DEVELOPMENT OF A TESTER FOR EVALUATION OF PROTOTYPE THERMAL CELLS AND BATTERIES

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Abstract

A tester was developed to evaluate prototype thermal cells and batteries--especially high-voltage units--under a wide range of constant-current and constant-resistance discharge conditions. Programming of the steady-state and pulsing conditions was by software control or by hardware control via an external pulse generator. The tester was assembled from primarily Hewlett-Packard (H-P) instrumentation and was operated under H-P's Rocky Mountain Basic (RMB). Constant-current electronic loads rated up to 4 kW (400 V at up to 100 A) were successfully used with the setup. For testing under constant-resistance conditions, power metal-oxide field-effect transistors (MOSFETs) controlled by a programmable pulse generator were used to switch between steady-state and pulse loads. The pulses were digitized at up to a 50 kHz rate (20 μs/pt) using high-speed DVMs; steady-state voltages were monitored with standard DVMs. This paper describes several of the test configurations used and discusses the limitations of each. Representative data are presented for a number of the test conditions.

Introduction

During the development of a high-voltage thermal battery, it was necessary to study the battery response to a wide range of high-current pulses (ref. 1,2). The experimental setup under use then at Sandia was limited in both the speed of sampling and the minimum pulse width during testing. The test setup was revised and additional instrumentation was incorporated to allow ready programming of the load profile applied to individual cells or batteries. Provisions were made to test under either constant current (using an electronic load or programmable power supply) or constant resistance (using MOSFET switching of fixed resistances). The operating software was modified to make the new system user friendly. This paper describes the results of the tester-development effort.

Experimental

Most of the single-cell tests were done using 1.25"-dia. cells having nominal voltages of 1.8 to 2.0 V. The stack diameter of the batteries tested were 1.25 and 2.25 inches. The bulk of the batteries tested contained either 10 or 25 cells; one battery containing 95 cells was also tested. The currents used during testing were adjusted for the cell diameter to maintain comparable current densities for ease of data comparison.

The experimental setup used for constant-current tests is shown in Figure 1.

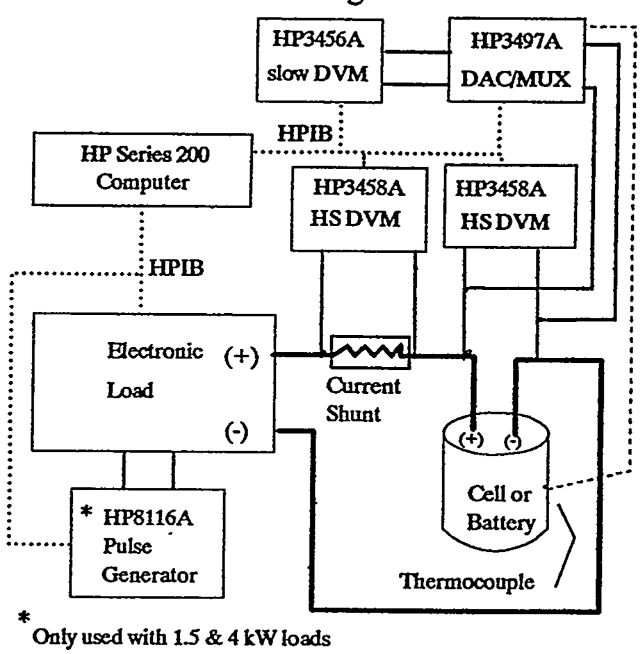

Figure 1. Experimental setup for constant-I tests.

RMB was used for instrument control and data analysis because of its programming ease and structure, versatility, error-trapping functions, and

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enhanced graphics capabilities for plotting test results. A HP6060B electronic load rated at 60 V or 60 A at 300 W was used for low-power tests, such as for single cells and smaller batteries. The HP6060B was the preferred choice for these tests, because of its wide-ranging programming capabilities, as listed in Table 1.

Operating mode: constant I, R, or V
Current Range: 0-60 A (300 W max.)
Resistance Range: 0.033-10,000 ohms
Pulse width: 100 μs-4 s (continuous mode)
Duty cycle: 3%-97% (0.25 Hz-1 kHz)
6%-94% (1 kHz-10 kHz)
Pulse width: 50 μs- 4 s (transient or pulse mode)
Current Slew rate: 1 A/ms-5 A/μs
Triggering: internal or external
Trigger output
HPIB (IEEE488) programmable

Table 1. Programming capabilities of HP6060B electronic load.

For 10-cell and 25-cell bateries, a 1.5 kW electronic load (Model DYNALOAD DLF 100-200-1500, Transistor Devices, Randoph, NJ) rated at 100 V at 50 A was used. For testing of 25-cell batteries under high-power conditions, in-house 4 kW electronic-load modules rated at 400 V were used. These could be used singly or ganged in parallel (for increased power) or connected in series (for increased voltage).

The 1.5 and 4 kW constant-current electronic loads did not have internal programming capabilities but, instead, were programmed remotely using an analog signal from a HP8116A pulse/function generator. This unit's capabilities are listed in Table 2. The wide range of programming possibilities allowed cells and batteries to be subjected to a continuous pulsing, where the frequency and duty cycle were varied as desired. Or, single pulses of a prescribed width and amplitude could be applied at predetermined times during discharge.

Frequency: 1 mHz-50 MHz (cont. mode)
(20 ms-1,000 s)
Duty cycle: 10%-90% (1 mHz-1 MHz)
20%-80% (1 MHz-10 MHz)
50% (10 MHz-50 MHz)
Pulse width: 10 ms-999 ms (pulse mode)
Output amplitude: 10 mV-16 V
Adjustable offset
HPIB (IEEE488) programmable

Table 2. Programming capabilities of HP8116A pulse/function generator.

The steady-state readings of battery voltage and temperature were taken using a "slow" DVM (HP3456A), multiplexed by a HP3497A data acquisition unit (DAC). The current and voltage response of the battery during pulsing was recorded with high-speed (HS) DVMs (HP3458A).

Constant-current Tests - Constant-current tests were conducted in two modes: *continuous* or *pulse*. In the *continuous* mode, a constant waveform (string of pulses) of a predetermined frequency and duty cycle were generated by the HP6060B. The current and voltage response of the cell or battery were then digitized by the two HS DVM.s These were triggered by the HP6060B which itself was triggered from the HPIB bus at the start of the test. Data were taken for a prescribed time which depended upon the sampling rate (which could be as high as 50 kHz) and the memory limit of the HS DVMs.

It was not practical to sample continuously during the test because of limitations of computer memory and unreasonable requirements for disc storage of test data. Instead, bursts of data were recorded periodically during discharge to characterize the discharge process. The data from each burst of readings stored in the HS DVMs in packed bainary format were downloaded to the computer and unpacked before the next burst. This took some time for large (70 K) numbers of readings, so that the true elapsed time for the test had to be corrected accordingly.

Timing for triggering of the slower DVM was provided by a programmed interrupt supplied by the DAC. Typically, interrupts were generated at 2-s intervals. This provided sufficient data to characterize the thermal response of the battery.

Constant-current testing of cells and batteries in the *pulse* mode utilized the HP3456A to monitor both the voltage and temperature of the cell or battery under test. These inputs were multiplexed through the DAC, which also provided the timing interrupt as for the continuous mode.

The cells or batteries were pulsed at periodic intervals that were multiples of the interrupt time. During constant-current single-cell tests with the HP6060B electronic load, the load was triggered internally (off the HPIB bus). The HS DVMs were then triggered by the load to digitize the current and voltage response of the cell or battery.

During tests with the higher-power (1.5 and 4 kW) electronic loads, the trigger pulse to initiate pulsing was provided by either the HP6060B or the D/A output of the DAC. The same trigger pulse caused the pulse generator to output a single pulse to the load and the HS DVMs to digitize the cell or battery response.

When testing thermal batteries, activation of an electrical igniter (squib) is necessary for functioning of the battery. This was accomplished by using a D/A output of the DAC to turn on a power supply in series with a solid-state switch and the igniter.

The pulse generator can also be used with a programmable power supply. The programmable amplitude of the pulse generator can be used to set the magnitude of the output current for both the steady-state as well as the pulse during testing. The data acquisition part of the testing remains the same as when the electronic load is used.

Constant-resistance Tests - The setup of Figure 2 was used for tests conducted under constant resistance.

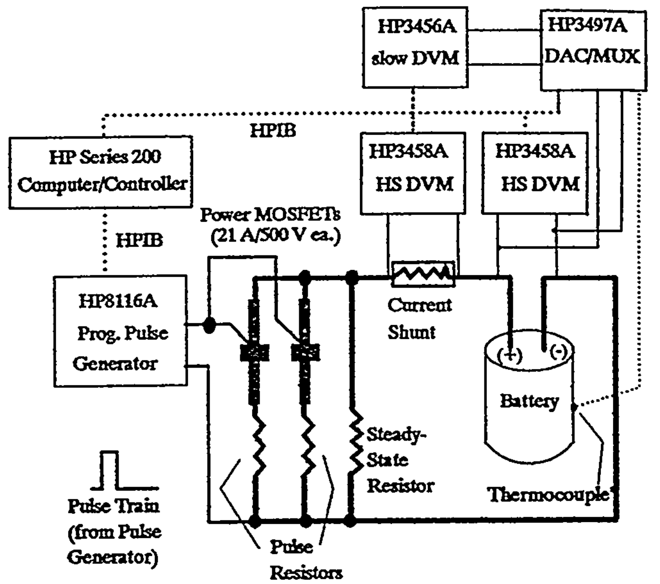

Figure 2. Experimental setup for constant-R tests.

Since it was desired to test high-voltage (up to 300 V) batteries at high power (up to 4 kW), the requirements for the power MOSFETs were severe. It was not possible to locate a single MOSFET that could meet the test requirements. Consequently, it was necessary to parallel two units (Solitron Devices, Inc., Riviera Beach, FL) in order to handle up to 40-A pulse loads.

Some Problem Areas - Some difficulties were encountered in the development of the tester. The large data files that were generated at times would overwhelm the 40 MB hard disc associated with the Series 200 computer. This problem was eliminated by the incorporation of a 90 MB Bernoulli drive. The limitation of an array size to 32,767 bytes by the RMB language necessitated the use of multiple arrays which made code development cumbersome. This was alleviated by using third-party software that eliminated the array-size limitation (XRMB, Dtack Systems, Inc., Anaheim, CA),

The timing and synchronization of the various instruments associated with the test setup were critical for proper operation. This required careful coding, because some of the instrument commands required execution in a paraticular sequence. The multitude of options associated with the HS DVMs made the desired programming difficult and confusing. At one point, it was necessary to solicit the assistance of H-P in the final programming of the HS DVMs.

Simultaneous triggering of the load or pulse generator and the HS DVMs caused some data to be lost at the start of the pulse. Since we were primarily interested in the cell or battery response at the *bottom* of the pulse, this was generally not a problem. To obtain complete information at the onset of the pulse as well, one can insert a time delay of 1-5 ms after triggering the HS DVMs in the trigger line to the electronic load or pulse generator. This effectively acts to provide "pretriggering" information. One can accomplish this by hardwiring a time-delay circuit (e.g., based on operational amplifiers) in series with the trigger output of the HS DVMs and the trigger input of the load or pulse generator.

Results and Discussion

Continuous Mode - Representative voltage and current traces are shown in Figures 3a and 3b for a portion of one 10-ms cycle for a 1.25"-dia. $Li(Si)/CoS_2$ thermal cell based on LiCl-LiBr-LiF eutectic. The cell was tested at 550°C in the continuous mode using the HP6060B electronic load.

The cell was subjected to a 10% pulse duty cycle, where a 1.5-A background load was applied for 9 ms and a 9-A pulse load was applied for 1 ms each cycle. (This corresponds to current densities of 189 and 1,136 mA/cm^2, respectively.) The sampling rate for this data was 100 kHz or 100 μs/point. Comparable results were obtained for 10-cell and 25-cell batteries tested using this setup.

The software allows the width of the pulse, the repetition rate, and sample rate to be readily varied to suit customer needs. As part of data analysis, the software allows plots of the following parameters as a function of discharge time:

- Steady-state voltage
- Minimum voltage during pulse
- Voltage change during pulse
- Maximum and average current during pulse
- Average resistance
- Individual pulse voltage and current profiles
- Battery temperature
- Voltage and current for battery during activation

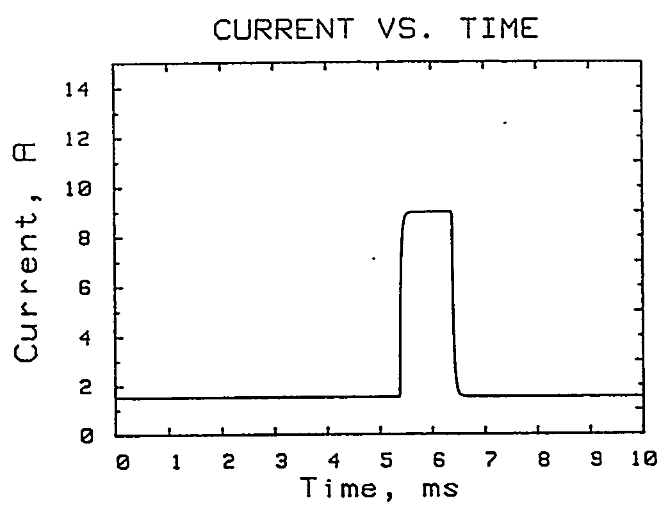

Figure 3a. Current-time trace for pulse using HP6060B load with thermal cell.

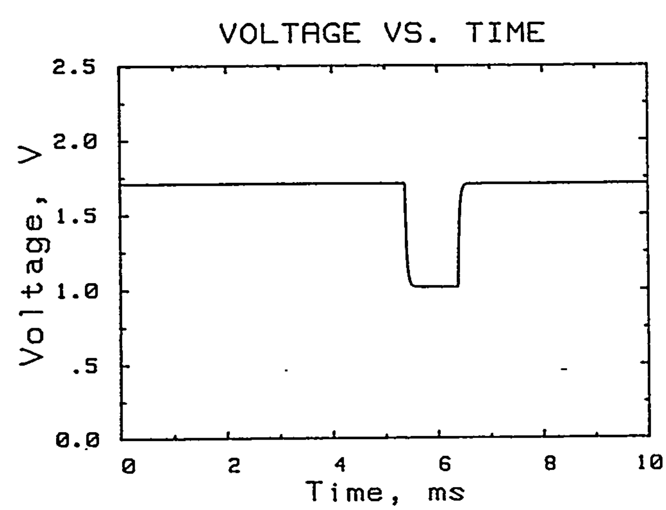

Figure 3b. Voltage-time trace for pulse using HP6060B load with thermal cell.

Pulse Mode/Electronic Load - To test the program for high-voltage applications, ten 12-V lead-acid car batteries were connected in series to provide a nominal 120 V system. The assembly was tested in the pulse mode using a steady-state current of 6 A. Every 2 s, a 43-ms pulse of 36 A was applied. This cycle would normally be repeated until the battery reaches a preset cutoff voltage which defines end of life. The 2-s interrupt for taking steady-state readings was provided by the DAC. The magnitude of the steady-state and pulse currents, as well as the width of the pulse, were established by the pulse generator to control the 4 kW electronic load.

Representative current and voltage traces for one of the pulses from the test are shown in Figures 4a and 4b, respectively.

The current trace (Figure 4a) shows transients at the beginning and end of the pulse, when the load switches. The voltage trace (Figure 4b) reflects the presence of the current spikes. The addition of a 1,000 μfd electrolytic capacitor across the load removed the voltage transients from the pulses, although the current spikes remained. The use of a 2,000 μfd capacitor, however, interfered with proper operation of the electronic load, by reducing the slew rate. This caused significant rounding of the leading and trailing edges of the pulse waveform.

The above test setup up was used to test a 95-cell, 175-V thermal battery. The results obtained were comparable to those with the lead-acid battery assembly, in terms of the performance of the instrumentation and software.

Pulse Mode/MOSFET Switching - The 120-V lead-acid battery assembly was also tested using the MOSFET test setup (Figure 2), for relative comparison to the electronic-load setup. For convenience in testing, a steady-state resistance was not used; the assembly was simply pulsed from open circuit to the resistance load at 2-s intervals. The pulse generator was used to generate 43-ms/6-V pulses to turn on the MOSFETs. The load consisted of two windings of Nichrome® wire (5.95 ohms and 5.61 ohms) on ceramic forms; these were connected in parallel through the MOSFETs to the load when the MOSFETs were triggered.

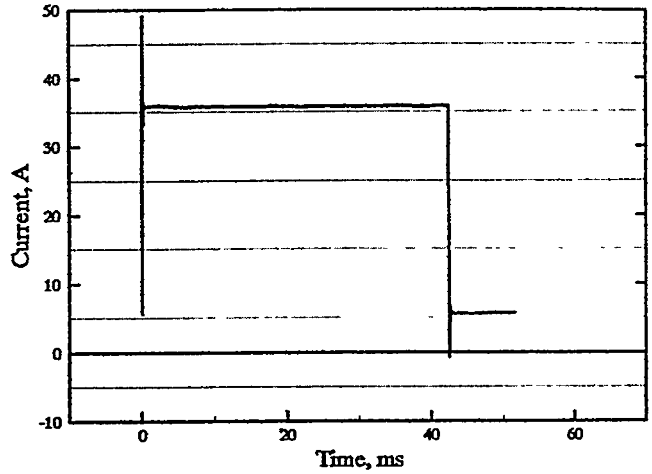

Figure 4a. Pulse-current response using 4-kW electronic load with 120-V lead-acid battery.

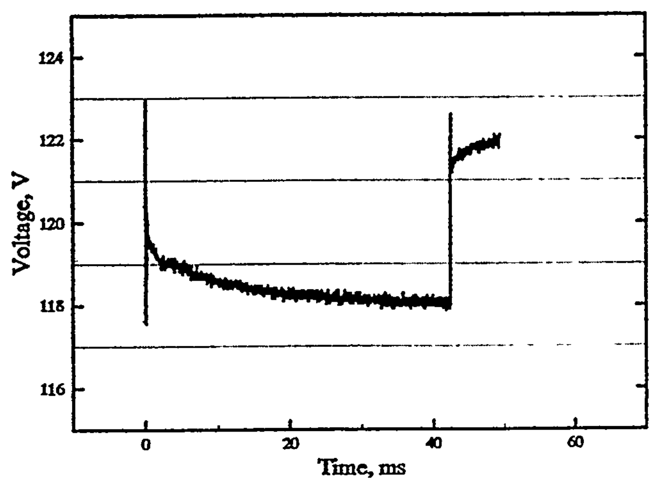

Figure 4b. Pulse-voltage response using 4-kW electronic load with 120-V lead-acid battery.

Representative current and voltage traces for one of the pulses from the test are shown in Figures 5a and 5b, respectively. The differences relative to the corresponding traces for the 4-kW electronic load are very evident. The current trace (Figure 5a) shows none of the transient behavior at the beginning and end of the pulse. The corresponding voltage trace (Figure 5b), however, still shows the voltage transient at the end of the pulse, when the MOSFET is turned off. The test arrangement still worked quite well overall.

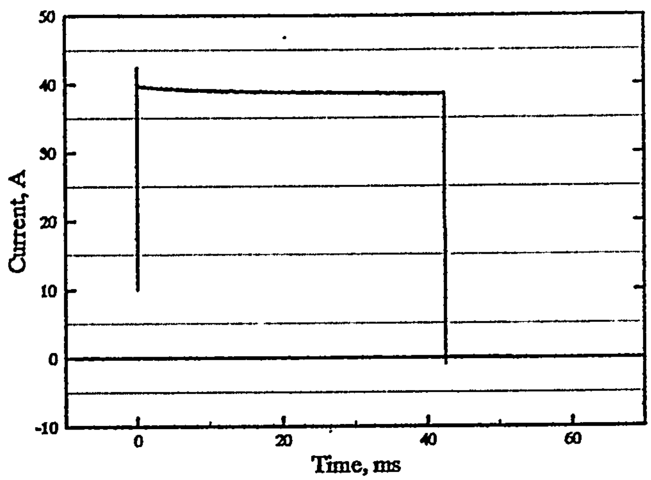

Figure 5a. Pulse-current response using MOSFET-switched resistance load with 120-V lead-acid battery.

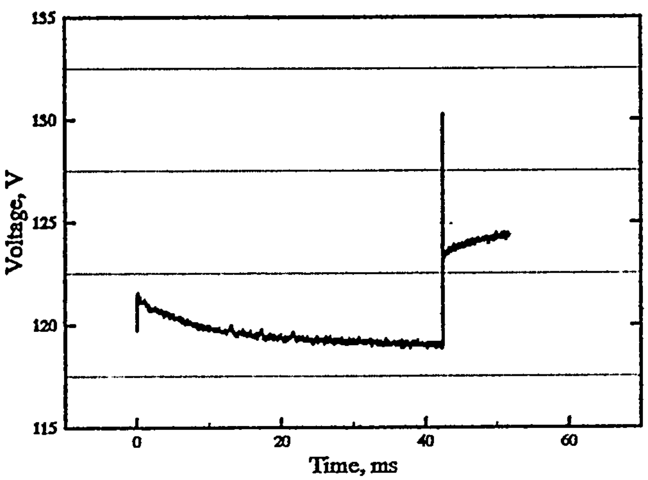

Figure 5b. Pulse-voltage response using MOSFET-switched resistance load with 120-V lead-acid battery

The relative merits of the use of the electronic load versus MOSFET switching are described in Table 3.

Conclusions

Experimental setups are described for testing prototype thermal cells and batteries--especially batteries with voltages in excess of 100 V. The setups have the capability of applying pulses

<u>Electronic Load</u>:
- Easy to program over wide range of load conditions (true constant current)
- Can become unstable if battery voltage is too low (voltage stability window) or power is too high (power limited)
- Tendency for current spikes at both start and end of load change
- Relatively expensive

<u>MOSFET Switching</u>:
- Requires different resistances for different load conditions (can only approximate constant current)
- Some voltage loss across MOSFET junction
- Performance generally not affected by battery voltage
- Able to apply load immediately upon activation of battery
- Power capabilities readily adjusted by wire gauge size
- Tendency for current spikes when MOSFET turns off
- Relatively inexpensive

Table 3. Comparison of testing with electronic load and MOSFET switching.

ranging in duration from under a millisecond to seconds, in a predefined pattern and at levels limited only by the battery under test or the capacity of the load.

For low-power (<300 W) applications, the HP6060B provides the greatest range of programmatic capabilities: pulse width, amplitude, duty cycle, load, and mode (constant current, resistance, and voltage). The use of higher-powered, constant-current electronic loads (1.5 kW and above) requires the use of a pulse generator to provide an analog signal for programming the load. A programmable power supply can be used in place of the electronic load with this test setup. Both techniques require somewhat elaborate instrumentation. In comparison, power MOSFETs can be used with inexpensive wirewound resistors and a programmable pulse generator to achieve comparable testing capabilities.

The hardware for data acquisition is based on a "slow" DVM (HP3456A) for multiplexing the cell or battery voltage and temperature through a DAC (HP3497A). Two high-speed DVMs (HP3458A) are used for digitizing the current and voltage response of the cell or battery during pulsing. A computer running under H-P's Rocky Mountain Basic functions quite well for instrument control, data acquisition, and data analysis. While the bulk of the hardware is based upon H-P instrumentation, comparable results should be possible with a conventional PC using plug-in boards for data acquisition.

While the tester is designed for thermal cells and batteries, it is equally suitable for testing other types of cells and batteries.

References

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Acknowledgement

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