SAMPLE WRITTEN REPORT

TESTING COMMERCIALLY AVAILABLE BATTERIES

by

Albert Einstein, Max Planck, Marie Curie, Robert A. Millikan, Isaac Newton and Archimedes

Abstract

A large range of batteries is commercially available these days some claiming superior performance but at a significant cost. This report details tests conducted to measure the service time and rated capacity of 4 such AA batteries manufactured by Eveready under the names: General Purpose, Heavy Duty, Super Heavy Duty and Energizer. The alkaline based Energizer is shown to have a significant performance advantage but the best performance per cost was displayed by the General Purpose battery. Measurement of the open circuit voltage and internal resistance are shown to be good indicators of the battery condition.

Introduction

In recent years the market place has been saturated with various types and models of small electrical batteries. These range from the standard primary dry batteries to the high power alkaline primary batteries and the relatively new rechargeable secondary batteries. Despite their very similar appearance and apparent ability to fulfil most uses the prices per unit range from less than $0.25 for general purpose batteries to over $10 for rechargeable batteries. This means the comparison of performance per price and the question of appropriateness of the various batteries for particular uses are very important issues.

This report contains a description of experiments undertaken on various types of AA cells (the common Zn-C and newer alkaline batteries) to test their performance. The tests included simulated continuous use under high and low power demands. This allows not only a direct comparison of the various models and types of batteries but also their appropriateness for high and low power demands. The results obtained are also compared to the manufacturer's technical data where available.

Theory

All dry cells whether the common Zn-C, alkaline or rechargeable Ni-Cd cell produce a current by a series of electrochemical oxidation-reduction reactions. In the Zn-C battery a zinc can forms the anode and serves as the mechanical container for the cell. This is usually covered by protective and insulating layers of plastic and paper. The cathode consists of a mixture of powdered manganese dioxide and carbon moulded onto a central carbon rod. The anode and cathode are separated by an electrolyte made from a paste of ammonium chloride and zinc chloride. A complicated sequence of reactions occurs both at the cathode and in the electrolyte: the overall reaction can be considered as the oxidation of zinc at the anode and the reduction of manganese at the cathode.

In the case of alkaline cells the reactions can be thought of as similar and in fact both a zinc can and manganese dioxide are used. The main difference is the use of potassium hydroxide as the electrolyte. This is a much better conductor than the ammonium chloride and zinc chloride paste and allows the cell to generate much higher currents. It is usually recommended by the manufacturers for high power applications.

An ideal battery (or voltage source) can supply a given voltage independent of the load resistance. A real battery, however, has an internal resistance and hence the voltage measured across its terminals depends on the load. As such a simple model for a battery is an ideal battery with a resistor in series, as indicated in Fig. 1

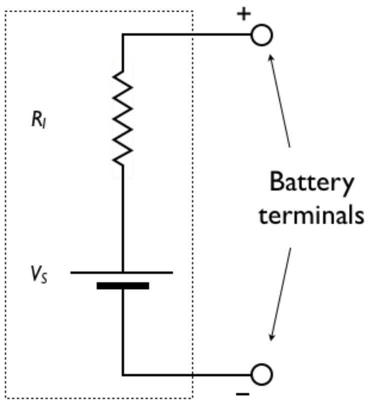

Figure 1: *Equivalent circuit for a real battery.*

Experimental

Tests were performed on a selected range of batteries. The following batteries were included in the tests. EVEREADY General Purpose, EVEREADY Heavy Duty, EVEREADY Super Heavy Duty, ENERGIZER Alkaline.

All the batteries were purchased brand new in packs of 4.

Two series of tests were conducted. In Series 1 the open circuit voltage (OCV) and internal resistance of each battery were measured using a voltmeter (Yokogawa DMM Model 7532-02) and a known resistor. The OCV was measured by simply placing the voltmeter across the terminals of the battery as indicated in Fig. 2.

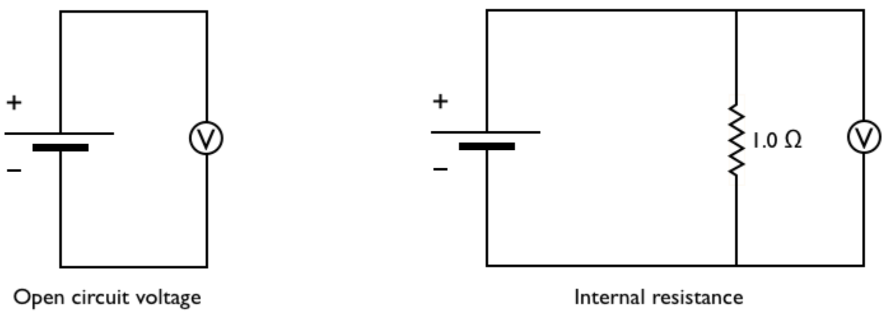

Figure 2: *Circuits used to measure the OCV and internal resistance of batteries.*

This measurement was used along with a measure of the voltage drop across a 1 Ω resistor to calculate the internal resistance of each battery. Considering the model of a real battery discussed earlier and the circuit shown in Fig. 2 we obtain the following relation,

$$V_s - IR_I - V = 0 \tag{1}$$

$$V = V_s - IR_I \tag{2}$$

where V_s is the ideal voltage of the battery, V the measured voltage drop across the resistor, I the current through the resistor and R_1 is the internal resistance. From the measurement of V

across the 1 Ω resistor the corresponding value of I was calculated while for the measurement of the OCV I was assumed to be zero (the internal resistance of the voltmeter was given as 11 $M\Omega$). The internal resistance of the battery was then calculated using the following expression

$$V = \frac{V_{OCV} - V_{1\Omega}}{I_{1\Omega}} \tag{3}$$

In the second part of the experiment, Series II, the batteries were tested under operating conditions. The voltage applied by each battery was monitored as a function of time for 2 different fixed load resistor values, 2 Ω and 100 Ω (corresponding to nominal currents of 0.75 A and 15 mA respectively). A different battery of each type was used for each test. The tests were designed to represent different power requirements, high and low respectively. The voltage was monitored until it dropped to 0.9 V. In the case of the high power tests the data was collected by hand using a voltmeter and wrist watch. For the low power tests the time taken for the voltage to drop to the required level meant that a computer controlled data acquisition system had to be used. This allowed the collection of data around the clock for long periods of time. The PC-26 data acquisition card was used and a program written in Pascal to collect and store the required data. This data not only allows a quick comparison between the various batteries but also a calculation of the ampere-hour capacity.

At the conclusion of the Series II experiments the OCV and internal resistance of the batteries were measured once again.

Results

The OCV for each battery used in the tests is shown in Table 1.

Table 1 : *Measurements of OCV for the various batteries.*

Battery	$V_{1OCV}(V)$	**Uncertainty** (V)	$V_{2OCV}(V)$	**Uncertainty** (V)
General Purpose	1.473	± 0.008	1.471	± 0.008
Heavy Duty	1.527	± 0.009	1.527	± 0.009
Super Heavy Duty	1.753	± 0.010	1.752	± 0.010
Energizer	1.581	± 0.009	1.579	± 0.009

Since 2 batteries of each type were going to be used for the Series II tests the results in Table l indicate the measurements for 2 batteries. The uncertainties indicated were calculated using the manufacturer's specifications for the calibration uncertainty in voltage readings.

Equation 3 was used to calculate the internal resistance of the batteries. The resistance was measured accurately using a Keithley 160B meter. The uncertainties indicated were

Table 2 : *Calculation of the initial internal resistance for the various batteries.*

Battery	$R_{1I}(\Omega)$	**Uncertainty** (Ω)	$R_{2I}(\Omega)$	**Uncertainty** (Ω)
General Purpose	0.49	± 0.02	0.47	± 0.02
Heavy Duty	0.51	± 0.02	0.52	± 0.02
Super Heavy Duty	0.47	± 0.02	0.45	± 0.02
Energizer	0.53	± 0.02	0.51	± 0.02

obtained by combining the uncertainties in the voltage measurements. The uncertainty in the resistance was neglected since it was so small. The results for the internal resistance are presented in Table 2.

The results for the Series II tests are indicated in Fig. 3 and Fig. 4 showing how the voltage supplied varies with time. Voltage readings from the PC-26 card have a resolution of 0.0025 V and calibration uncertainty of 0.5% of reading. The time was obtained from the computer's clock and is accurate to within a few seconds. Measurements were taken every 10 minutes. For quick reference the time taken to reach the cut-off voltage of 0.9 V is presented in Table 3 for both sets of graphs.

Table 3: *Service times for high and low power tests to end voltages of 0.9 V.* Cost of 4-packs also indicated.

Battery	**High Power Time(hrs)**	**Ratio**	**Low Power Time(hrs)**	**Ratio**	**Cost($)**
General Purpose	0.504	1	33.2	1	0.99
Heavy Duty	0.648	1.29	59.7	1.80	2.25
Super Heavy Duty	0.759	1.51	65.3	1.97	3.35
Energizer	2.64	5.24	160	4.82	5.69

The capacity in ampere-hours of the batteries during the tests was also calculated using the expression

$$Rated\ capacity = \int I dt = \int \frac{V}{R} dt \tag{4}$$

This was obtained by taking the area under the graphs in Fig. 3 and Fig. 4 divided by the load resistance. The capacity for both high and low power uses is presented in Table 4. Typical uncertainties in the capacities are less than 0.5 %.

At the end of the Series II tests the OCV and internal resistance of the batteries was determined once again. The results are indicated in Table 5. Note that the batteries labelled 1 were used in the high power tests and those labelled 2 in the low power tests.

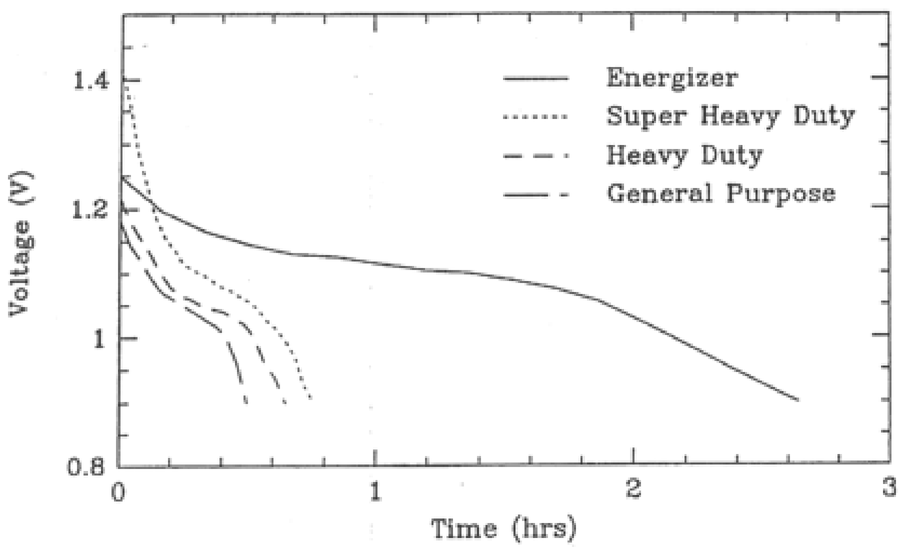

Figure 3: *Measurements of voltage supplied as a function of time for a constant load resistance.*

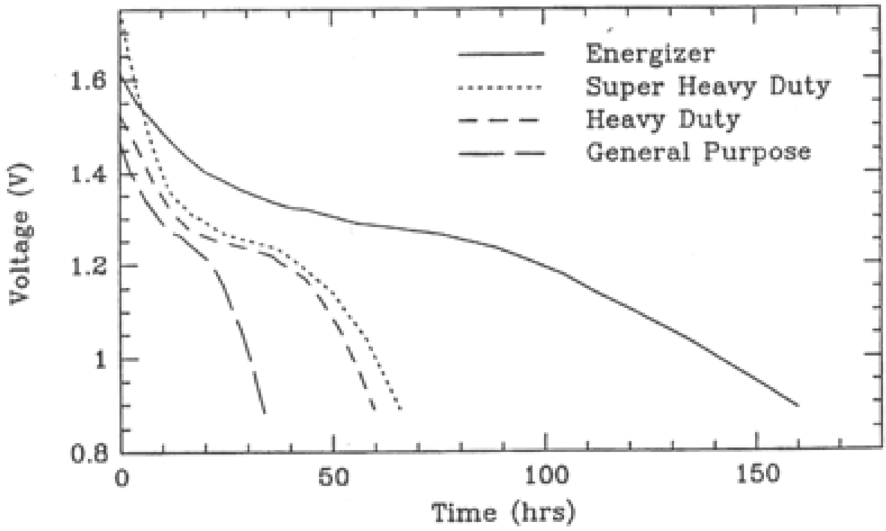

Figure 4: *Measurements of voltage supplied as a function of time for a constant 100 Ω load resistance.*

Table 4: *Calculated values for the capacity to a voltage of 0.9 V. for both the high and low power tests. Manufacturer's values are also included for comparison. The range indicates differences due to high and low power demands.*

Battery	**High Power Capacity** ($mA.hrs$)	**Low Power Capacity** ($mA.hrs$)	**Manufacture's values**
General Purpose	265	402	240-400
Heavy Duty	341	733	320-75
Super Heavy Duty	423	817	400-800
Energizer	1450	1890	1440-1850

Discussion

The AA batteries used in these tests are rated by the manufacturer at a nominal voltage of 1.5 V. Initial measurements of the OCV for the various batteries available indicate a significant range in values from 1.47 V to as much as 1.75 V. These values seem to be consistent between batteries bought in the same packets. One possible explanation for low readings could be deterioration of the batteries due to shelf life. Although they were purchased brand new the time and conditions under storage may vary. Such factors have been shown to influence battery characteristics (Cahoon and Heise, 1976). It has also been noted that the presence of artificial manganese dioxide tends to increase the OCV (Muller, Tye and Wood, 1965). Based on our measurements of OCV it is highly likely that the Eveready Super Heavy Duty batteries used had a significant proportion of artificial manganese dioxide. However, this is only one possible explanation.

The internal resistance of the various batteries also shows a significant variation and strong correlation with batteries from the same packet.

Comparison of the initial and final measurements of OCV and internal resistance clearly indicates that OCV drops with usage whilst the internal resistance increases. This means that together the OCV and internal resistance can be used to indicate the relative condition of a battery i.e. whether brand new or used for a significant time. The decrease in OCV can have

Table 5 : *Measurements for the OCV and internal resistance at the conclusion of the service tests.*

Battery	$R_{1I}(\Omega)$	$V_{1OCV}(V)$	$R_{2I}(\Omega)$	$V_{2OCV}(V)$
General Purpose	1.473	± 0.008	1.471	± 0.008
Heavy Duty	1.527	± 0.009	1.527	± 0.009
Super Heavy Duty	1.753	± 0.010	1.752	± 0.010
Energizer	1.581	± 0.009	1.579	± 0.008

significant consequences on the apparent battery life time in the case of devices that require a given minimum voltage to function e.g. logic devices. The increase in internal resistance implies battery efficiency decreases with usage and this effect is even more important for high power applications where the load resistance is comparable to the internal resistance.

Looking at the graphs from the Series II tests we can identify 3 main common features: an initial steady decrease in the voltage supplied; a plateau region of more gradual decrease in voltage; and finally an extended region of greater voltage decrease. The most significant differences are evident in the plateau region. The extent of this region and the voltage at which it occurs depends on the battery type and the application (high or low power demands). This can again influence the apparent life time of batteries depending on the minimum voltage or power required by a device.

In order to use the data collected in the Series II experiments to make a comparison of the various batteries we must select some criteria. Two results have been chosen, the time taken to reach a supply voltage of 0.9 V and the capacity available to that stage. The cut-off value of 0.9 V represents a significant drop in voltage and will probably produce noticeable deterioration in performance, signifying 'dead batteries'. Also since this value occurs well inside the final region of steady voltage decrease the conclusions drawn are equally valid for a range of similar cut-off voltages (0.8 - 1.0 V).

Table 3 indicates the times taken to reach a cut-off value of 0.9 V (the service time) for the various batteries in both the high and low power tests. For ease of comparison these times have been normalised to the smallest time. There is a significant difference evident between the alkaline Energizer and the other normal Zn-C batteries. In addition there is also a difference in relative service time between the high and low power tests. The Energizer clearly displays higher performance gains for high power applications. The cost of a 4-pack of batteries is also included in Table 3 to enable a cost-performance assessment. It is clear that the General Purpose batteries offer the best performance per dollar in both high and low power applications. The Energizer batteries, however, offer the convenience of significantly longer service with a single set of batteries. This means for some applications it will not be necessary to provide additional sets of batteries and no need to change them. It is this convenience that must also be considered. Certain applications require long service times without the possibility of changing batteries e.g. running an experiment in the field. In such cases the Energizer is the preferred choice. The calculated capacity is indicated in Table 4 and the manufacturer's values are also included for comparison. The manufacturer's values are represented as a range that includes results from high and low power applications, continuous and intermittent use. The notes provided state that the lower values correspond to high power demands while the higher values to low power demands. This corresponds very well with our results and indeed the actual rated capacity values also agree with the manufacturer's specifications. Again in terms of cost-performance the General Purpose batteries offer the best value for money.

Calculation of the internal resistance of the batteries after use shows a significant increase of resistance with usage. The batteries used during the low power tests have deteriorated more in that their OCV is much lower than those used in the high power tests. This accounts for their much higher internal resistance. Such measurements suggest that the OCV and internal resistance of a battery are good indicators of the condition of that battery.

Conclusion

In tests conducted to determine the rated capacity and service time of various AA batteries (Eveready General Purpose, Heavy Duty, Super Heavy Duty and Energizer) significant performance differences were evident. In both high and low power tests the General Purpose battery produced the best performance per cost. However, the significantly longer service time and larger rated capacity of the Energizer makes it more suitable for high power applications or where long service times are required. During the tests it was clear that the OCV of batteries decreases with usage while the internal resistance increases. Measurements of these quantities serve as good indicators of the condition of a given battery provided typical values are known.

References

[1] Cahoon N.C. and Heise G.W., (1976) *The Primary Battery: Volume II*, John Wiley & Sons Inc

[2] Muller J., Tye F.L. and Wood L.L., (1965) *Batteries 2* Pergamon Press Ltd.

[3] Halliday D., Resnick R. and Walker. (1993) *Fundamentals of Physics*, 6th Edition John Wiley & Sons, Inc.

Acknowledgements

Albert Einstein and Max Planck	Wrote data acquisition program and set up apparatus for automated Series II experiments. Performed some calculations on rated capacity and internal resistance.
Marie Curie and Robert A. Millikan	Performed Series I experiments and high power tests for Series II experiments.
Isaac Newton and Archimedes	Prepared report and talk. Responsible for research and obtaining manufacturer's data sheets.

Appendices

Pascal Program for data acquisition card Program listing (omitted for sample report). Manufacturer's data sheet - photocopy is sufficient (again omitted for sample report).