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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON

Letter Circular
LC 677

January 21, 1942

Electrical Characteristics of Dry Cells and Batteries

Contents

I. General Information

The new American Standard Specification for dry cells and batteries, C18-1941, was approved by the American Standards Association (29 West 39th Street, New York) on November 28, 1941. This specification was prepared by a committee which included representatives of the industry, large industrial users of batteries and several of the Government departments. It covers a wide variety of sizes and types of dry cells and batteries, including miniature cells recently developed. The new standard specification is being printed in Circular No. 435 of the National Bureau of Standards.

Many new uses for dry cells have arisen within the last year or two. For these and others still to come, it is advantageous to employ the standard sizes of cells and batteries as given in the specification whenever possible.

The Federal Specification, W-B-101a, last issued in May 1935, is being revised to conform to the technical requirements of the new American Standard. When issued, the new Federal Specification will be designated as W-B-101b.

Many inquiries are received at the National Bureau of Standards about operating characteristics of dry batteries. An attempt will be made in this brief summary of available information to answer questions relating to size, output and low-temperature characteristics of the cells. A more adequate publication to supersede the familiar circular No. 79 entitled, "Electrical Characteristics and Testing of Dry Cells" which was last published in 1923 is in preparation, but this will not be available for some time. In the meantime, it is hoped that this leaflet may be of service to those who use dry batteries in the operation of defense equipment.

The data given in this leaflet are intended to be illustrative of the behavior of dry batteries. The numerical values given in the tables are based on tests, but these values should not be construed as applying exactly to any particular make or type of cell. Relative performance under varying conditions is more significant than the precise values.

II. Standard sizes of cells, dimensions and weight

The sizes of cells recognized as standard are listed in table 1, which includes also the approximate volume and weight of the cells. When cells of any particular size are assembled into batteries the weight of the battery will be the aggregate weight of the cells plus the weight of the structural materials exterior to the cells. No definite statement about the latter can be made. The excess weight of the battery over the aggregate weight of the cells is usually in the range of 5 to 15 percent.

All of the cells listed in table 1 are cylindrical in form, but cells of other forms, such as flat cells, may be used in batteries, subject to specified output and dimensions for the particular battery.

III. Average Output on Standard Tests

Dry cells and batteries are subject to tests which should simulate working conditions. The test which best represents any particular service is that which most nearly duplicates the rate of energy output of the battery when in actual use. There is no direct relation between the results of continuous tests and intermittent tests of longer duration.

Table 1.--Sizes of cylindrical dry cells

Cell Designation	Nominal Dimensions Diameter inches	Nominal Dimensions Height inches	Approximate Volume cubic inches	Approximate Weight pounds	Principal uses
AA	17/32	1 7/8	0.42	0.033	Flashlights, radio and miscellaneous
A	5/8	1 7/8	0.57	0.045	Radio B batteries
BB	3/4	1 5/16	0.58	0.046	Flashlights, radio and export
B	3/4	2 1/8	0.95	0.077	Radio B and C batteries
C	15/16	1 13/16	1.25	0.10	Flashlights
CD	1	3 3/16	2.51	0.20	Hearing aid batteries
D	1 1/4	2 1/4	2.76	0.22	Flashlights and radio
E	1 1/4	2 7/8	3.52	0.28	Portable telephones
F	1 1/4	3 7/16	4.22	0.35	RR lantern, group and radio
G	1 1/4	4	4.92	0.40	Large B batteries
J	1 1/4	5 7/8	7.20	0.60	Group batteries
No. 6	2 1/2	6	29.3	2.2	Telephone, ignition and general purposes.
Miniature Cells					
R	17/32	1 5/16	-	-	Mostly radio
P	17/32	1	-	-	" "
N	7/16	1 1/16	-	-	" "
M	17/32	3/4	-	-	" "
K	17/32	1/2	-	-	" "

It is not practicable to include any complete description of the tests in this leaflet. They are familiar to most users of batteries and are available (except for the new requirements for B batteries) in specifications previously published. Complete information will be available in Circular 435, when issued.

The standard temperature for dry-battery tests is 21°C (70°F) unless otherwise stated. Recently, there has been increased interest in the performance of all kinds of batteries at low temperatures and a later section of this circular contains the results of various tests on dry batteries at such temperatures.

The output of a given type of battery on standard tests is usually expressed as the time in days, hours or minutes that the battery can maintain a closed-circuit voltage above a specified cut-off voltage which marks the end of the test. Except for B batteries, these cut-off voltages are essentially the same as for tests described in the earlier specifications. The present cut-off voltage for B batteries is given in the new American Standard specification as 15 volts for each section of 22 1/2 volts (nominal voltage), instead of 17 volts formerly specified. Much of the radio equipment now is usable to lower B battery voltages. The Radio Manufacturers Association recognized this tendency to go to lower voltages in its Standard data sheet No. 408B, dated January 22, 1941, specifying 17, 15 and 12 volts as optional cut-off voltages. The proper choice of the end point depends on the characteristics of the apparatus with which the batteries are used.

Another recent change in procedure for testing B batteries is the increased current drain on all but the smallest sizes. The 5000-ohm test, commonly used in the past, is now specified only for the smaller sizes of cells, N and P. The 2500-ohm test is specified for cells of the AA, A, BB, B and D sizes. The 1250-ohm test is also specified for D-size of cells and for the larger cells F and G. Each of these resistances applies to tests of 22 1/2-volt units in the battery. The user should specify the cut-off voltage, 17, 15 or 12 volts, best suited to his needs.

Average results of tests of first-grade batteries, made in 1940, are given in tables 2, 3, and 4. These tables are limited to include only those brands of batteries which fulfilled the requirements of the new American Standard Specification C18-1941 or the Federal Specification, W-B-101a. Numbers in parenthesis appearing in some of the tables are the minimum required performance figures of the new American Standard specification. Data given in the tables should be construed to apply to the industry as a whole rather than to any particular make or brand of batteries.

IV. Capacity (Approximate) in Ampere Hours

Because dry batteries are ordinarily tested on circuits of constant resistance, the results are usually expressed as the time of discharge rather than as the capacity in ampere hours. The ampere hours can be calculated, however, by determining the average value of the current. As a first step the voltage throughout the test should be plotted and the average voltage determined. From this and the known fixed resistance the average current is computed. This in turn is multiplied by the total time of actual discharge.

The voltage characteristics of various makes and brands of dry cells differ and, therefore, the average current delivered by any particular cell can be regarded as only an approximation of the performance of other cells and batteries under comparable conditions.

Table 2.--Flashlight batteries

Average test results of various brands (1940) which comply with the requirements of ASA specification shown in parenthesis.

Part 1.

Type of battery	Number of brands	Size of Cell	Intermittent test: Household test minutes	Continuous tests: Initial minutes	Continuous tests: after 6 months minutes
General purpose	8	AA	85 (65)	32(*)	22(*)
" "	14	C	331 (300)	131(*)	118(*)
" "	21	D	723 (600)	459(*)	391(*)

Part 2.

Type of battery	Number of brands	Size of Cell	Intermittent tests: Light minutes	Intermittent tests: Heavy minutes	Intermittent tests: Lantern hours
Industrial type	9	D	1084(850)	842(750)	--
Railroad lantern type	4	F	--	--	49(45)

*Continuous tests are not required by the ASA specification.

Table 3.--Radio B batteries

Average test results on various brands (1940) complying with the Federal Specification W-B-101a, to 17 volts.

(Tests made on 22 1/2-volt units)

Type of battery	Number of brands	Size of Cell	Intermittent tests 5000 ohms hours	Intermittent tests 1250 ohms hours	Continuous tests 5000 ohms initial hours	Continuous tests after 6 months hours
Small	6	A	221	-	179	179
Small	13	B	387	-	340	329
Medium	13	D	994	280	1245	1170
Large	11	F	-	505	2335	2179
Large	6	G	-	634	2964	2745

Table 4.--No. 6 and Group Batteries

Average test results of various brands (1940) complying with requirements of ASA Specification, shown in parenthesis.

Type of cell	Number of brands	Size of Cell	Intermittent tests Light days	Intermittent tests Heavy hours	Continuous Tests Initial hours	Continuous Tests after 6 months hours
Industrial	3	No.6	350(275)	123(100)	428(*)	418(*)
General purpose	13	No.6 & group	258(200)	83 (70)	296(*)	278(*)
Telephone	4	No.6	273(250)	-	-	-
Special telephone	11	No.6	360(325)	-	-	-

*Continuous tests are not required by the ASA specification.

There are other factors also which affect the ampere-hour capacity of dry batteries. (1) Temperature-see Section V of this circular, (2) The cut-off voltage-the capacity delivered is greater as the cut-off voltage is lower, (3) The relative time of discharge and recuperation--the performance is normally better when the discharge is intermittent, (4) The rate of discharge--the capacity is greater as the discharge current is less, down to a certain point beyond which the service efficiency decreases because the spontaneous reactions within the cells become an increasingly important factor. The point of maximum service efficiency of the cell varies with the make and type of cell and the conditions of its use. That is, whether the drain is continuous or intermittent, whether the temperature is low or high and whether the cut-off voltage is high or low. No very definite statement can be made, but the maximum service efficiency for continuous discharge of a No. 6 cell is obtained on a circuit of 60 to 100 ohms or at a current of 0.01 to 0.02 ampere. For smaller cells this current is proportionately less. In general, other considerations of size, weight, availability, convenience and initial cost outweigh too meticulous attention to conditions of the ultimate service efficiency which can be attained.

Table 5.--Relative ampere-hour capacity of a No. 6 cell at various rates of discharge and to various cut-off voltages.

		Capacity		
Current	Cut-off Voltage	Discharged 4 hours/day	Discharged 8 hours/day	Discharged 24 hours/day
ampere	volts	amp-hr	amp-hr	amp-hr
0.1	0.9	40	36	28
0.1	1.0	37	32	23
0.1	1.1	34	28	21
0.2	0.9	30	24	14
0.2	1.0	29	22	12
0.2	1.1	27	20	11
0.3	0.9	25	13	10
0.3	1.0	23	12	9
0.3	1.1	19	11	8
0.5	0.9	16	9	-
0.5	1.0	15	8	-
0.5	1.1	12	7	-
0.7	0.9	9	-	-
0.7	1.0	8	-	-
0.7	1.1	5	-	-

Table 6.--Approximate Capacity of Small Dry Cells

(Intermittent light service, 5 minutes discharge per day through 4 ohms per cell to 0.75 volt per cell)

Cell Designation	Approximate Capacity ampere-hours
AA	0.4
A	0.6
B	1.1
C	1.5
D	3.4
E	4.3
F	5.2
G	6.1

Table 7.--Approximate ampere-hour (amp-hr) and watthour (whr) capacity at various current drains.
(Cut-off voltage 1.13 volts per cell)

Continuous drain	Size A		Size B		Size D		Size F	
	amp-hr	whr	amp-hr	whr	amp-hr	whr	amp-hr	whr
ma								
10	0.38	0.46	0.70	0.86	3.20	4.00	7.00	8.70
25	0.20	0.25	0.37	0.47	1.50	1.89	3.50	4.40
50	0.14	0.17	0.28	0.35	1.05	1.29	2.00	2.45
100	0.10	0.12	0.18	0.22	0.45	0.55	1.20	1.47
150	0.07	0.09	0.15	0.18	0.33	0.41	0.66	0.79

Table 5 gives the ampere-hour capacity of a No. 6 dry cell for various conditions of use. Table 6 gives the approximate capacity of smaller sizes of dry cells when tested under specified conditions of the so-called household intermittent test, that is, 5 minutes discharge once in 24 hours through a resistance of 4 ohms per cell to a cut-off voltage of 0.75 volts per cell. Table 7 gives the approximate ampere-hour and watt-hour capacities of several sizes of cells used in Radio B batteries at various constant current drains from 10 to 150 milliamperes. The cut-off voltage for these is 1.13 volts per cell

If comparison is made of the discharge of any particular kind of dry cell through a constant resistance circuit with comparable discharge at a fixed current, it is found that the latter is a more severe test. This is because both voltage and current decrease during discharge through the fixed resistance, but when a comparable current is held constant throughout the test, the load on the battery, as it approaches exhaustion, is proportionately more severe.

V. Effect of Temperature

Low temperatures have a marked effect on the output of dry cells. In a paper* published in 1922 it was shown that dry cells become practically inoperative at a temperature of -21°C (-6°F). More recent determinations have confirmed this conclusion, but there is some variation among different makes and types of cells. Depending on the requirements, some cells may be usable a few degrees lower. Information available now is hardly adequate to answer the many questions which have arisen. The effect of low temperature will be discussed from the standpoint of voltage, flash current, internal resistance, capacity and storage of dry cells.

*Electromotive force of cells at low temperatures, by G.W. Vinal and F.W. Altrup, Sci. Papers, BS 17, 627 (1922), No. 434.

1. Voltage

The electromotive force of the dry cell, that is, the true open-circuit voltage, decreases about 0.02 volt when the temperature is decreased from 25°C (77°F) to -20°C (-4°F). That is, the decrease averages 0.0004 volt per degree Centigrade. This is slightly more than for a lead storage battery. However, the open-circuit voltage is usually measured by a voltmeter which draws a small current from the cell and the effect of temperature on the emf may appear to be greater in proportion as the IR drop in voltage within the cell itself is greater. Using a voltmeter having 100 ohms per volt and a total resistance of 300 ohms the error in measuring emf at -20°C (-4°F) is from 2 to 3 percent depending on the size of the cell. Below the freezing point this error becomes much larger. The relative electromotive force of one brand of No. 6 dry cells at various temperatures is given in table 8.

Table 8.--Relative electromotive force of a No. 6 dry cell at temperatures between +25° and -20°C.

Temperature °C	Temperature °F	Electromotive Force volts	Temperature °C	Temperature °F	Electromotive Force volts
+25	+77	1.577	0	+32	1.566
+20	+68	1.574	-5	+23	1.564
+15	+59	1.572	-10	+14	1.561
+10	+50	1.570	-15	+5	1.558
+5	+41	1.568	-20	-4	1.556

For practical purposes the actual working voltage at the terminals of the cell or battery under specified conditions of load and temperature is of more significance than the emf. Table 9 shows the results of measurements on a cell of size F under such conditions. The values for open-circuit voltage given in this table happen to be higher than those reported for the emf of another cell in table 8. The difference is attributable to inherent differences in materials and construction of the two cells. It is apparent, therefore, that in applying any of these data to a particular cell the relative changes produced by temperature or current drain are more important than actual voltages. Calculations should be based on the measured open-circuit voltage of the particular cell at normal temperature. Data given in table 9 do not apply directly to other sizes of cells, but a rough approximation may be made by assuming the load to be inversely proportional to the ratio of the volumes (see table 1).

Table 9.--Initial voltages of a dry cell, size F, under varying conditions of temperature and current drain.

Temperature		Terminal voltage at indicated drains					
°C	°F	open circuit	.020 amp.	.050 amp.	.075 amp.	.10 amp.	.14 amp.
30	86	1.645	1.641	1.632	1.621	1.612	1.605
25	77	1.644	1.639	1.628	1.617	1.607	1.599
20	68	1.643	1.637	1.624	1.613	1.603	1.591
10	50	1.641	1.634	1.620	1.605	1.592	1.579
0	32	1.640	1.631	1.614	1.595	1.581	1.568
-10	14	1.639	1.627	1.605	1.584	1.564	1.537
-20	-4	1.630	1.61	1.59	1.56	1.54	1.52
-25	-13	1.622	1.60	1.57	1.54	1.51	1.49
-30	-22	1.610	1.49	1.28	1.10	0.96	0.86

2. Flash or short-circuit current

Low temperatures produce a much greater effect on the flash or short-circuit current than on the electromotive force. Short-circuit current is defined as the maximum current, observed on a dead-beat ammeter, which the cell or battery can deliver through a circuit of 0.01 ohm resistance, including the ammeter. Such a measurement is useful as a test of uniformity or to show whether the cells can meet some specified condition requiring large flash current, but it gives no reliable indication of the capacity or quality of the cells for other purposes.

Table 10 gives the average results of measurements of the short-circuit current, as defined above. The figures apply to No. 6 cells and to cells of the D size. Here again the proportional changes produced by temperature variations are of more significance than the actual readings. The table shows that the percentage change for cells differing in volume by a ratio of 10 to 1 is essentially the same at corresponding temperatures above 0°C (32°F). Below this temperature the smaller cell is more seriously affected. If the flash currents of other sizes of cells are known at specified temperatures, an approximation of their performance at other temperatures may be made on the basis of this table.

Table 10.--Flash (short circuit) currents of dry cells

(Average of several brands)

Temperature °C	Temperature °F	No. 6 Cells: Flash Current amp.	No. 6 Cells: Percentage of current at 25°C	Size D Cells: Flash Current amp.	Size D Cells: Percentage of current at 25°C
40	104	35.3	112	7.7	117
30	86	33.2	105	7.0	106
25	77	31.6	100	6.6	100
20	68	29.7	94	6.1	92
10	50	25.7	81	5.2	79
0	32	21.6	68	4.2	64
-10	14	17.6	55	3.1	47
-20	-4	10.0	32	1.0	15
-30	-22	1.0	3	0.1	1.5
-40	-40	0.1	0.3	0.0	0.0
-50	-58	0.0	0	-	-

3. Internal resistance

Decreased flash current at low temperatures is the result of increased resistance of the cells. The internal resistance of a battery varies somewhat with the rate of current discharged. For the present purpose it is defined in terms of the flash current. The formula is $R = \frac{E}{I} - 0.01$ where R is the resistance of the cell, E its electromotive force at a specified temperature, I the flash current and 0.01 the resistance of the external measuring circuit. Table 11 gives the average result of measurements on twelve No. 6 cells of six different brands. At -30°C and below the measurements were limited to one of these brands. This table gives similar data also for cells of size D. It may be noted that the percentage change in resistance is practically independent of the size of the cells at temperatures of 0°C and above. With the average values of internal resistance of various sizes of cells given in table 12 a fair approximation of the average internal resistance of various sizes at specified temperatures may be obtained.

Table 11.--Internal resistance of dry cells

(Flash current method, average of several brands)

Temperature °C	Temperature °F	No. 6 Cells: average resistance (ohms)	No. 6 Cells: percentage of R at 25°C	Size D Cells: average resistance (ohms)	Size D Cells: percentage of R at 25°C
40	104	0.033	87	0.195	86
35	95	.034	89	.202	89
30	86	.036	95	.214	94
25	77	.038	100	.227	100
20	68	.041	108	.246	108
15	59	.045	118	.264	116
10	50	.049	129	.291	128
5	41	.055	145	.322	142
0	32	.061	161	.362	159
-5	23	.068	179	.424	187
-10	14	.077	203	.493	217
-15	5	.095	250	.733	323
-20	-4	.144	379	1.551	684
-30	-22	1.5	4000	15.6	6900
-40	-40	15.0	40000	--	--

Table 12.--Approximate Internal Resistance of Dry Cells

(Average of several brands at 25°C, calculated from flash currents)

Size of Cell	Average Flash Current (amperes)	Internal Resistance of single cell (ohms)
AA	4.6	0.311
C	5.4	.284
D	6.6	.227
F	8.8	.173
No. 6	32.0	.038

When apparatus is designed to operate momentarily on a relatively large current, the internal resistance of the cells becomes important. If the internal resistance of a single cell is too high to provide the current, either two or more cells must be connected in parallel or a larger size of cell selected. Connecting additional cells in series will not accomplish the desired result. Since the internal resistance increases at decreased temperature, calculations should always be based upon the lowest temperature likely to be attained by the battery. This is not necessarily the lowest temperature to which the battery is exposed. The battery does not take the temperature of its surroundings immediately and thermal insulation is helpful.

4. Capacity

The capacity of dry cells is usually expressed as the output of the cells, measured in some unit of time, on some specified test (see Sections III and IV above). The effect of temperature on the output may be expressed as a ratio or percentage based on the normal output. Thus in table 13, the relative capacity of a 22 1/2-volt battery containing F cells at various temperatures is given on the basis of the 1250-ohm test to a cut-off voltage of 15 volts. Actually the capacity for any particular size of cell will vary with the following factors (a) the load, (b) the temperature, (c) the cut-off voltage. Table 13 shows the variation with temperature alone, assuming the specified conditions of the test which define the load and the cut-off voltage. The effect of temperature on the capacity of dry cells is analogous to its effect on other types of batteries.

Table 13.--Effect of temperature on the capacity of dry cells

(Tests on a 22 1/2-volt unit of F cells discharging through 1250 ohms to a cut-off voltage of 15 volts

Temperature		Capacity
°C	°F	(based on value at 70°F taken as 100 percent)
		percent
38	100	140
27	80	115
21	70	100
16	60	90
4	40	69
-7	20	48
-18	0	27
-29	-20	6

5. Storage

The temperature of dry cells and batteries has considerable effect on their shelf life, that is on the length of time they can be stored without serviceability decreasing more than a specified amount. Delayed service tests are made after a specified period of storage at 21°C (70°F). The decrease in service capacity allowed by the specification varies with the type of battery and the test to which it is subjected. For example, after 6 months, an industrial type cell of the No. 6 size on the heavy intermittent test is expected to give 90 percent of the initial requirement. Cells designed for light intermittent drains should normally have better shelf life characteristics than those intended for heavy service. The difference is largely the result of using materials which are the best suited to differing service conditions. The smallest cells deteriorate on the shelf more rapidly than the larger sizes. Specifications for B batteries allow a deterioration of 11 percent in service capacity in 6 months for batteries containing F cells, and 25 percent in the same period for the much smaller cells of size AA. Shelf deterioration should in no case be excessive. In this respect cells of the present day are superior to those made 20 or more years ago.

Shelf tests are distinguished from delayed service tests by the fact that the shelf tests are continued until the open-circuit voltage falls below a specified value. No discharge is made. Such tests apply particularly to radio C batteries, but there are other applications requiring such tests. Table 14 gives the average results of 60 batteries of 20 different brands. While 2 of these batteries lasted 8 years on this test, the table shows that only half of the batteries completed 2 years and only a third of the batteries lasted 3 years. These batteries were stored at 21°C (70°F).

When dry cells are stored for future use, the temperature of the batteries should not be above normal room temperature. Lower temperatures are beneficial because spontaneous reactions occurring within the cells are retarded and evaporation of moisture is less. Table 15 gives the average results on a large number of No. 6 cells stored at several temperatures, including temperatures above and below normal room temperature. Although the difference between the highest, 40°C and the lowest, 9°C, is not very great, the effect on the batteries is remarkable. Those which were stored at 9°C were in better condition at the end of 5 years than the others at 40°C after one year. Dry batteries may be stored at temperatures which

Table 14.--Shelf life of "C" batteries

Batteries contained D size cells, 1 1/4 by 2 1/4 inches. They were stored at 70°F (21°C).

Time	Number of brands	Number of batteries*	Average OCV per battery volts	Average OCV per cell volts
Initial	20	60	4.73	1.57_6
1 year	20	57	4.58	1.52_6
2 years	13	33	4.52	1.50_6
3	11	21	4.50	1.50_0
4	3	8	4.55	1.51_6
5	2	5	4.54	1.51_3
6	2	4	4.46	1.48_6
7	1	2	4.47	1.49_0
8	1	2	4.42	1.47_3

*Batteries were discarded from the test when the open-circuit voltage fell to 4.35 volts (1.45 volts per cell). The OCV is the average of all batteries remaining on test at the end of each period of time.

Table 15.--Effect of temperature on deterioration of No. 6 dry cells in storage

(Average values of open-circuit voltage in volts and percentage of initial values for the flash currents*)

Time	+40°C (+104°F)		+20 to 25°C (+68 to 77°F)		+9°C (+48°F)	
	open-circuit voltage	flash current	open-circuit voltage	flash current	open-circuit voltage	flash current
years	volts	percent	volts	percent	volts	percent
0	1.58	100	1.58	100	1.58	100
1	1.43	28	1.54	83	1.57	91
2	1.27	5	1.51	59	1.55	76
3	-	-	1.49	33	1.54	58
4	-	-	1.48	22	1.53	44
5	-	-	1.46	12	1.52	31
6	-	-	1.28	-	1.48	19

*The flash currents were measured in accordance with the method specified above for short-circuit currents. The actual values in amperes initially ranged from 24 to 34 amperes as several types of cells are included in the average. All measurements were made at 20 to 25°C.

are not below the freezing point of the cells. This is about -21°C (-6°F). Repeated tests have shown, however, that dry cells which have been frozen are usable after they have been thawed and brought to a reasonable operating temperature. When batteries are taken from cold storage, moisture is likely to condense on them ("sweating"). This should be avoided as far as possible since the jackets may be destroyed and electrical leakage increased.