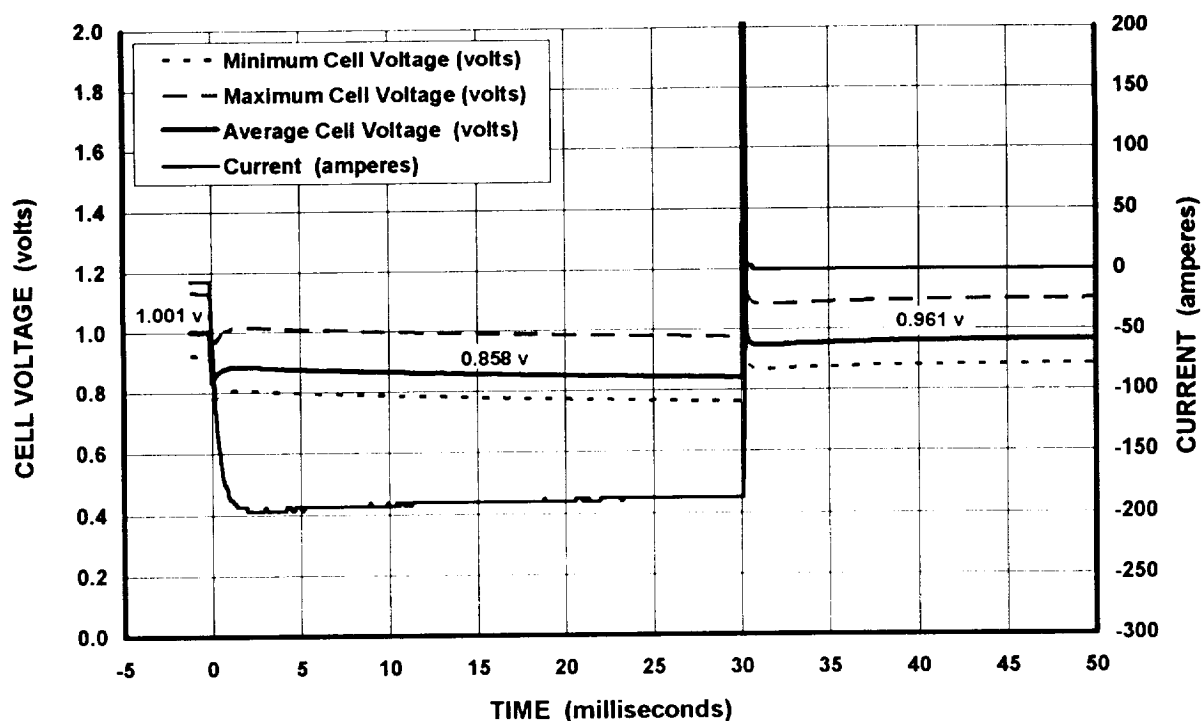
The 75-ampere curve shows fault clearing data following a C/20 discharge to 1.0 volt per cell. As can be seen from the chart the plateau voltage is stable and the voltage level, following the pulse, returned to within a few millivolts of the starting voltage. This is interpreted as meaning that very little mass transfer occurred.

350-AMPERE 3-MILLISECOND PULSE AT LOW STATE OF CHARGE



The 350-ampere curve shows data following a C/20 rate discharge to 1.0 volt per cell and is similar to the previous 75-ampere rate curve. However the plateau voltage is lower than the 75-ampere case and the post fault clearing voltage is lower than the starting voltage. The lower plateau voltage is simply a function of the higher current (Ohms Law) and the lower post fault clearing voltage is due to reduction of the cell capacitance by an amount equivalent to the energy expended during the fault clearing event.

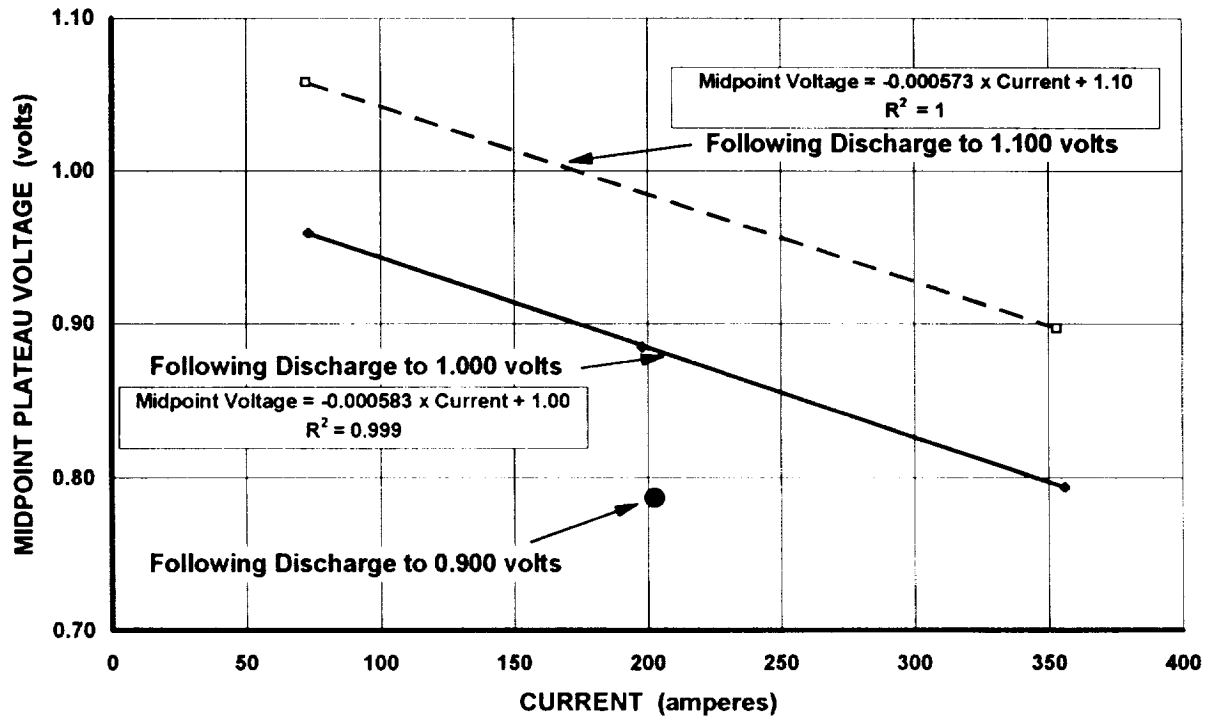
200-AMPERE 30-MILLISECOND PULSE AT LOW STATE OF CHARGE



Thirty-millisecond pulse data, at low state of charge, is shown to demonstrate that the plateau voltage trajectory exhibits a negative slope as energy is removed. This slope, plus the lower post fault clearing voltage, is interpreted as indicating that the cell capacitance is changing significantly, in this time domain, at these operating conditions.

AVERAGE PLATEAU VOLTAGE

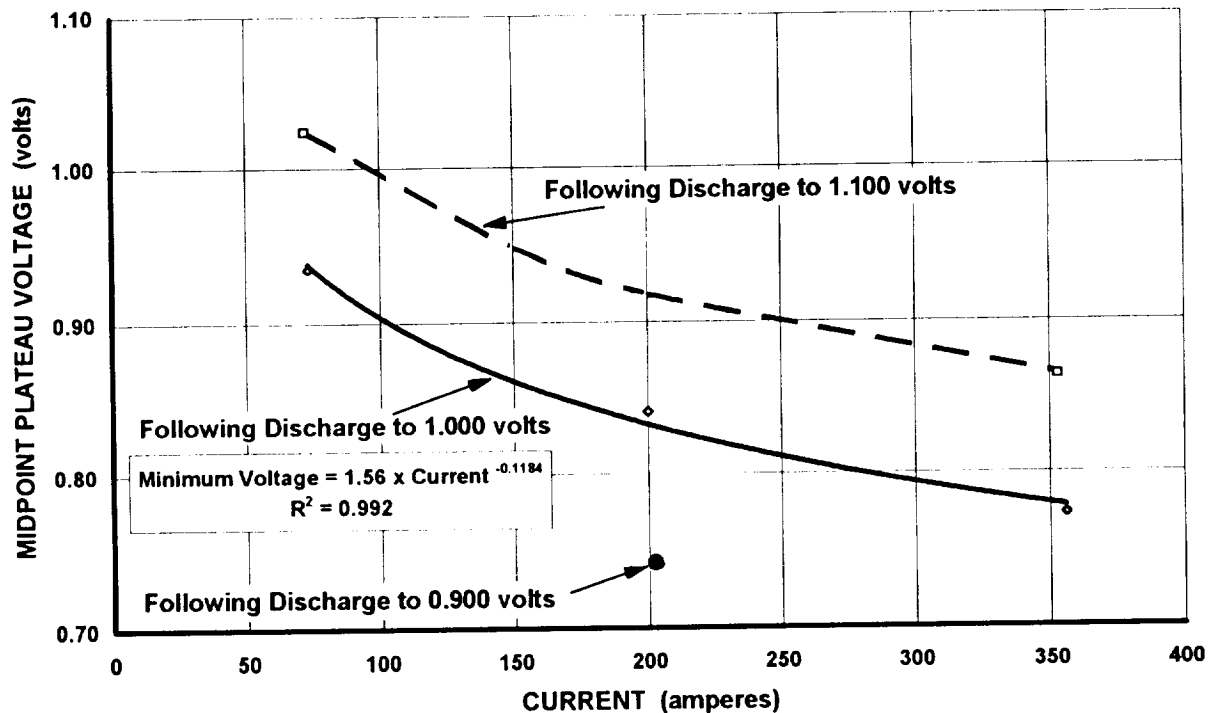
3-MILLISECOND PULSES AT LOW STATE OF CHARGE



Midpoint plateau voltage data obtained at low states of charge are summarized in this plateau voltage *versus* pulse current chart. As in the case of the high state of charge data the slope of the linear relationship is cell resistance. Inspection of the chart reveals that the intercept of the regression line is the voltage at which the fault clearing pulse was started. The intercept, by definition, is the value of the plateau voltage at zero current. In fact, the C/20 discharge rate is non-zero, but is low compared to the fault clearing rates. Simple linear regression analysis yields intercept values statistically indistinguishable from the starting voltages. The slopes at low states of charge appear to larger than observed at high state of charge. It is reasonable to assume that the cell impedance is slightly higher at lower states of charge, however the statistical significance of the difference is marginal.

AVERAGE MINIMUM VOLTAGE

3-MILLISECOND PULSES AT LOW STATE OF CHARGE



This chart shows the relationship between the average minimum fault clearing voltage and the pulse current for the fault clearing data obtained at low state of charge. As in the case of the data obtained at high state of charge, this data can be fit with a power curve.

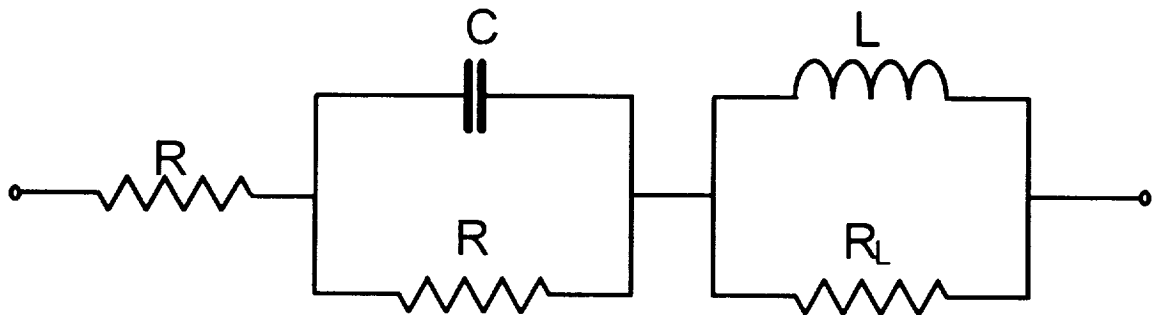
NiH₂ Cell Equivalent Circuits

Millisecond Time Domain

- Applicable to the 3-millisecond pulse



- Applicable to the 30-millisecond pulse



Cell performance can be described by simple equivalent circuits for the simulated fault clearing events presented here. A complete description of cell impedance includes inductive, resistive, and capacitive elements, as well as terms dealing with electrochemical phenomena. A "complete" cell equivalent circuit would contain all these elements and would be very complex. However, in the time domain, and at the operating conditions studied, significant simplifying assumptions are possible.

The "3-millisecond" data can be described simply by an inductance in series with a resistance. Cell capacitance is large enough and the time constant long enough to allow the capacitance term to be ignored. Mass transfer effects are insignificant in this time domain and are also ignored. Because the time constant for the inductive term is very short it too can be ignored if only the plateau voltage is needed.

If the pulse duration is extended, as in the 30-millisecond pulse data, a capacitance term is added to provide the proper plateau voltage trajectory.

SUMMARY

- Fault clearing currents were achieved and maintained at discharge rates from C/2 to 3C at high and low states of charge.
- The fault clearing plateau voltage is a strong function of
 - discharge current and
 - voltage-prior-to-the-fault-clearing-event
 and a weak function of state of charge.
- Voltage performance, for the range of conditions reported, is summarized as

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where

- VMPP = Fault clearing midpoint voltage, volts
- SOC = State of charge, %
- IDSCHG = Fault clearing current, amperes
- VSTRT = Voltage at the start of the fault clearing event, volts

