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A Digital Current Capacity Tester for Rechargeable Batteries

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A battery capacity tester has been built that indicates the amount of energy that can be released from a rechargeable multi-cell battery. The capacity tester is easily configured for the types of battery packs common in industrial hygiene field equipment. It provides a digital display of the milliampere-hour capacity of a battery for direct comparison to battery manufacturer's rating. A properly functioning instrument, when equipped with a battery that does meet its capacity rating, can be expected to operate for the interval claimed by the instrument manufacturer. Some newer field equipment can detect low battery voltage while sampling, then reduce power consumption and save the collected data. But some applications will require an uninterrupted sampling interval, and the capacity tester can assure this. Although batteries can be tested just before use, a program of regular testing and recharging will assure operational readiness at all times. Kovein, R.J.; Hentz, P.A.: A Digital Current Capacity Tester for Rechargeable Batteries. *Appl. Ind. Hyg.* 3:51-54; 1988.

Introduction

Valuable information has often eluded the occupational safety and health community due to unexpected battery failure in portable instrumentation. Power loss can be particularly abrupt in battery packs composed of rechargeable nickel-cadmium cells. For this reason, instruments featuring state-of-charge indicators have frequently failed to warn the user of impending battery deficiencies. While newer instruments employing microprocessor control circuitry will salvage data when low battery voltage is detected, there will be instances where that data is deemed unusable because of the shortened sampling interval. Since reliable results depend so heavily on acceptable battery performance, an effective means of determining battery fitness is necessary. One method is to test the battery by operating the equipment for a period of time. If the instrument has automatic shutoff, an estimate can be made of battery performance with a minimum risk of damaging the battery due to overdischarging.

The preferred method of battery testing is to discharge the battery through a load external to the instrument, thus eliminating unnecessary wear and tear on the equipment. Assuming that the manufacturer has placed within the instrument only those rechargeable cells that are sufficiently rated to sustain up to eight hours of continuous operation, the load should deplete a fully-

charged battery in approximately 10 hours (as discussed below). To prevent overdischarging, a sensing circuit should be included to automatically remove the load as soon as depletion occurs. An ideal system would regulate the load current, determine the time required to deplete the battery, and display the result in milliampere-hour units. This result could be compared with the battery manufacturer's rating. A battery having a current capacity measurement that is less than its rated capacity should not be used unless the measured capacity is determined to exceed the application's demands.⁽¹⁾

A device incorporating the preferred method of battery testing has been built by researchers at the National Institute for Occupational Safety and Health (NIOSH). The device is referred to as the digital current capacity tester, or simply capacity tester. The capacity tester is a multi-port device, capable of simultaneously measuring the current capacities of four individual battery packs which can differ in the number and size of their component cells. It was built using readily available parts costing about \$300. The capacity tester is easily configured to accommodate the types of battery packs commonly found in industrial hygiene equipment. The capacity tester is simple to use and provides an accurate digital display of battery capacity in milliampere-hours (mA·h). This measurement can be compared directly with the battery manufacturer's rating or the known energy demands to be placed on the battery. The digital current capacity tester was designed originally for nickel-cadmium cells, although it can be easily modified to test any rechargeable power source, e.g., lead-acid cells. The design and use of the capacity tester are described in this paper.

Design of the Tester

The digital current capacity tester (Figure 1) is housed in an aluminum cabinet with a hinged front panel. Attached to one side of the cabinet are four sets of input ports (jacks) and push-button switches. Attached to the front panel are four printed circuit (pc) boards, each an independent battery tester.

Mounted to each pc board is a liquid crystal display (LCD), a light-emitting diode (LED), and a pair of slide switches. The LCD provides a mA·h readout of the test result; the LED indicates that

Mention of any manufacturer or product name does not constitute endorsement by the National Institute for Occupational Safety and Health.

a test is in progress. One of the slide switches allows the user to select the desired constant-current discharge rate; the other switch is positioned according to the number of cells in the battery, establishing the cutoff voltage at which discharging will be discontinued.

A battery is connected to one of the pc boards by plugging a patch cord into a jack on the side of the cabinet. The pushbutton above the jack initiates the test of the battery, resetting the LCD on the pc board to zero. During the test, the LED is lit, and the LCD counts the elapsed milliampere-hours. When the battery voltage drops below the preselected cutoff voltage, the discharge is discontinued, the LED is turned off, and the LCD retains the final measurement.

A toggle switch on the top of the cabinet provides 110 VAC to a regulated DC power supply. The four-station capacity tester requires +12 VDC at 180 mA and +5 VDC at 95 mA. A Radio Shack switching power supply (catalog #277-1016) satisfies this requirement.

The circuit for each of the four pc boards found in the capacity tester is shown in Figure 2. The Parts List specifies the components of a single pc board. The circuit takes advantage of an integrated, multi-function, display module that was previously unavailable to designers of similar capacity-measuring devices.⁽²⁾ The module, designated DS1, contains a monolithic counter/driver chip that performs all the counting functions together with the six-digit LCD readout. An elastomeric connector allows solderless snap-on mounting to the pc board.

As stated earlier, switches S1 and S2 are multi-position slide switches that set the constant-current discharge rate and discharge voltage cutoff, respectively, for the battery (B1) to be tested. Switch S3(A,B) is a momentary contact, normally open, push-button switch used for reestablishing the battery's discharge path and resetting the display/counter module DS1. As drawn, relay K1 is not energized. K1 is energized when the DC power supply is on and either no battery is being tested or the battery under test is below cutoff voltage. A battery under test will dis-

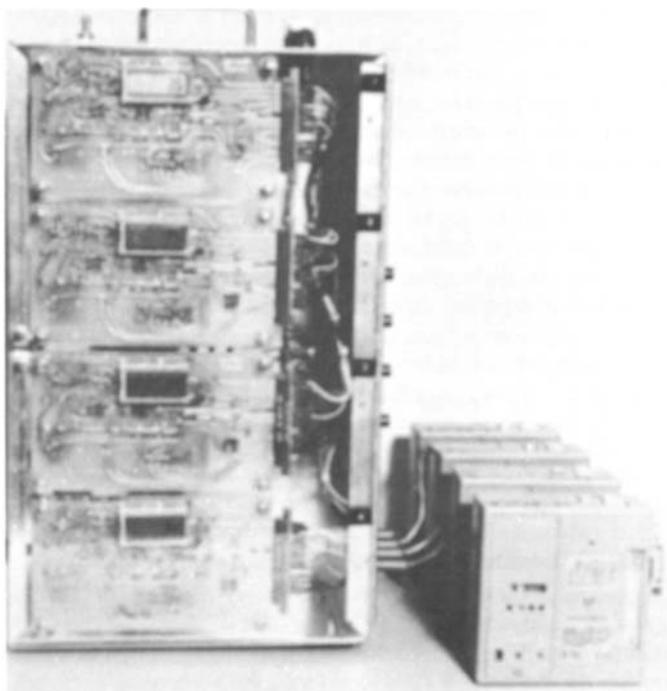


FIGURE 1. Photograph of the digital current capacity tester discharging four SKC battery packs.

TABLE I. Discharge/Timing Rate Selector S1

Switch Pos	Cell		Transistor Q1		Timer U3	
	Size	Rated Capacity (mA-h)	Collector Current (mA)	Emitter Resistance (ohms)	Timing Resistance (k ohms)	2048RC Period (s)
#1	AA	500	50	27	360	72
#2	C	2000	200	6.8	91	18
#3	D	4000	400	3.3	47	9

charge through Q1 as long as its terminal voltage is above the preselected discharge voltage cutoff. Its rate of discharge will depend on the switch position of S1. Placing S1 into position #1 establishes R10 as the emitter resistor. For any given emitter resistance (Table I), the discharge current can be determined from the following expression:

$$I_C = (V_{D1} + V_{D2} + V_{D3} - V_{BE})/R_E = 1.4V/R_E$$

Note that I_C is constant since V_{D1} , V_{D2} , V_{D3} , and V_{BE} are constant quantities.

Timer U3, an XR-2243, must produce a square wave at pin 3 of a frequency that is proportional to the current from the battery if DS1 is to display an accurate milliampere-hour reading. For example, DS1 must increment every 18 seconds to measure the current capacity of a battery being discharged at a constant 200 mA rate. The period necessary to update DS1 for any discharge rate can be calculated from $T_{PIN3} = (3600\text{mA}\cdot\text{s})/I_C$, where I_C is the discharge rate (in mA). When +5V is initially supplied to the timing section, a trigger pulse (delayed in time for a 1.1 R7C2 duration) is applied to pin 6 of U3, causing all internal counters of U3 to be set to "1." In addition, the trigger pulse activates an internal time base oscillator so that, once triggered, U3 will generate a square wave at pin 3 that has a period $T = 2048 RC$, where R and C are the external timing components at pin 7. Since C4 is fixed at 0.1 microfarad, only R is permitted to vary according to the position of S1. In switch position #2, when R is the sum resistance of R2 and R5, the period of the square wave at the pin 3 output of U3 will be 18 seconds (Table I). The negative-going transitions of this pulse train are used by DS1 to increment its count. To accomplish this, the latch input must be held low. When K1 energizes, the battery is removed from discharge and the total number of negative transitions that have been counted since reset is latched in DS1 to provide a direct readout in milliampere-hours.

U1, an LM393, is a dual voltage comparator. Each output serves as an internal SPST switch to ground, with the capability of sinking up to 16 mA, whenever the voltage level on the inverting input (-) exceeds the voltage level of the corresponding noninverting input (+). The function of U1 is to continuously monitor the terminal voltage of the battery under discharge: U1A switches Q2 on which, in turn, energizes K1; U1B turns the light-emitting diode D5 off when K1 energizes. Should the terminal voltage become less than the discharge voltage cutoff that was preselected using S2 (Table II), the base current to Q2 is no longer lost to the output of U1A. Instead, current is supplied directly into the base of Q2 so that it will conduct. The conduction of Q2 energizes the coil of K1, terminating discharge after the relay contacts switch.

Table II lists the 2-cell, 4-cell, 5-cell, and 10-cell batteries that can be evaluated on the capacity tester. Respectively, the voltage drop across either R22, or R23, or R24, or R25 determines the cutoff voltage. Again, the proper cutoff voltage must be selected

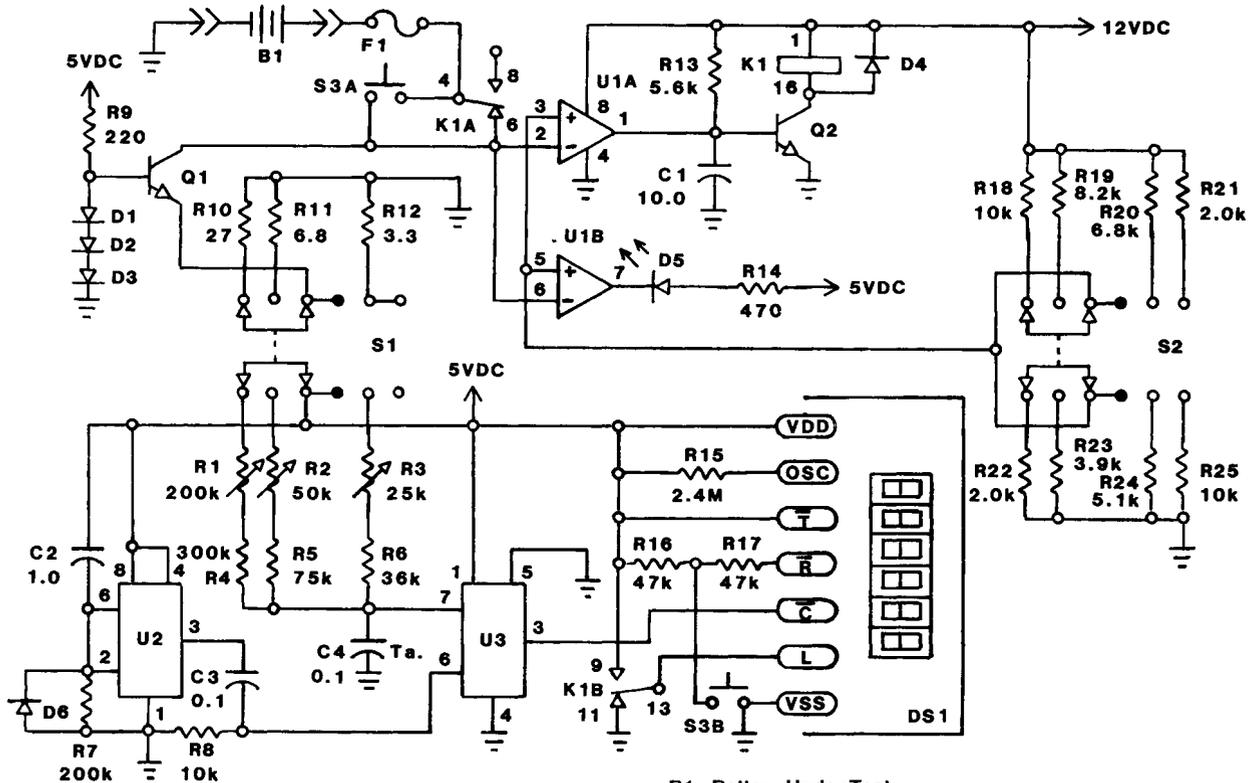
using S2 before testing any battery. In position #2, for instance, the capacity test will be concluded after the battery has discharged below $[R23/(R23 + R19)] \cdot 12V$.

Calibration and Use of the Capacity Tester

Before the capacity tester can be used, it must be calibrated. This is done by adjusting an output of U3 to agree with the exact rate

of discharge current. Potentiometers R1, R2, and R3 permit this adjustment. Two methods of making this calibration adjustment are described here. The first method requires the use of a stopwatch; the second method requires the use of an oscilloscope, or a frequency counter.

In the first calibration method, the period required to increment the display is measured. It is performed with S1 set to discharge a battery at a constant rate of 50 mA (switch position



Relay K1 is shown not energized (B1 is discharging at a 50mA rate and DS1 is incrementing once every 72s).

All capacitance values are in microfarads.

B1 - Battery Under Test.

S1 - Discharge/Timing Rate Selector (50mA/72s, 200mA/18s, and 400mA/9s).

S2 - Voltage Cutoff Selector (2.0V, 4.0V, 5.0V, and 10V).

U1 - 393 Dual Comparator IC.

U2 - 555 Timer IC.

U3 - 2243 Timer IC.

PARTS LIST

- C1, Electrolytic Cap., 10 μ F, 16 V, SPRAGUE 106F016KA
- C2, Tantalum Cap., 1.0 μ F, 35 V, SPRAGUE 196D105X9035HA1
- C3, C4, Tantalum Cap., 0.1 μ F, 35 V, SPRAGUE 196D104X9035HA1
- D1-D4, D6, Silicon Diode, 50 PIV, MOTOROLA 1N4001
- D5, LED, INDUSTRIAL DEVICES 4304H1
- DS1, Display/Counter Module, RED LION CONTROLS SCUB-2000/A
- F1, PicoFuse, 0.5A, LITTLEFUSE 275.500
- J1, Connector, PC, Edge, CINCH (TRW) 50-15A-20
- K1, Relay, DIP, DPDT, OMRON G2V-234P-US-DC12
- Q1, Transistor, NPN, RCA SK3199
- Q2, Transistor, NPN, MOTOROLA 2N3904
- R1, Potentiometer, 200k Ω , 1/4W, BOURNS 3266W-1-204
- R2, Potentiometer, 50k Ω , 1/4W, BOURNS 3266W-1-503
- R3, Potentiometer, 25k Ω , 1/4W, BOURNS 3266W-1-253
- R4, Resistor, 300k Ω , 1/4W, 5%
- R5, Resistor, 75k Ω , 1/4W, 5%
- R6, Resistor, 36k Ω , 1/4W, 5%
- R7, Resistor, 200k Ω , 1/4W, 5%
- R8, R18, R25, Resistor, 10k Ω , 1/4W, 5%

- R9, Resistor, 220 Ω , 1/2 W, 5%
- R10, Resistor, 27 Ω , 1/2 W, 5%
- R11, Resistor, 6.8 Ω , 1/2 W, 5%
- R12, Resistor, 3.3 Ω , 1 W, 5%
- R13, Resistor, 5.6k Ω , 1/4 W, 5%
- R14, Resistor, 470 Ω , 1/4 W, 5%
- R15, Resistor, 2.4M Ω , 1/4 W, 5%
- R16, R17, Resistor, 47k Ω , 1/4 W, 5%
- R19, Resistor, 8.2k Ω , 1/4 W, 5%
- R20, Resistor, 6.8k Ω , 1/4 W, 5%
- R21, R22, Resistor, 2.0k Ω , 1/4 W, 5%
- R23, Resistor, 3.9k Ω , 1/4 W, 5%
- R24, Resistor, 5.1k Ω , 1/4 W, 5%
- S1, S2, Switch, Slide, DP4T, ALCOSWITCH SS-24
- S3, Switch, P.B., DPDT, N.O., MOM. ALCOSWITCH MSP-205R
Plastic Button for MSP-205R, ALCOSWITCH C12
- U1, Comparator, Dual Voltage, NATIONAL SEMICONDUCTOR LM393N
- U2, Timer, NATIONAL SEMICONDUCTOR LM555CN
- U3, Timer, Long Range, EXAR XR-2243CP

FIGURE 2. Schematic diagram of the digital current capacity tester.

TABLE II. Voltage Cutoff Selector S2

Switch Position	Nominal Battery Voltage (volts DC)	Cutoff Voltage (volts DC)
#1 (2 cells)	2.5	2.00
#2 (4 cells)	5	4.00
#3 (5 cells)	6.25	5.00
#5 (10 cells)	12	10.0

#1). Using either a charged battery pack or a DC power supply, one measures the actual current through the collector of Q1 with a milliammeter. Assuming that the collector current is measured to be exactly 50 mA, the LCD must increment once every 72 seconds to provide an accurate readout of current capacity. While observing the LCD readout, a stopwatch is used to measure the time it takes the least significant digit (represents 1 mA·h) to change. Any deviation from the 72-second interval is corrected by adjusting R1. The procedure is repeated for the other potentiometers using switch positions #2 and #3 (Table I).

In the second calibration method, the period of the pulse train from pin 2 of U3 is measured. While pin 3 supplies pulses with a period of 2048 RC, the secondary output at pin 2 consists of pulses with a period of 2RC. Since pin 2 is 1024 times faster than pin 3, considerable time can be saved by attaching an oscilloscope to pin 2. For discharge current rates of 50 mA, 200 mA, and 400 mA, the period of the pulse train would be 70.3 ms, 17.6 ms, and 8.8 ms, respectively. Deviations of the standard discharge rates can be easily compensated using $T_{pin 2} = 3.5156 \text{ mA}\cdot\text{s}/I_C$, where I_C is the discharge rate (in mA). For even faster results, the oscilloscope can be replaced with a digital frequency counter. Convert period into frequency using the relationship $f = 1/T$.

Once the capacity tester has been calibrated, it is ready for use. Batteries to be tested must first be charged, but it is recommended that they rest for 24 to 48 hours before testing. Without this wait, inflated capacity readings are obtained, particularly from older batteries.

Use of the tester to determine the current capacity of a battery is as follows. With the power off, the proper discharge rate and voltage cutoff for the battery to be tested is selected with the slide switches on one of the tester's four pc boards (Tables I and II). The battery is connected to the input jack for that pc board using a suitable patch cord. The AC power switch is then turned on, and the pushbutton above the inserted patch cord is depressed. The LED on the pc board will be illuminated, and the digital display will increment as the battery is discharged at the preselected, constant-current rate. When the preselected battery cutoff voltage has been reached, discharging stops, the LED turns off, and the final mA·h figure remains displayed on the LCD until power to the capacity tester is switched off.

The capacity in milliampere-hours for a new battery should exceed its manufacturer's rating because the capacity tester provides a less strenuous test. Battery manufacturers often base current capacity on a one-hour discharge rate to 1.0 V per cell.⁽³⁾ The capacity tester will discharge a good, fully-charged battery to 1.0 V per cell in approximately ten hours. This ten-hour discharge more closely approximates the discharge rate for typical industrial hygiene equipment so that the battery capacities mea-

sured are more accurately applied to such equipment. Because the capacity tester provides a less strenuous test, the user can rightfully be concerned when a capacity measurement goes below a manufacturer's rating. Again, it is the responsibility of the user to determine his/her needs because the battery may still meet the application's requirements.

Although batteries can be tested before use to determine their suitability for a particular task, a program of regular testing is preferable. Regular testing provides a history of a battery's capacity upon which usage decisions can be made. The frequency of battery testing will depend on the condition of the batteries in the inventory but will typically be three to eight weeks. Battery tests will divide a battery inventory into three categories relative to the battery manufacturer's ratings: 1) those that routinely test above their rating, 2) those that test below one-half their rating, and 3) those that test below their rating but better than one-half their rating. Batteries in the first category can be used as needed with a high degree of confidence. Batteries in the second category should not be used in any application, but should be recharged and retested before the battery pack is discarded. Batteries in the third category can still be used for some applications if better batteries are not available. However, these batteries should be tested before use. Since battery capacity in milliampere-hours is directly proportional to the hours of service available from an instrument, knowing the actual capacity of a battery allows an estimate of operating time. For example, if a battery that is at the manufacturer's rated capacity can power an instrument for ten hours, but the only available battery is at 80 percent of that capacity, the instrument will operate for eight hours.

Conclusions/Recommendations

Manufacturers of battery-powered instruments, as routinely used by the industrial hygienist, have been unwilling to provide their equipment with a reliable means of evaluating battery performance. Recent design improvements, as a whole, have focused on compensation systems for inadequate battery voltage levels. While this may reduce the impact of a battery problem, it does not identify one until after the fact. Until capacity testing is incorporated into the design of battery-powered instruments, there will be a periodic need to judge those batteries externally.

Although there are many commercial battery testers available, it is difficult to find one that measures current capacity. Typical testers simply check battery terminal voltage, which is not a true indicator of the energy available from a nickel-cadmium battery. Use of the battery capacity tester described provides increased confidence in any battery-powered instrument, old or new.

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