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SYMPOSIUM ON ALUMINUM ELECTROLYTIC CAPACITORS

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INTRODUCTION TO ALUMINUM ELECTROLYTIC CAPACITORS

by

HENRY D. HAZZARD

Introduction

Aluminum electrolytic capacitors were introduced to the industry in the late 1920's and early 1930's. Since that time, a multitude of aluminum electrolytic capacitor configurations have flooded the market. It is the purpose of this paper to express certain views of the present state of the art dealing with this type of capacitor. By so doing, it is hoped that old prejudices which were propagated with the use of very early designs will be overcome.

In an attempt to indicate their present capabilities, the discussion will open with a general explanation of the mechanics of an electrolytic capacitors and what are considered to be the basic application types. This will be followed by detailed breakdown of the geometry of these application types. A disscussion of the merits of the individual styles will be followed by special application problems and solutions to these problems.

Manufacturing Process

For the benefit of those who are not familiar with the mechanics of the aluminum electrolytic capacitor, a brief description will be given of how a typical aluminum electrolytic capacitor is manufactured. Figure 1 is a schematic breakdown of a typical unit. A piece of aluminum foil, sometimes plain but normally etched to increase the surface area, is treated electro-chemically to form aluminum oxide directly on the surface of the foil. This oxide is the dielectric material of the capacitor. It is extremely thin. The thickness of this oxide is a function of the voltage applied during the electro-chemical formation. The higher the formation voltage, the thicker the oxide film.

By definition, capacitance is equal to $\frac{KA}{D}$, where K is the dielectric constant of the dielectric material, A is the surface area of the electrode material, and D is the thickness or distance between the two plates of the capacitor. With an increase in formation voltage, D also increases, thereby reducing the effective capacitance. This difficulty is overcome by etching the surface of the plates to increase the effective surface area of the electrodes. An increase in D also allows higher applied voltages on the finished capacitor.

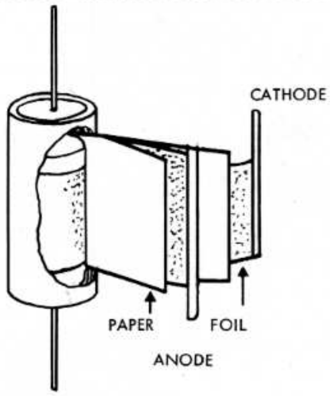


FIGURE 1
CROSS-SECTIONAL VIEW OF A TYPICAL CAPACITOR

Following these procedures, the anode foil has a system of paper spacers applied next to it. The spacers perform two functions. First, they prevent the possibility of direct shorts between cathode and anode foil because of rough surfaces or jagged edges. Secondly, when the capacitors are finally rolled, they are impregnated with an electrolyte. The spacer material absorbs this electrolyte, allowing it to maintain uniform and intimate contact with all of the surface eccentricities of the anode foil.

The last portion of the system is a cathode foil. The cathode foil serves only as an electrical connection to the electrolyte. The electrolyte is, in reality, the cathode. This foil-spacer-foil system is then rolled into a cylinder and impregnated with the aforementioned electrolyte. The electrolyte performs two functions. First, it is the cathode. It maintains contact with the entire surface of the plates, thereby forming a second plate of equivalent area. Further, it has the ability to chemically oxidize any imperfections that might occur. The convolutely wound capacitor section is then inserted into a suitable container and sealed.

Evaluation of Parameters

In order to evaluate the completed, functional capacitors, consideration must be given to the meaningful and measurable parameters. The ones customarily considered when dealing with electrolytic capacitors are the capacitance, d-c leakage current, the equivalent series resistance (ESR) and the dissipation factor.

Capacitance is usually measured on a Wien type bridge with a small amount of a-c voltage applied to the capacitors. Experience has shown that if the RMS, a-c voltage is no more than half a volt, there is no necessity to apply d-c polarizing voltage. In fact, the repeatability and accuracy of the measurement is improved. In general, capacitance will decrease with a rise in frequency and it will increase with rising temperatures.

Similar to tantalum electrolytic capacitors, aluminum electrolytics allow a small amount of direct current to pass through them. This is termed the d-c leakage current. It is the current that passes through the capacitor when a properly polarized d-c voltage is applied. This current normally vaires directly with with temperature and should be kept in mind when considering the use of electrolytic capacitors over a wide temperature range.

The energy losses associated with an electrolytic capacitor are due primarily to its internal resistance (equivalent series resistance). Figure 2 is a simplified equivalent circuit of an electrolytic capacitor. Note that two resistances are indicated. The shunt resistance represents d-c leakage current. The series resistance is responsible for the energy loss and heating effects within the unit. In aluminum electrolytic capacitors, this resistance is due primarily to the spacer-electrolyte-oxide system. Generally, the ESR of an electrolytic capacitor varies inversely with temperature.

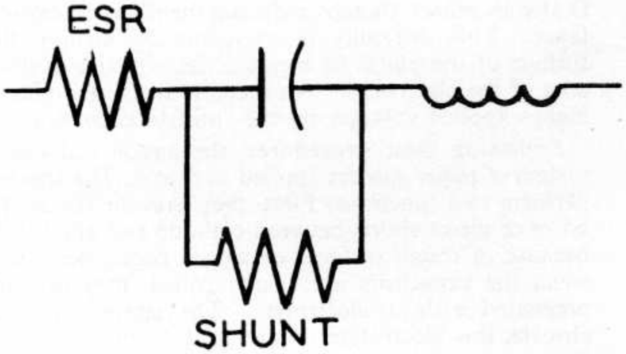


FIGURE 2
EQUIVALENT CIRCUIT OF AN ELECTROLYTIC CAPACITOR

Figure 3 is a typical curve of impedance as a function of frequency. The initial downward slope of the curve at room temperature is due to capacitive reactance. The trough of the curve is almost totally resistive and the upper portion of the curve is due to the self-inductance of the unit. However, if the equivalent series resistance were plotted separately, it would be observed that on the initial downward slope. the ESR decreases up to a frequency of approximately 4 kc and remains relatively constant throughout the remainder of the impedance curve.

The final parameter mentioned was dissipation factor. This is simply the ratio of ESR to capacitive reactance. It is used in practice as most of the precision bridges balance the ESR and capacitance of the units simultaneously. This normally results in a direct measurement of ESR or dissipation factor. Below 15%, power factor and dissipation factor are approximately equal. This establishes a basis for comparison and allows a description of what are considered the four basic application types. Before the description is considered, it is necessary to consider the capacitor section and suitable containers and seals in more detail.

Capacitor Section Design

The basic characteristics of the capacitor depend entirely on the section just described. The basic parameters decided upon also depend entirely upon the section design. The section design is a function of the amount of derating, the type of oxide obtained in the electro-chemical formation, the type and quantity of spacer used, and the choice of electrolyte.

A good electrolytic capacitor cannot be produced until a good section has been designed. However, the useful life of the section can be extended by the proper choice of encapsulant and end seals.

As mentioned in the basic description, the electrolyte is essentially the cathode or counter electrode of the capacitor, and electrolyte-spacer-oxide system determines the ESR of the unit. The electrolyte contains volatile materials, which, if allowed to escape, increases the ESR of the unit drastically. Additionally, drying out of the electrolyte effectively reduces the

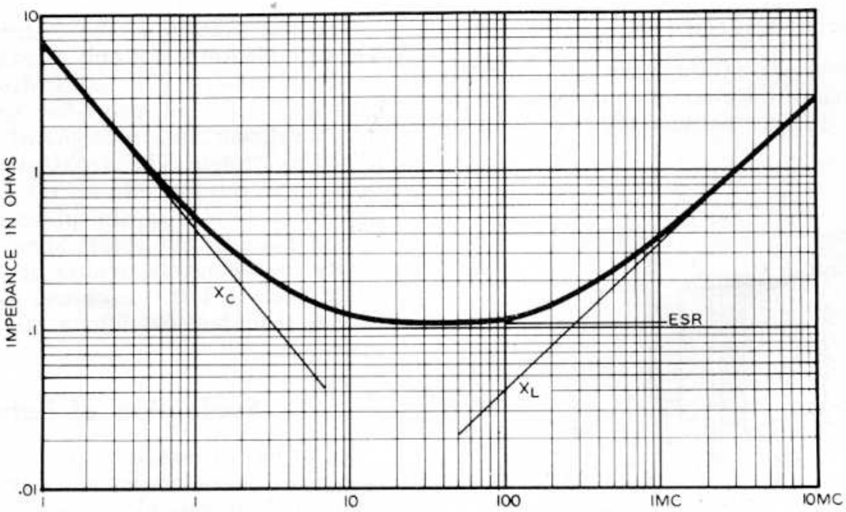


FIGURE 3
IMPEDANCE AS A FUNCTION OF FREQUENCY

cathode area, reducing the effective capacitance of the unit. The selection of end seals and containers for their diffusion properties is extremely important if it is desired to lengthen capacitor life through a reduction in the loss of electrolyte.

In general, there are two design sections available. The so-called "standard" section, which gives satisfactory electrical characteristics and the "premium quality" section, which gives the finest electrical characteristics. Admittedly, interim types can be made, but for the sake of comparison, consider just these two basic types. Regarding hardware, there are also two basic configurations which are termed "commercial" and "premium quality". The premium quality hardware has the lowest diffusion characteristics available today, short of a glass-to-metal hermetic seal. The commercial hardware is an economic compromise using an end seal sufficiently good to prevent physical leakage of electrolyte, but lacking the optimum diffusion characteristics.

Application Styles of Capacitors Available

Combining basic sections and basic hardware, there are four application styles of capacitors. The first is the standard commercial unit, or as it has come to be called, the radio and TV type. This utilizes a standard section and commercial hardware. The unit is used where life span and electrical parameters are not critical.

Next is the instrument grade capacitor utilizing the premium quality section and commercial hardware. This capacitor is normally used in bridges, vacuum tube voltmeters, oscilloscopes, and other high-quality test equipment. In this market, replacement is not generally a problem nor is extremely long life required. However, during this expectant life, electrical characteristics of the capacitor must be excellent or exceed the commercial unit for acceptable parameter change limits. The third basic application area is the so-called extended life unit. A standard section and premium quality hardware are combined to do precisely what the term connotes, i.e. extend the life of an average section. This is normally employed where use conditions are very benign, for example, 65 C maximum with probably 80% of the rated voltage applied. Replacement is usually a problem however because of the large quantities employed. Business machine systems are an ideal example of such an application.

Finally, consider the premium quality unit, which, as its title denotes, utilizes the finest section and the finest hardware yielding the best electrical characteristics and the longest life possible. Typical applications of this capacitor are in computers, computer power supplies, and high quality commercial and military gear which must endure severe environmental conditions. These definitions may raise numerous questions, but this paper has purposely avoided going into them in detail because such information will be provided in the subsequent presentations.

Basic Considerations in Selecting Capacitor Designs.

Table 1 compares the basic considerations that the majority of application engineers find themselves dealing with. Column 1 indicates the maximum voltages (d-c) normally supplied in the four types.

The second column describes CV products, a method of discussing volumetric efficiency. Considering the CV product in a given case size, obtainable in the premium quality unit, as a base of one, it is seen that the instrument grade unit obtains about 10% more capacitance than the premium quality. The extended life is approximately 30% greater and the commercial unit yields 30 to 40% more capacitance in a given can size at a given voltage.

Items 3 and 4 describe the maximum and minimum temperatures for the various types.

Item 5 describes capacitance tolerances available. Note that in the premium quality unit, it is possible to obtain tolerances as tight as −10, +30%. These are special items supplied upon request.

Items 6 through 12 compare basic parameters. As would be expected, premium quality units exhibit the best electrical characteristics of any of the four types. There is a noticeable shuttling back and forth between extended life and instrument grade in this area. This is due to a compromise condition of premium quality end seals and commercial section vs. premium section and commercial end seals. For this reason, they fulfill definite industrial needs.

TABLE I

	Commercial	Instrument Grade	Extended Life	Premium Quality
1. Volt (maximum)	500	450	450	450
2. CV Product	1.4	1.1	1.3	1
3. Temperature (maximum)	65 C, 85 C	85 C	65 C, 85 C	85 C
4. Temperature (minimum)	−20 C	−20 C or −40 C	−20 C	−40 C
5. Capacitance Tolerance	−10, +100%	−10, +100%	−10, +50%	−10, +30%
6. D-C Leakage Current	3	2	2	1 = Lowest
7. Equivalent Series Resistance	4	2	3	1 = Lowest
8. Impedance	4	2	3	1 = Lowest
9. △Parameter vs. Temp. °C	4	3	2	1 = Lowest
10. △Parameter vs. Time	4	3	2	1 = Lowest
11. A-C RMS	4	2	3	1 = Highest
12. Surge VDC	4	2	3	1 = Highest
13. Reverse VDC	< 1 VDC	2 VDC	2 VDC	2 VDC
14. Polar or Non-Polar	Yes	Yes	Yes	Yes
15. Mode of Failure	Degradation	Degradation	Degradation	Degradation
16. Reliability	4	3	2	1
17. Expected Life	3-5 yrs.	5 yrs.	10 yrs.	10-20 yrs.
18. Price	4	3	2	1

Aluminum, in the presence of air, oxidizes to about the equivalent of a 1 volt electro-chemical formation. Because of basic designs, electrolytic capacitors, in general, may take a 1 to 2 volt d-c reversal for extended periods of time without any visible evidence of degradation within the capacitor.

It is possible to obtain all types as polarized or non-polarized units, the limiting factor being mechanical design.

Item 15 attempts to generalize on the mode of failure for all types of electrolytics. It is shown that the basic mode of failure, regardless of quality, is degradation. This is true in the long run of extended life testing. However, in later presentations, a contradiction will appear to this generalization. It is possible when extremely good section and hardware design are achieved, degradation in the short term is no longer a mode of failure. It may change to some other mode since production irregularities become the major source of difficulties.

Relative reliabilities, based on long term testing and the most stringent environmental conditions, show the premium quality unit to exhibit the highest reliability.

Item 17 is an estimated life under the use conditions which are normally seen by the various application fields and the requirements of these fields.

Last, but not least, is a comparison of prices.

With this basic familiarity of the fundamental types, the symposium will continue with detailed discussions of the families broken down by geometries.

AXIAL-LEAD AND MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS

by

STANLEY W. BUBRISKI

Introduction

As the tantalum capacitor market developed and grew, there was considerable concern for the future of the aluminum electrolytic capacitor. If one appraises the electrolytic capacitor market carefully, it is obvious that, in spite of the advances made by the tantalum capacitors, the aluminum electrolytic has a permanent and growing place in the electronics of today and the future.

Miniature aluminum electrolytics provide the highest capacitance per cubic inch at the lowest cost per microfarad of any type capacitor in use today. In the past, prior to the advent of the tantalum capacitor, aluminum electrolytic capacitors were used in military equipment only when space and weight requirements would not permit the use of paper capacitors. It is interesting to note that in the past five years tremendous strides have taken place in up-grading the aluminum electrolytic through the following improvements.

1. The use of high purity (99.95% minimum) aluminum anode foil.
2. Better and more compatible electrolyte systems.
3. Better understood and improved etching and anodizing techniques.
4. More stringent controls and more frequent process check points.

The "state of the art" of electrolytic capacitors has been developed to such a degree that, today, aluminum capacitors are being widely used in many military applications and are even being proposed in high "reliability" applications such as the Minuteman missile program.

The following discussion will attempt to present an up-to-date picture of the "state of the art" of axial-lead and miniature aluminum electrolytic capacitors.

Miniature Aluminum Electrolytic Capacitors Available

Today, the Sprague Electric Company manufactures a variety of miniature types to fit the needs of commercial radio and television applications on the one hand, and the needs of telephone systems or military applications on the other hand. The various types are illustrated in Figure 1 and their features are summarized in Table 1.

Design and Construction

All these capacitors are made by rolling two layers of aluminum foil separated by porous paper spacers. Usually, the anode foil is oxidized electrochemically. The cathode foil which serves as the counter electrode is normally not oxidized, although it inherently is covered with a very thin oxide film which enables slight voltage reversals in finished capacitors without detrimental effects. The cylindrical capacitor section is impregnated with a conducting electrolyte and the impregnated section is finally housed in appropriate hardware to prevent entry of contaminants and loss of electrolyte.

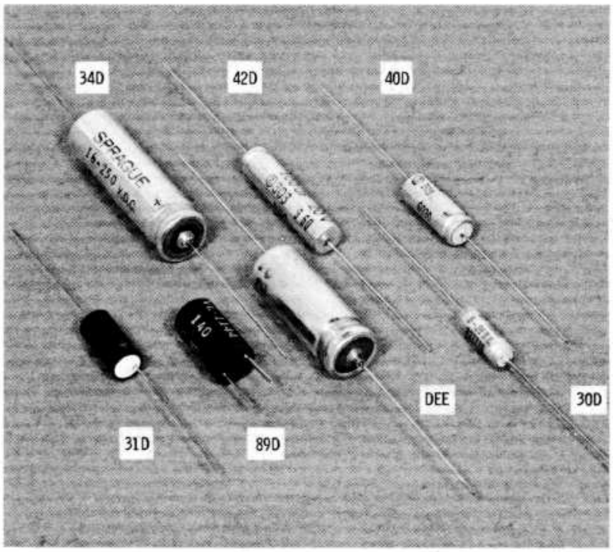


FIGURE 1
VARIOUS TYPES OF MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS MANUFACTURED BY SPRAGUE

TABLE 1
MINIATURE ALUMINUM ELECTROLYTICS

Type	Rated Temperature	Voltage Range	Max. CV Product	Uses	Engineering Bulletin
31D	−20, +65C	1- 25 volts	1,500	Radio, TV	3010B
89D	−20, +65 C	1- 50 volts	25,000	Radio, TV, Printed Circuit	3060A
DEE	−20, +65C, +85 C	3-450 volts	41,000	Radio, TV	3130*
30D	−20, +85 C	3-150 volts	1,800	Business Machines, Mobile Equipment	3110A
40D	−40, +85 C	3-150 volts	1,500	Military Equipment	3205
42D	−40, +85 C	5-150 volts	1,500	Telephone Systems	3410*
34D	−40, +85 C	3-450 volts	22,000	Military Equipment	3411*

*Now in preparation

The Types 31D and 89D, which are rated for 65 C operation, use plastic cases and epoxy end seals, making these capacitors resistant to solvents often used in cleaning printed wiring boards. The use of such materials for cases and end seals limits using these capacitors to temperatures of 65 C and below because of the inability of the plastic case and epoxy end seal to contain the electrolyte at the higher temperatures. It is noted that the 89D is designed with both leads coming out one end to facilitate use in printed circuit boards.

The Types 30D and 40D are different from the others in that the capacitor section is wound on a solid rod or riser which comprises part of the anode lead. The other types contain anode tabs which are tab stitched onto the anode foil. The anode tabs are further attached in various ways to solderable leads.

The Type 42D, which is Sprague's latest contribution to the field of highly reliable miniature capacitors, does not contain a riser-wound section but rather has a unique internal weld connection to an insert contained in the molded cover. Its outstanding feature is the superior seal which is accomplished by using a special molded cover and rubber "O" ring.

It is pointed out that Sprague Electric Company pioneered the use of the "all welded" construction in the 30D design about seven years ago. Many problems arise with aluminum capacitors which use a pressure contact for the cathode electrode or a rivet connection for the anode electrode. These difficulties are magnified in extremely low voltage applications. Since the development of the 30D, Sprague has applied the same principles and has developed all these types which contain welded cathode connections. Types 34D and the new DEE capacitors use the all-welded cathode connection. The Type 34D anode connection is similar to that used in the Type 32D, which has proven itself over many years. The new DEE uses an all new welded anode connection. These connections will be discussed at greater length later. Note also that the cover assembly for Type 34D capacitors uses the molded cover and the Type DEE uses a laminated bakelite-rubber cover. These types are very similar to the DFQ and DEC covers which will be described in detail in a later discussion.

Since galvanic action within a housing is likely to lead to serious trouble, all elements which come into contact with the electrolyte are selected with greatest care to insure that only "compatible" materials are used.

All the metal-encased capacitors can be obtained with insulating sleeves. Various types of sleeves are available, depending on application and cost. The premium grade capacitors use a shrinkable polyester sleeve.

Other differences in the various type capacitors can best be explained by considering some of the manufacturing processes and final inspection. Those capacitors in Table 1 which are designed for −20 C operation can be considered as the standard design while the others may be considered as the premium design. These are not absolute black and white differences since the 30D capacitor can be considered as higher quality than the "standard". For the "standard" design, in-process controls are not as stringent nor the check points as numerous as for the "premium" type. Also, the final testing for the standard design is held to a minimum to keep cost down. Very rarely are lots of commercial type capacitors (those with a standard section design) held for acceptance tests in contrast to the premium type, which are often held until certain performance tests are completed successfully.

Generally, the "commercial" capacitors are designed with less derating because the ratio of anodizing voltage to actual rated voltage is smaller than in the premium grades. They also incorporate a spacer-electrolyte system that does not have the excellent electrical characteristics found in the premium grade capacitors. However, it is emphasized that adequate and long life can be expected if the capacitors are used within their recommended operating ranges of temperature and voltage. The premium grade capacitors contain more foil derating and the spacer-electrolyte combination is such that optimum electrical and life characteristics are obtained.

It is possible to use a premium grade capacitor section with standard grade hardware. For example, Sprague has developed new premium DEE and DFP capacitors composed of premium grade sections and commercial hardware. The DFP capacitor is discussed in detail later. A tentative specification has been written covering this type of capacitor which is used extensively in applications where initial characteristics must be superior and where exceptional life is not required.

Electrical Parameters

The standard capacitance tolerance of all aluminum electrolytic capacitors has been rather broad, ranging from −10, +250% to −10, +50% of nominal rated capacitance. Sprague aluminum electrolytic capacitors exhibit tolerance ranges from −10, +100% to −10, +50%. Wherever possible, Sprague plans to tighten the capacitance tolerance on premium quality capacitors to −10, +50%. Closer tolerances can be obtained on request, at slightly increased cost.

Typical variations of 120 cycle capacitance with temperature is shown in Figure 2. Note that the premium grade capacitors retain, at −40C, approximately 80% of room temperature capacitance while the standard grade retains approximately 50%. It is interesting to note that at −55 C (the low temperature criterion used for tantalum capacitors) the premium type retained approximately 45% of room temperature capacitance while the standard grade has nearly zero capacitance remaining. The effect of temperature on the equivalent series resistance is shown in Figure 3. Again, the premium grade shows low temperature characteristics that are vastly superior to those of the standard grade.

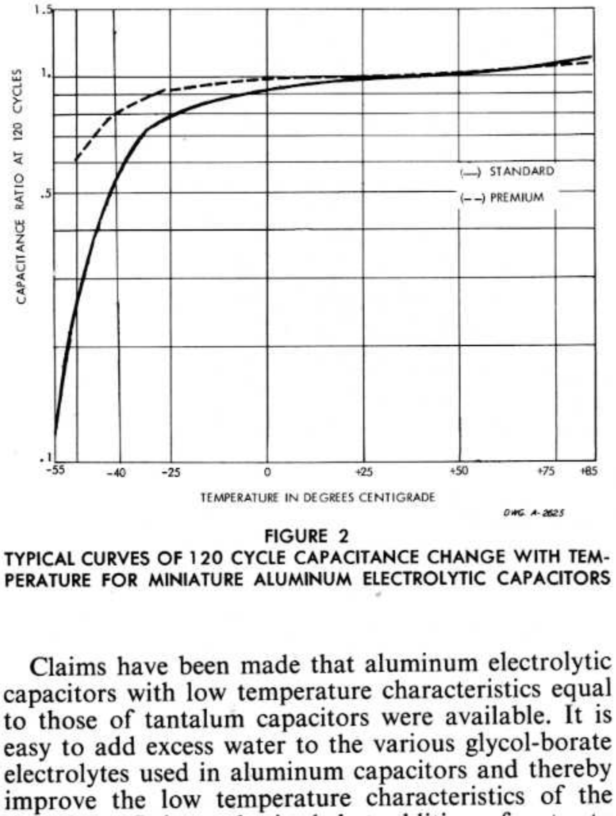


FIGURE 2
TYPICAL CURVES OF 120 CYCLE CAPACITANCE CHANGE WITH TEMPERATURE FOR MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS

Claims have been made that aluminum electrolytic capacitors with low temperature characteristics equal to those of tantalum capacitors were available. It is easy to add excess water to the various glycol-borate electrolytes used in aluminum capacitors and thereby improve the low temperature characteristics of the capacitors. It is emphasized that addition of water to the electrolyte can improve low temperature characteristics but also it can adversely affect the stability of the oxide film by initiating chemical reactions which will cause catastrophic failures. It has been observed that these "active" electrolytes even under normal shelf conditions start such active chemical reactions that end seals can be blown away from the capacitor housing. On the other hand, if the proper electrolyte is used, not only can good low temperature characteristics be obtained, but also long and stable life can be achieved. In order to check the stability of the oxide film under shelf conditions, Sprague has devised a "build test" which will be described in detail later.

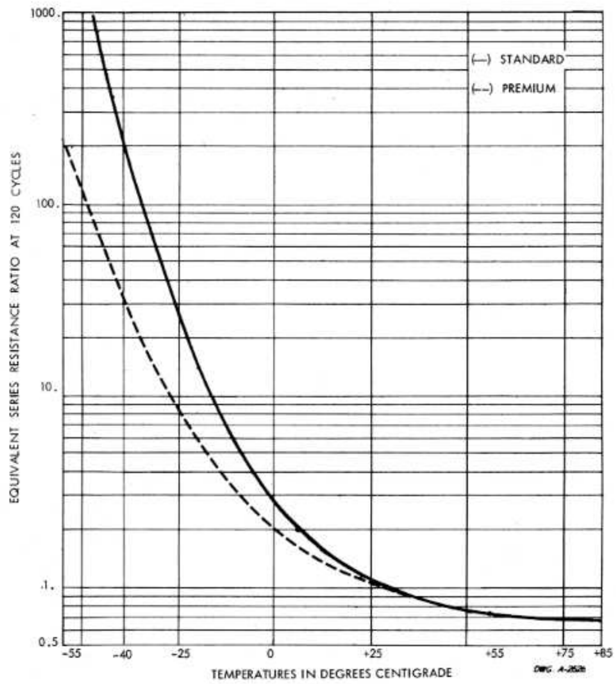


FIGURE 3
TYPICAL CURVES OF 120 CYCLE EQUIVALENT SERIES RESISTANCE CHANGE WITH TEMPERATURE FOR MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS

The effect of frequency on capacitance and dissipation factor is shown in Figures 4 and 5, respectively. Dissipation factor is defined as R/X_C; where R is the resistance and X_C is the capacitive reactance. The high values of dissipation factor at the various frequencies are due to various resistive elements such as the oxide film itself, the cathodic polarization effect and the resistance of the electrolyte-spacer combination. This range of capacitance and dissipation factor is dependent on section design and CV product.

Miniature aluminum electrolytics exhibit extremely low d-c currents. Leakage current as a function of temperature and as a function of applied polarization voltage is shown in Figure 6 and Figure 7.

Aluminum electrolytics usually will show a decreasing d-c leakage current with increased time on voltage. Also, d-c leakage current of properly designed and manufactured aluminum electrolytics (contrary to many misleading statements) can be very stable even when the capacitors are stored at increased temperatures for extended periods of time with no voltage applied. Tables 2 and 3 contain examples of data showing the behavior of miniature aluminum electrolytics under various conditions of shelf test. Note that shelf data is listed at 25 C, 65 C, and 85 C. It may be possible to determine meaningful acceleration factors as more data is obtained from the continuing tests. Generally, the parameters are quite stable at the no load conditions. It is noted that the stability of the oxide film is due to:

1. Good anodizing techniques which result in a superior oxide film.
2. Electrolyte systems most compatible with all materials used inside the capacitor.
3. Proper derating.

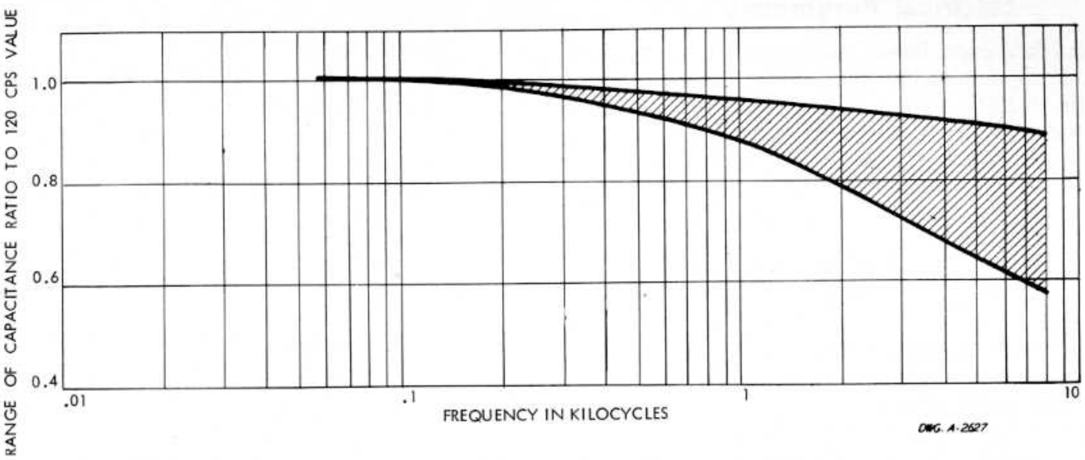


FIGURE 4
THE EFFECT OF FREQUENCY ON CAPACITANCE FOR MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS.

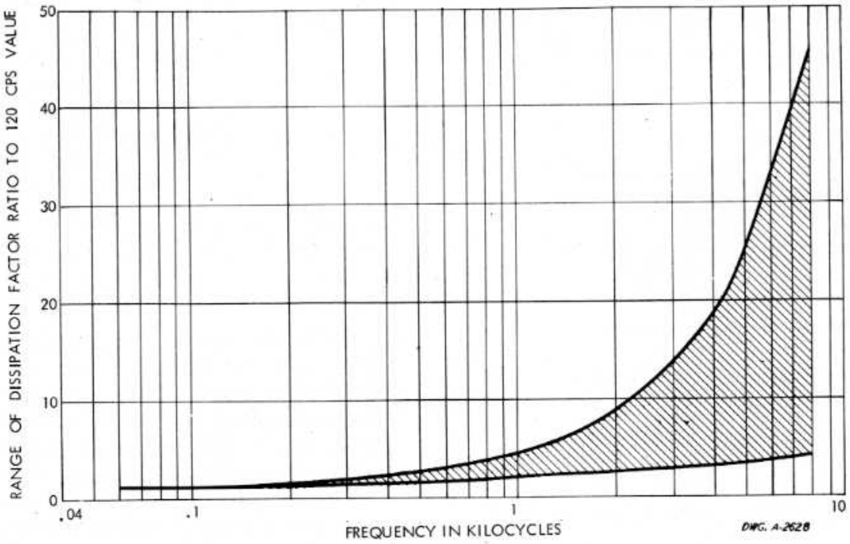


FIGURE 5
THE EFFECT OF FREQUENCY ON DISSIPATION FACTOR FOR MINIATURE ALUMINUM ELECTROYLTIC CAPACITORS

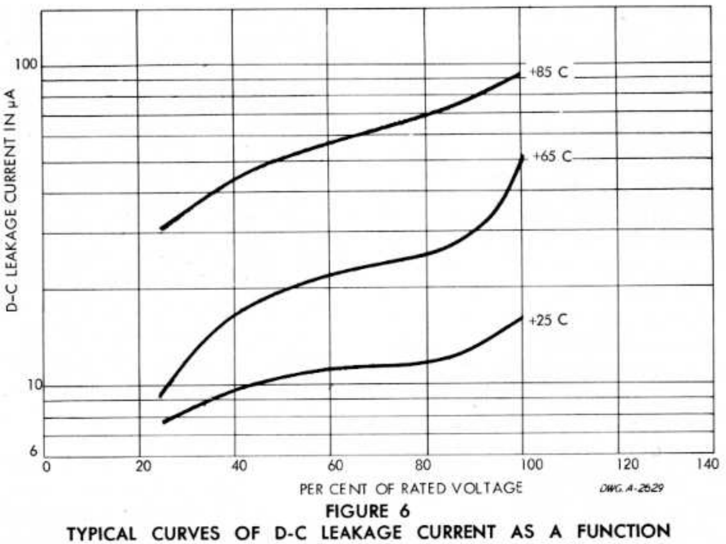


FIGURE 6
TYPICAL CURVES OF D-C LEAKAGE CURRENT AS A FUNCTION OF APPLIED VOLTAGE FOR TYPE 34D; 4μF 450 VOLT CAPACITORS.

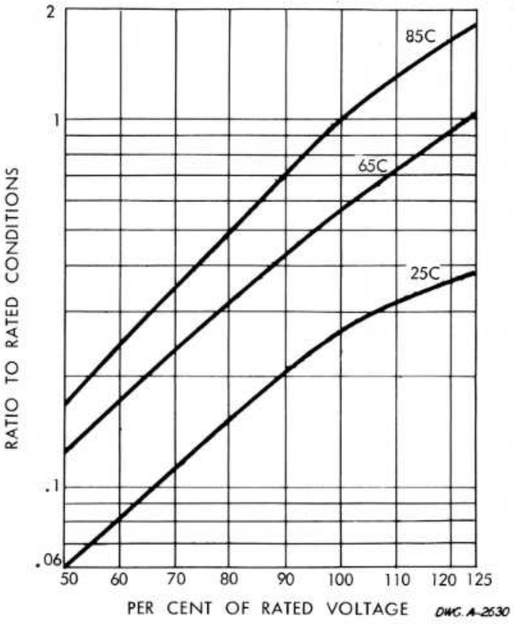


FIGURE 7
TYPICAL CURVES OF LEAKAGE CURRENT NORMALIZED TO THE 85 C VALUE AT 100% OF RATED VOLTAGE AT VARIOUS TEMPERATURES AND APPLIED VOLTAGE FOR MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS.

TABLE 2
SHELF LIFE – MINIATURE ALUMINUM

				Initial			Final			
Type	μF	Volts D-C	Shelf Condition	Cap.	RXC	D-C Leakage 5 min. (μA)	Cap.	RXC	D-C Leakage 5 min. (μA)	Shelf Factor
30D	50	50	85 C, 100 Hrs.	56.0	32	8.0	56.6	30	25	1.08
				56.8	35	6.0	56.4	33	22	
40D	30	50	85 C, 100 Hrs.	30.3	56	2.0	30.0	54	18	1.41
				31.8	50	10.0	31.5	48	18	
42D	40	60	85 C, 100 Hrs.	46.7	34	7.0	46.4	34	21	1.51
				44.5	35	7.0	44.3	36	23	
30D	50	50	65 C, 1000 Hrs.	57.4	35	7.0	56.9	33	55	1.29
				56.9	32	5.0	56.3	31	50	
40D	30	50	65 C, 1000 Hrs.	30.7	58	5.0	30.2	58	23	1.39
				29.6	71	2.0	29.1	68	30	
42D	40	60	65 C, 1000 Hrs.	44.7	31	16.0	44.2	34	26	1.56
				45.3	31	15.0	44.8	32	26	
30D	50	50	25 C, 8000 Hrs.	58.2	30	7.0	57.8	29	28	1.67
				50.7	43	5.0	50.4	41	10.5	
40D	30	50	25 C, 8000 Hrs.	32.3	49	8.0	32.0	48	12.0	1.89
				31.8	55	16.0	31.5	52	21.0	
42D	40	60	25 C, 8000 Hrs.	44.7	31	18.0	44.7	31	9.5	1.45
				45.4	31	35.0	45.3	32	13.5	

TABLE 3
SHELF LIFE - TYPE 40D

μF	Volts D-C	Shelf Condition	Initial			Final			Shelf Factor
			Cap.	RXC	D-C Leakage 5 min. (μA)	Cap.	R X C	D-C Leakage 5 min. (μA)	
5	50	85 C, 100 Hrs.	6.6 6.1	180 90	.7 .4	6.4 5.9	172 127	2.1 1.6	1.31
		85 C, 500 hrs.	6.2 6.3	127 126	1.9 1.9	6.23 6.24	138 139	2.4 1.8	1.90
		85 C, 1000 hrs.	6.2 6.4	160 92	2.0 2.1	6.25 6.46	167 92	3.0 3.0	3.32
		85 C, 2000 hrs.	5.9 6.1	172 172	1.8 1.6	5.96 6.15	191 194	3.6 3.7	5.96
15	100	85 C, 100 hrs.	17.3 16.7	184 157	7.6 3.5	16.7 16.3	160 90	18.0 11.5	1.35
		85 C, 500 hrs.	16.7 16.3	90 120	18.0 11.5	16.2 16.4	153 148	12.0 10.0	1.41
		85 C, 1000 hrs.	16.4 16.4	119 120	14.5 15.0	16.2 16.0	147 164	10.0 10.0	2.65
		85 C, 2000 hrs.	16.5 16.7	144 160	15.0 13.0	16.2 16.4	161 170	15.0 13.0	5.34

Many users of aluminum electrolytic capacitors have the misconception that an aluminum electrolytic will "deform" its oxide film if it is used at voltages under rated voltage. The data just shown on the shelf test of the 30D, 40D, and 42D capacitors certainly indicate that the oxide film is quite stable at the no load condition.

The data in Table 4 show what happened to an 80μF, 450 volt d-c commercial Sprague DEE capacitor which was tested at various per cents of rated voltage for 250 hours at 85 C and then subjected to 450 volts d-c at 85 C for an additional 250 hours. Note that capacitance and dissipation factor are extremely stable after test. The d-c leakage increases in capacitors tested at less than rated voltage for the first 250 hours. However, note that after the second 250 hours, all d-c leakages are lower than the initial measured values. These data verify the fact that Sprague aluminum electrolytic capacitors do not "deform".

Earlier it was mentioned that Sprague aluminum electrolytic capacitors contain anode foil of 99.95 per cent minimum purity. Various claims have been made by other manufacturers of aluminum electrolytic capacitors that 99.99 per cent pure aluminum foil is used in their products. It is noted that the latest revised MIL-C-62B specification covering military grade aluminum electrolytic capacitors specifies a 99.95 per cent minimum purity. This requirement resulted at a joint meeting held by the military and manufacturers and users of aluminum capacitors. At the meeting, it was brought out by a major supplier of capacitor grade aluminum foil that presently available analytical techniques could not test aluminum capacitor foil to an accuracy greater than 99.95 per cent.

Aluminum foil capacitors are designed to provide satisfactory life at rated voltage at maximum rated temperature. Extended life tests for Types 30D and 42D show the effect of combined voltage and temperature stress. Normally, measurements of d-c leakage current, capacitance, and dissipation factor over a period of time are used as a means of evaluating capacitor performance. Data on 10,000 hours of life at 85 C and rated voltage are shown for Types 30D and 42D in Figures 8 and 9.

Note the excellent stability of capacitance and dissipation factor of the premium grade capacitors. D-C leakage for both types, although not shown, is extremely low (less than 1.0uA). Tests are continuing to determine the ultimate life of these capacitors. The effect of accelerated temperature is shown in Figure 10. Note that the standard grades lose capacitance sharply after approximately 20 hours at 125 C and 75% of rated voltage. Again, note the good stability of the 42D design. It is cautioned that this 125 C data is shown strictly for emphasis and should not be interpreted that these types of capacitors are recommended for 125 C operation.

TABLE 4
Life Test at Various Percents of Rated Voltage at 85 C
80μF, 450 volt d-c commercial DEE

Per Cent Rated Voltage	Capacitance, μF			% Dissipation Factor			D-C Leakage in μA		
	0 Hrs.	250 Hrs. at % Vr	250 Hrs. at 450 V	0 Hrs.	250 Hrs. at % Vr	250 Hrs. at 450 V	0 Hrs.	250 Hrs. at % Vr	250 Hrs. at 450V
0	110	112	113	11.1	8.5	9.4	88	353	44
10	110	116	116	11.2	7.9	8.7	81	485	65
40	105	107	109	10.1	7.3	7.4	53	225	56
70	109	113	113	10.0	7.9	8.6	98	159	58
100	110	112	113	10.3	8.7	8.5	70	46	48

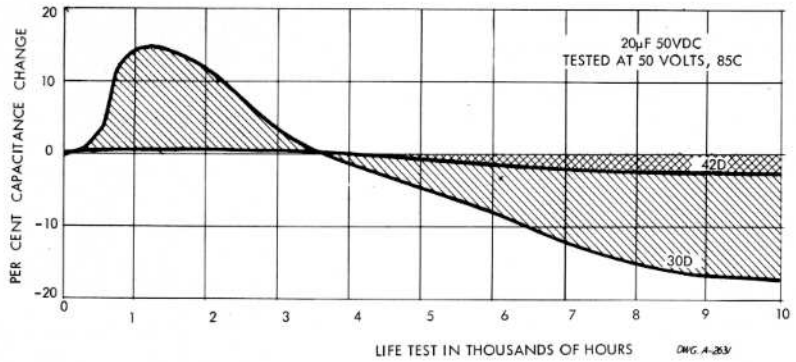


FIGURE 8
TYPICAL CURVES OF CAPACITANCE CHANGE WITH LOAD LIFE FOR TYPE 30D AND 42D 20μF, 50 VOLT CAPACITORS TESTED AT RATED VOLTAGE AND 85C.

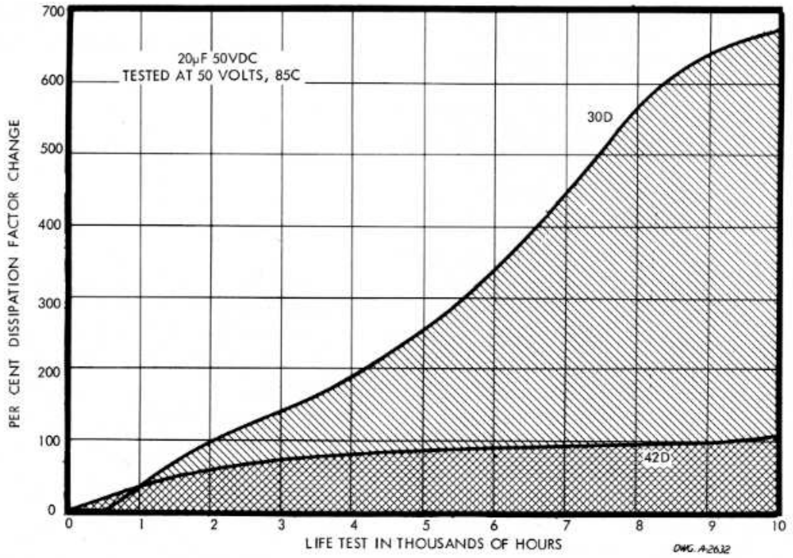


FIGURE 9
TYPICAL CURVES OF DISSIPATION FACTOR CHANGE WITH LOAD LIFE FOR TYPE 30D AND 42D 20μF, 50 VOLT CAPACITORS TESTED AT RATED VOLTAGE AND 85 C

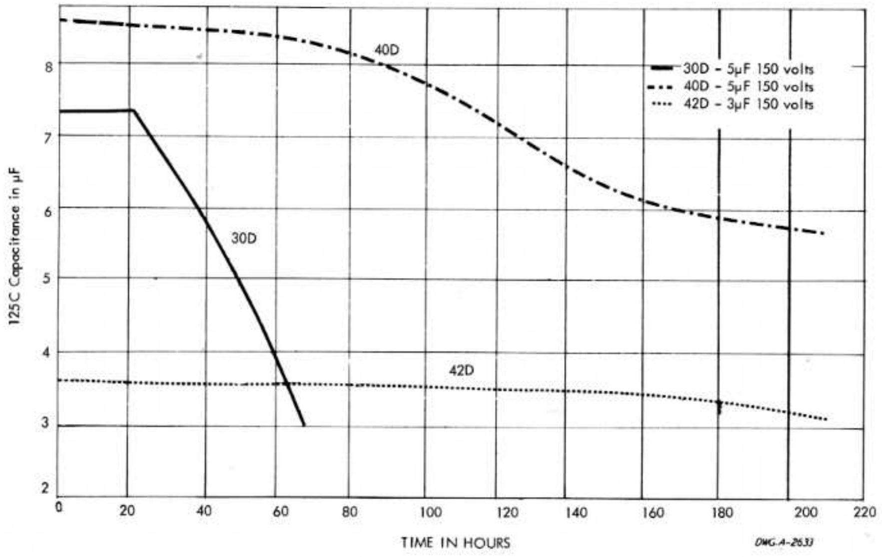


FIGURE 10
TYPICAL CURVES OF CAPACITANCE CHANGE WITH LOAD LIFE AT 125 C FOR MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS TESTED AT 112 VOLTS.

Application of Miniature Aluminum Electrolytics

Miniature aluminum electrolytics are used widely in filtering and by-pass in the following:

1. Power supplies of radio and television and other electronic equipment
2. Remote control instruments
3. Calculating machines
4. Computers
5. Photoflash equipment
6. Automatic controls
7. Telephone systems
8. Guided missile mechanisms
9. Meter-damping

In deciding which type capacitor is to be used in a particular application, the design engineer must consider the following:

1. Environmental problems such as temperature, shock, and vibration. Also, the effects of salt spray, humidity, and altitude and mounting.
2. Electrical requirements would include ripple currents, frequencies, pulses, peak voltages, transients and retrace characteristics of the various parameters.
3. Reliability - desired life without failure.
4. Space requirements - volume vs cost.

Miniature aluminums can meet rugged shock and vibration conditions provided care is exercised in mounting. Generally, capacitors up to 3/8″ diameter can withstand 55 cycle vibration without supplementary mounting means. The premium grade capacitors will meet the high frequency requirements of method 204, MIL-STD-202A, provided they are mounted so that the body is secured properly. With the pressing demands for less weight in satellites and missiles, it is interesting to note that miniature aluminum capacitors are capable of operating at high altitudes for extended periods of time. Table 5 summarizes data on 50 volt capacitors which were life tested at rated voltage at 85C in a vacuum equivalent to less than 100 microns (approximately 230,000 feet altitude) for a total of 3000 hours.

These miniature electrolytics can be used where reverse voltages may be encountered. Polarized capacitors will sustain a 2.0 volt reversal without any detrimental effects. Where appreciably higher reversals may be encountered, it is best to use a non-polarized capacitor. Non-polar capacitors are available in ratings up to 25 volts in case sizes of 3/8″ diameter or less. In the large diameter cases, non-polar capacitor ratings can be extended to 450 volts.

The permissible RMS ripple current for the various capacitors is limited by temperature or by the rate of heat dissipation. The rate of heat dissipation is greatly affected by the equivalent series resistance of the capacitor and by the geometry and surface area.

Rough approximations for allowable 120 cycle ripple currents at 85 C for the various premium grade capacitors can be calculated from the formula:

$$I_{RMS} = k\sqrt{C}$$

where C is the nominal capacitance in microfarads
k is a proportional constant:

Case Size Dia.	k
¼″	.012
⅜″	.014
⅝″	.016
¾″	.017
1″	.020

I_{RMS} is in amperes (in no case should the I_{RMS} be greater than 1.2 amperes at 85 C)

For conditions of temperature and frequencies different from the above, multiple I_{RMS} by the factors shown:

	Temperature in °C			Frequency in CPS			
Rated Volts	+65	+45	+25	60	400	800	2400
0-50	1.5	2.0	2.5	.9	1.1	1.3	1.4
51-200	1.5	2.0	2.5	.8	1.3	1.4	1.6
201-450	1.5	2.0	2.5	.7	1.3	1.4	1.6

Note that the usual precautions should be followed to insure that the d-c bias voltage plus a-c peak voltage does not exceed the d-c rating of the capacitor. The formula above is a guide in determining how much ripple can be tolerated at the various conditions. This

TABLE 5
HIGH ALTITUDE - LIFE TEST
85 C 50 Volts - 200,000 Feet

				Initial			500 Hours				2000 Hours				3000 Hours			
Type	µF	VDC		Cap.	RxC	DCL	Cap.	RxC	DCL	Wt. Loss (mg)	Cap.	RxC	DCL	Wt. Loss (mg)	Cap.	RxC	DCL	Wt. Loss (mg)
40D	20	50	Max.	20.47	66	4.0	20.47	81	.04	14.2	20.46	80	.02	43.0	20.41	87	.04	61.9
			Min.	19.77	49	3.1	19.75	59	.03	11.7	19.69	60	.02	33.5	19.56	64	.04	46.9
			Avg.	20.09	55	3.3	20.11	69	.035	13.2	20.08	71	.02	37.8	20.00	78	.04	54.1
	15	50	Max.	16.68	68	10.0	16.80	75	.04	11.9	16.8	74	.02	34.1	16.94	73	.05	49.0
			Min.	15.22	53	8.6	15.36	60	.02	6.6	15.5	60	.01	16.4	15.49	58	.04	23.3
			Avg.	16.11	57	9.5	16.25	64	.026	9.4	16.3	64	.01	25.2	16.37	63	.05	36.0
42D	8	60	Max.	8.95	40	7.4	9.15	53	.16*	8.8	9.38	58	.04	25.5	9.50	62	.10	36.3
			Min.	8.55	23	1.7	8.58	34	.04*	6.0	8.62	35	.01	17.8	8.63	35	.02	25.7
			Avg.	8.73	30	3.4	8.81	42	.087*	7.7	8.87	44	.02	22.5	8.90	45	.04	32.2
34D	60	50	Max.	60.28	44	16.0	61.39	70	.09	46.1	61.66	83	.25	194.2	61.46	97	.15	290.3
			Min.	57.16	32	6.0	58.18	45	.05	37.5	58.38	48	.04	133.7	58.12	55	.09	189.5
			Avg.	58.85	41	11.8	60.02	56	.06	42.5	60.30	68	.10	153.7	60.19	80	.11	224.9

*D-C Leakage measured in microamperes at room temperature at 60 volts after exposure to 50 volt test.

is not an absolute limitation, however, for it is possible in some instances to design capacitors capable of withstanding more ripple than indicated by the formula.

Reliability of Miniature Electrolytic Capacitors

The increasing use of miniature aluminum electrolytic capacitors in applications where reliability information is demanded is an indication that the "state of the art" has improved quite noticeably in the past few years. To get known reliability of the end equipment, the design engineer insists on components whose reliability has been proven or can be approximated from actual test data. Even though the aluminum electrolytic capacitor does not have the low temperature characteristics of the tantalum capacitor, the various data presented herein indicate that it should not be underestimated. The outstanding features which qualify it for high reliability uses are:

1. High purity (99.95% minimum) aluminum foil.
2. Improved electrolyte systems.
3. Welded electrode connections.
4. Superior seals.
5. More frequent process control check points.
6. More stringent requirements at check points.
7. 10C% outgoing inspection.
8. Quality assurance testing.

For over two decades, the Sprague Electric Company has been supplying substantial numbers of various aluminum electrolytic capacitors for use in telephone systems. The field performance of these capacitors has been outstanding. Confidence in Sprague capacitors is further evidenced by the wide use of the Type 42D capacitor, which was developed specifically for telephone system applications requiring the highest reliability.

To aid the design engineer, failure rate curves for the miniature aluminum electrolytic capacitors are are shown in Figures 11 and 12. Figure 11 shows the various failure rates at different temperatures and various per cents of rated voltage for the Type 30D capacitor. Figure 12 covers failure rates for similar conditions for the premium grade miniature aluminum electrolytic capacitors. It is noted that the failure rates in both figures are based on 60% confidence and that a failure is defined as a short, open, or parameter drift in excess of the limits shown below:

Capacitance change: −10, +20%
Rx C product change: 130% of initial requirement
D-C Leakage Current: initial requirement

Note that these curves are based on over 5,500,000 unit hours of testing involving approximately 1700 capacitors of various sizes and ratings. The points on the curves which are marked by (X) denote test conditions at which no failures have occurred to date. It is interesting to note that Figure 11 shows a failure rate of .1%/1000 hours at room temperature and 50% of rated voltage and 3.7%/1000 hours at rated voltage and rated temperature. However, it is pointed out that this is based on the fact that there have been no failures at this condition so that, with increased time on test, the failure rate should continue to improve. For similar test conditions on the premium grade miniature aluminum capacitor, the failure rate is approximately .053%/1000 hours and 1.7%/1000 hours at rated voltage and temperature. Again, this is based on no failures. Nevertheless, using the curves of Figures 11 and 12, it should be possible to approximate failure rates for various conditions of temperature and voltage which are encountered in the application of these capacitors.

Although the life test data on the Type 31D and 89D capacitors has not been very extensive, it appears that one could approximate from actual field feedback information a failure rate of .5%/1000 hours at 60% confidence at use conditions (room temperature and approximately 60% of rated voltage).

The question often arises as to which standards or MIL specifications cover a particular capacitor. The standard Types 30D, 31D, 89D, and DEE are covered by EIA Standard RS154B. ASESA has recently released MIL-C-62B, which deals with military quality electrolytic capacitors. Sprague Types 40D and 34D will meet the requirements of Type CE10 and CE11 and Type CE12 and CE13, respectively.

ACKNOWLEDGMENTS

The author wishes to acknowledge the efforts of Mr. M. Hutchinson and his staff in the preparation of the various curves and other data presented in this paper.

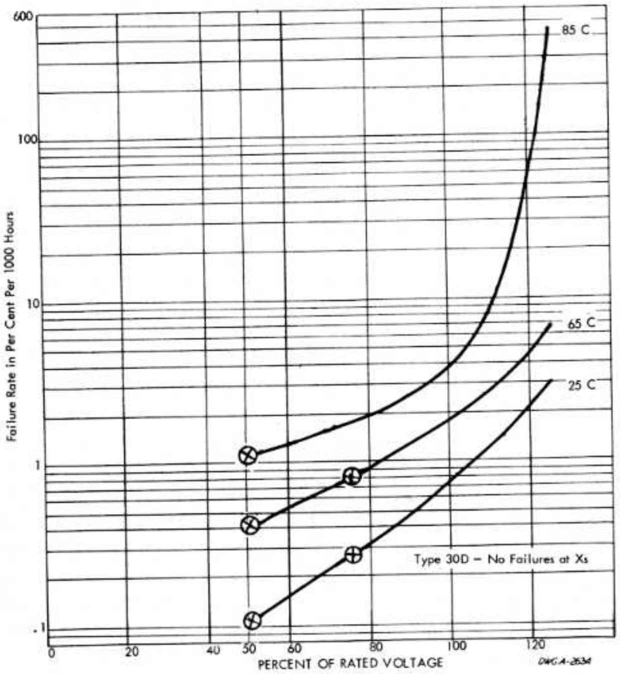


FIGURE 11
THE EFFECT OF TEMPERATURE AND APPLIED VOLTAGE ON FAILURE RATE FOR TYPE 30D ALUMINUM ELECTROLYTIC CAPACITORS.

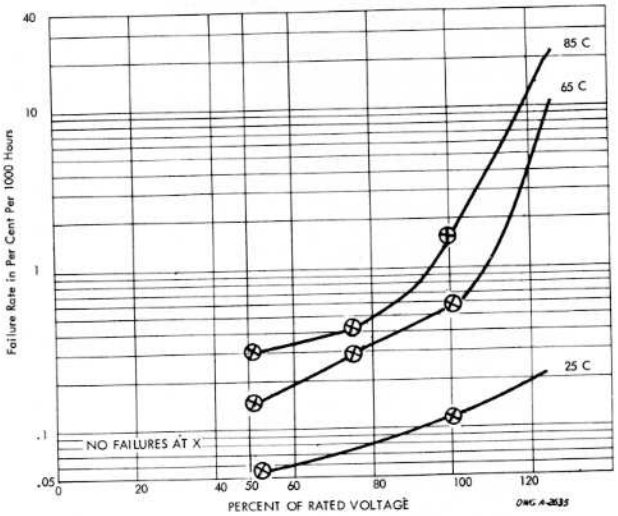


FIGURE 12
THE EFFECT OF TEMPERATURE AND APPLIED VOLTAGE ON FAILURE RATE FOR PREMIUM-GRADE MINIATURE ALUMINUM ELECTROLYTIC CAPACITORS.

CYLINDRICAL ALUMINUM ELECTROLYTIC CAPACITORS

by

JOSEPH A. MORESI

Introduction

This paper will elaborate on previously described miniature aluminum electrolytic capacitors and will also discuss volumetrically larger capacitors and their capabilities. A description of each specific type will be given, following a review of the four basic capacitor qualities available.

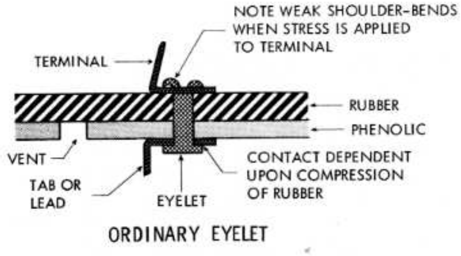
Cover Designs

In most instances, the volumetrically larger capacitors have evolved as upright mounted types affording a more efficient housing for the capacitor and a mounting configuration which may be more effectively packaged by the design engineer. Various applications requiring the use of these capacitors have made it necessary to offer a variety of cover designs or seal enclosures. For purposes of discussion, these are separated into two classes:

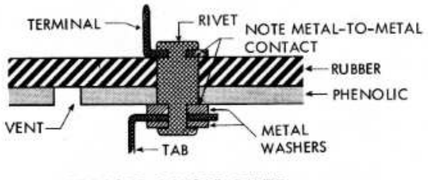
(A) Fabricated cover (commercial hardware)

(B) Molded cover (premium quality hardware)

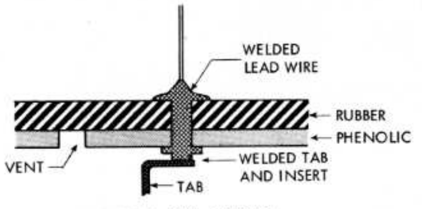
The fabricated cover may be a bakelite-rubber sandwich type or a laminated bakelite-rubber disc type. A cross-sectional view of each of these covers is shown in Figures 1 and 1a.



ORDINARY EYELET

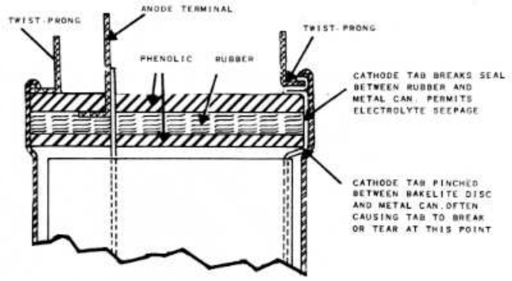


SPRAGUE DOUBLE RIVET

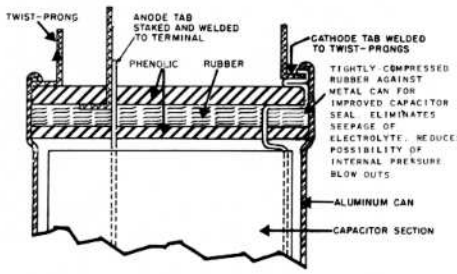


SPRAGUE ALL WELDED

FIGURE 1
CROSS-SECTIONAL VIEW OF FABRICATED COVERS



ORDINARY ELECTROLYTIC CAPACITOR



SPRAGUE ELECTROLYTIC CAPACITOR

FIGURE 1a

These cover designs possess an economic advantage over all other types of covers and are regarded as effective capacitor seals if their limitations are recognized and observed by the design engineer. Capacitor life and reliability is governed in part by the seal, whose reliability in turn is governed by the "use conditions" to which the capacitor will be subjected. Long, extended periods at elevated temperatures will eventually take its toll on the rubber and bakelite members. This may lead to capacitor failure due to loosened rivet connections which are dependent upon pressure against the cover, or electrolyte leaks, which will reflect capacitance loss, high resistance or shorts between terminals. The loose rivet problem has been a formidable one with these covers and it has been resolved through the use of welded connections in miniature and axial-lead capacitors and the patented Sprague metal-to-metal riveted terminal which is depicted in Figure 1. These cover designs are not generally recommended for severe temperature cycling, high vibration applications or for operation in reduced atmospheric pressures. They are recommended for most commercial applications, such as television, radio, instruments, photoflash, auto radio and mobile communication.

Molded covers, considered to be the premium quality hardware, are shown in Figure 2. Note that they are available in a variety of configurations which will permit chassis, plug-in, screw-in, or busbar mounting. This type of cover provides a rigid, low diffusivity deck which also houses the terminals. The rubber gasket is ideally located to give a positive and uncomplicated seal which rivals the hermetic seal. Enclosures of this type are recommended for all circuit applications with special requirements which cannot be met with the commercial hardware or where long capacitor life and maximum reliability are desired. Such parts have widespread usage in computer, telephone, telegraph, military, industrial welding and charge-discharge applications.

The molded cover affords such an effective capacitor seal that it is reasonable to question the hazards involved if a catastrophic failure were to occur. This problem was recognized at the outset and has been adequately solved by development of venting systems which are compatible with basic section and good capacitor design. Figure 3 depicts several of the venting mechanisms provided in these covers. They are the silicone diaphragm pressure vent, the pressed eutectic disc vent, the eutectic solder vent, wax and cork vent plugs. The first two are designed not only from a mechanical viewpoint but for their repeatability when tested to definitive vent specifications.

Problems in vent reliability and specifications to check this reliability are areas often over-looked by the user. The fact that a vent exists in a capacitor does not necessarily mean that it is efficient. It is possible that the vent is of such a design that it reduces the efficiency of the capacitor seal or it cannot be relied upon to function properly when required. The proper vent must provide both an effective seal and a reliable safety mechanism. This is necessary if long capacitor life is to be expected because a vent designed for too low a yield pressure or leak pressure will be subject to electrolyte leaks or loss of electrolyte volatiles at normal pressures within the capacitor.

Capacitor Section Design

The selection of the correct cover design and its associated hardware is not all that is necessary in choosing the proper capacitor for a particular application. As mentioned previously, the capacitor section design plays a most vital role in capacitor life and

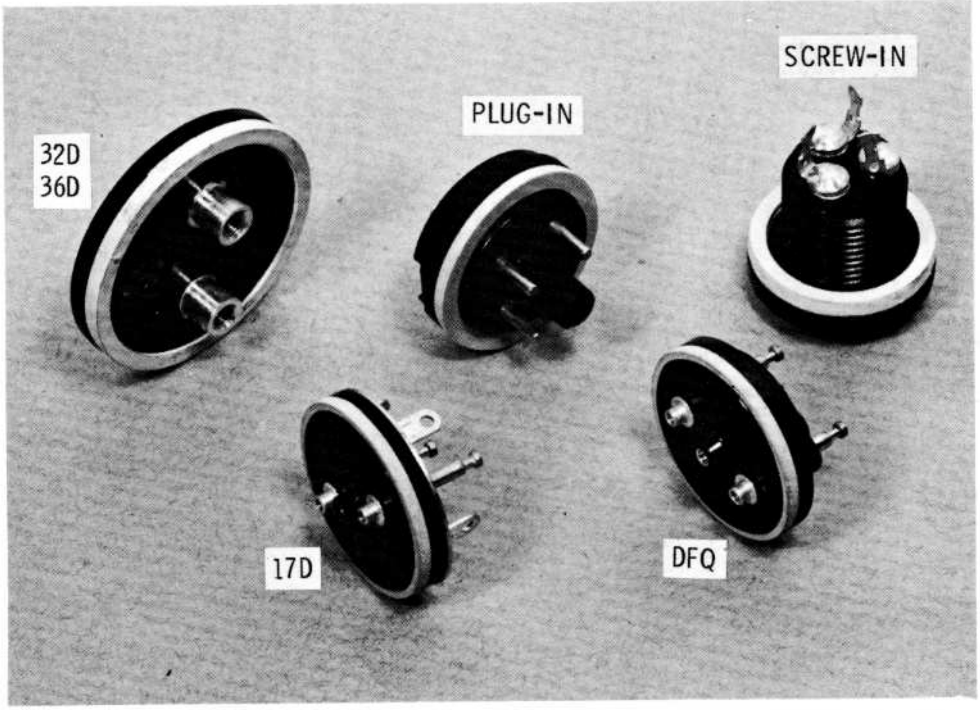


FIGURE 2
MOLDED PHENOLIC COVERS

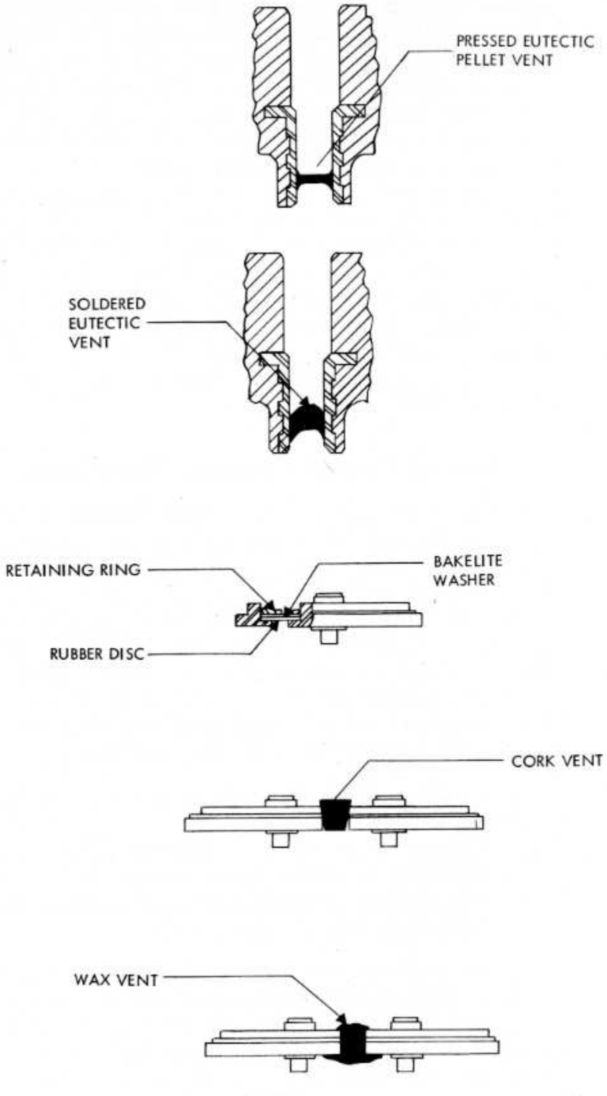


FIGURE 3
VENTING MECHANISMS

reliability. The capacitor section designs may be separated into two classes and are referred to as:

1. Standard quality capacitor section
2. Premium quality capacitor section

The standard quality capacitor section involves selection of proper capacitor voltage ratings in respect to the anodic aluminum oxide dielectric and temperature rating, and selecting paper separators to provide maximum protection against voltage breakdown and affording maximum capacitance per unit volume. The life and reliability of this capacitor design is extremely good as will be noted later. The shortcomings of such a design are perhaps apparent, but note that the capacitor characteristics are not optimized in this section design, but are compromised. Therefore, the leakage current, series resistance, cold temperature and frequency characteristics, shelf characteristics, overall life and reliability are certainly not the ultimate that can be achieved at the present state of the art.

In contrast with the standard capacitor section, the premium quality capacitor section affords the most reliable capacitor design obtainable consistent with economic feasibility. This capacitor design optimizes the previously-mentioned capacitor characteristics. Further refinements are possible for especially difficult or unusual requirements, but since requirements are few and the additional cost large, Sprague Electric normally does not include its complete capabilities even in premium quality units. The door is always open to the applications engineer and specific capacitor characteristics can be improved upon through special design techniques or manufacturing and processing controls. An example of this capability is in the area of electrical leakage current. Some of the Sprague Electric engineering bulletins, EIA and customer specifications, list maximum leakage currents which are greater than general production levels. In reality, it is possible to achieve and guarantee appreciably lower leakage currents through design and/or processing controls. Low and stable electrical leakage currents are a direct reflection of the quality of the anodic aluminum oxide film and a stable dielectric film is the key to superior shelf and life characteristics.

Shelf Characteristics

Shelf and life are two of the most important, but at the same time misunderstood, characteristics of electrolytic capacitors. Consider first the shelf characteristics of an aluminum electrolytic capacitor. There is a general misconception in the field that while the aluminum electrolytic capacitor remains on shelf, that is, no voltage applied for long periods of time, the unit deforms. The general conception of deformation is an actual dissolution of the oxide layer and subsequent reduction in thickness. Deformation is a misnomer and what actually is observed is the degradation of the anodic oxide film. This change is characteristic of aluminum electrolytic capacitors and may be measured. In fact, its measure can be used to compare capacitors. One of the difficulties in giving adequate shelf data of the duration required by the users, is the fact that such long term data, when finally obtained, usually applies to units that have become obsolete. Accelerated shelf factors are helpful but not positive, as they must have correlation with long term data and again obsolescence poses a problem.

The 100 hour shelf test at 85 C, as specified in our bulletins, can, with some measurement refinements, be turned into an extremely successful method of comparing or evaluating formation process, electrolyte systems and oxide film quality. This requires calculating the time required to build a capacitor to rated voltage at a fixed current, before and after exposure to shelf conditions. This calculation is based on the fact that an ideal or theoretically perfect capacitor, when charged with a constant current, will have a linear voltage rise. The following relationship holds:

$$T = \frac{V \times C}{I}$$

T = Time in seconds
C = Capacitance in farads
I = Current in amperes
V = Final or test voltage

The theoretical time to charge to rated voltage may be calculated and the actual charge time of a capacitor determined by experiment. The relationship or ratio of the former to the latter may be expressed as the "build factor".

$$\text{Build Factor} = \frac{\text{Actual Time}}{\text{Theoretical Time}}$$

The build factor or build ratio may be expressed numerically as a value greater than one (1), that can be used to significantly relate a given capacitor to an ideal capacitor or another capacitor. The time required to build a capacitor beyond the theoretical time is a direct reflection of the quality of the anodic oxide film, provided several factors are recognized and compensated for. The charging current selected should be at least ten times the leakage current of the capacitor at rated voltage to render the loss of charge due to leakage current negligible. The current should not be so large as to introduce so short a build time that it would be difficult to measure the build time accurately. The build test can be conducted for a capacitor before and after exposure to shelf and its build factor determined in each case. Manufacturing quality may be determined by conducting a build test on capacitors, as received. This test can be regarded as a measurement of shelf characteristics from the time of manufacture to the time of use by the purchaser. If the shelf test (100 hour, 85 C storage test) is to be a simultaneous evaluation of various manufacturers, it is suggested that successive build tests be conducted on each capacitor until a constant build time has been obtained. This will tend to equate each capacitor prior to shelf. Upon completion of the shelf test, it is important that only the first build time obtained be regarded as significant. The relationship of the latter build time to the former build time may be expressed as the shelf factor:

$$\text{Shelf Factor} = \frac{\text{Build Time After Shelf}}{\text{Build Time Before Shelf}}$$

The shelf factor or shelf ratio may also be expressed numerically as a value greater than one (1). This value can be interpreted as the degree of anodic oxide film degradation incurred due to the initially poor quality of the oxide film or its incompatability with the electrolyte system used. The build test method for determining the shelf characteristics of a capacitor offers a more efficient method for evaluating anodic oxide films than the mere measurement and observed changes in capacitance, resistance, and electrical leakage of a capacitor before and after shelf. Figure 4 shows the charging current and time to build two capacitors (A and B) after exposure to shelf conditions. Also shown is their subsequent leakage current decay at constant voltage after ten minutes. A simple leakage current measurement after ten minutes would show these capacitors to be equal. The build test, however, reveals that capacitor A has required considerably less charge than capacitor B and that the degradation is substantially less in capacitor A and its quality is superior to capacitor B. Table 1 shows typical build and shelf factor data that has been obtained on shelf tests.

Use of Specific Design Techniques

In other areas, the use of specific design techniques may also be applied to improve the low temperature properties of a capacitor, its impedance or resistance characteristics over wide frequency ranges, its ripple current carrying capacity, or its equivalent series resistance. In general, these characteristics reflect either the basic mechanical design of the capacitor or the physical constants of the integral capacitor parts that contribute to its equivalent series resistance. These capacitor members may be identified as:

1. Anodic oxide film. (Resistance is frequency dependent.)
2. Electrolyte and paper separator combination. (Resistance is not frequency dependent.)
3. Anode and cathode foil. (Resistance is not frequency dependent.)

The physical characteristics of the anodic oxide film are determined by the etching and formation processes, yet, design freedom exists which permits selecting the correct foil type to optimize either the resistance or frequency characteristics of a capacitor. The char-

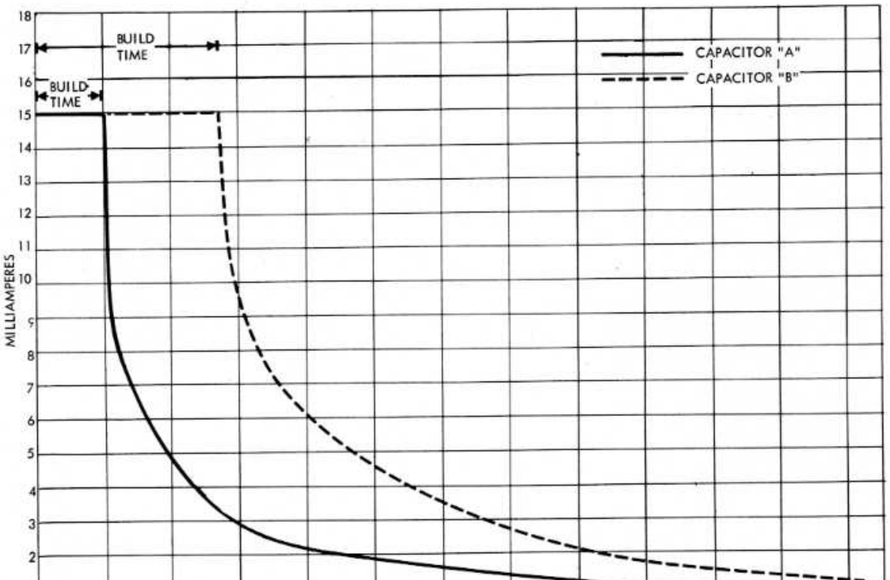


FIGURE 4
CHARGING CURRENT AND TIME REQUIRED TO BUILD CAPACITORS AFTER EXPOSURE TO SHELF CONDITIONS

TABLE 1

SHELF TEST—85 C, 96 Hours

BEFORE SHELF TEST								AFTER SHELF TEST					
μF	Volts D-C	Case Size	Cap. μF	Rx C	D-C Leakage in ma (1 min.)	Build Time (sec)	Build Factor	Cap. μF	Rx C	D-C Leakage in ma (1 min.)	Build Time (sec)	Build Factor	Shelf Factor
15000	10	2 x 4⅛	20070	379	0.21	17	1.31	19900	356	0.29	18	1.34	1.06
1350	350	3 x 4⅛	1550	180	0.52	28	1.29	1581	166	1.13	39	1.75	1.39
630	450	3 x 4⅛	837	123	0.75	25	1.66	853	110	1.8	37	2.43	1.50

acteristics of electrolytes and paper separators are such that any one of a wide range of resistivities may be obtained. The selection of the proper combination can optimize the resistance, impedance, and cold temperature properties of a capacitor. The resistance, inductance, and impedance contributions by the anode and cathode foils can be minimized by multiple tabs, proper tab positioning, swaging of foils and the geometrical configuration of the capacitor section.

An example in applying correct design techniques to a specific capacitor design can be illustrated by examining a high a-c or ripple current capacitor application. This capacitor is essentially a reactive element limiting the flow of alternating current. The resistance in an electrolytic capacitor is its equivalent series resistance, which is responsible for the power loss or wattage developed within the capacitor. A properly designed capacitor will minimize the resistive contributions of the various capacitor members, allow for maximum heat dissipation, cope with the a-c voltage reversal and provide a capacitor section design yielding an expected life and reliability commensurate with a comparable non-ripple design. Several of the design techniques which effect a reduction in resistance have been mentioned, but additional techniques may be employed to deal with other aspects of this problem. These include the use of formed cathodes to cope with voltage reversals and the selection of the most suitable geometric configuration for can and capacitor section to afford maximum heat dissipation. Heat dissipation is primarily a problem in heat transfer, which is a function of the distance from the midpoint of the capacitor to the outer wall of the container and the media between these points that the heat must traverse. Also included is the engineering experience and reliability data necessary to accurately and reliably determine permissible wattage levels for various capacitor ratings and can sizes to insure that capacitor life and reliability will not be impaired. Typical life test data obtained on capacitors operated with superimposed high ripple currents are shown in Figures 5, 6, and 7.

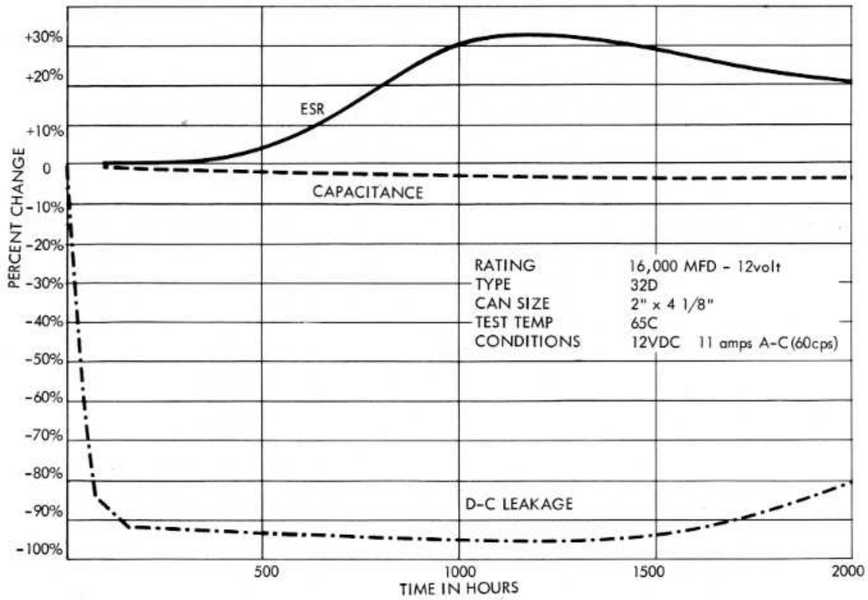


FIGURE 5
TYPICAL 65 C LIFE TEST DATA FOR 16,00 μF, 12 VOLT TYPE 32D CAPACITORS

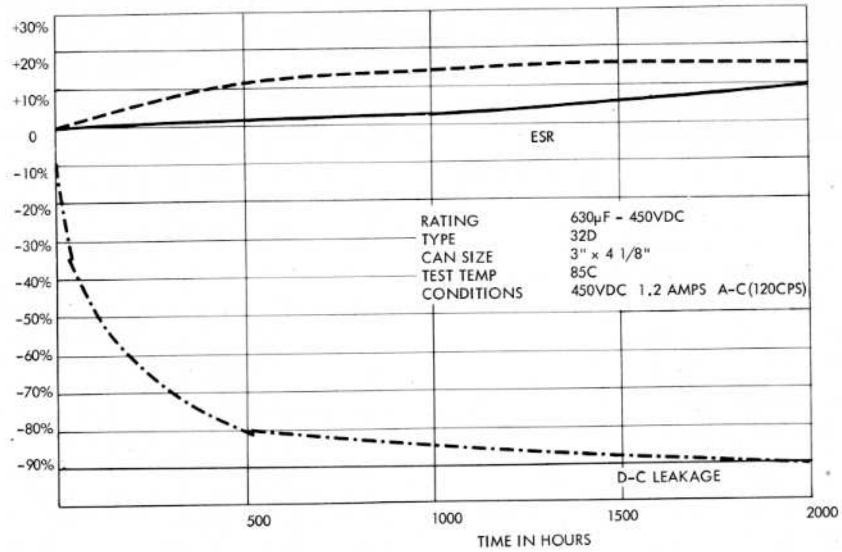


FIGURE 6
TYPICAL 85 C LIFE TEST DATA FOR 630 μF, 450 VOLT TYPE 32D CAPACITORS

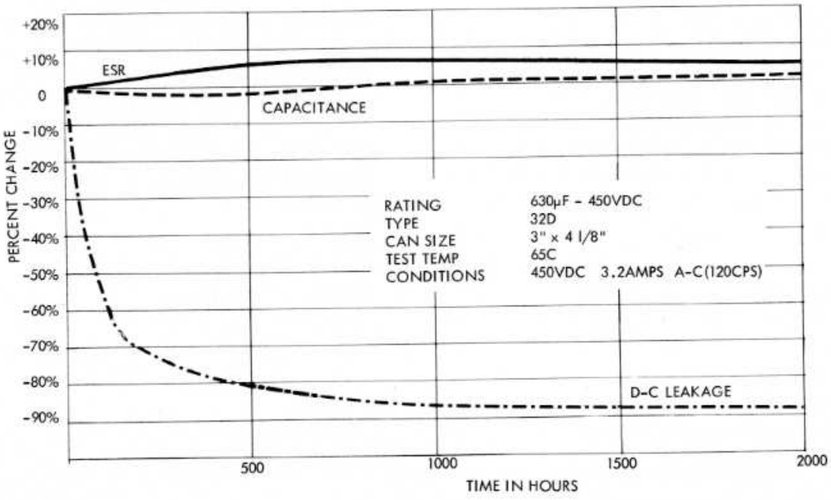


FIGURE 7
TYPICAL 65 C LIFE TEST DATA FOR 630μF, 450 VOLT TYPE 32D CAPACITORS

Capacitor Types Available

In having established some concepts for capacitor design, the applications engineer should now be better equipped to evaluate the aluminum electrolytic capacitor line being manufactured by the Sprague Electric Company. Table 2 designates the more common capacitor types which reflect the various quality levels of capacitor sections, seals, and hardware that have been discussed.

The DFP capacitor, shown in Figure 8, offers a wide range of design versatility. Its bakelite-rubber sandwich seal permits a multiple capacitor housing plus a mounting ring for chassis mounting which, in most cases, also serves as the cathode or common connection. As many as four individual capacitors with ratings through 450 volts d-c may be had in a single can. Special section design practices have made it possible to minimize any adverse electrical inter-action between capacitor sections. For example, an auto radio application requiring an extremely low coupling impedance requirement of less than .006 ohm at 20 kilocycles can be met. The short, oriented anode tabs in the DFP construction also reflect excellent inductance characteristics through the 10 megacycle range. Typical impedance and low temperature performance characteristics for these capacitors are shown in Figures 9, 10, and 11.

The Sprague Electric Company has obtained feedback information based on capacitor performance in TV sets at use conditions which established a failure rate of .05%/1000 hours at a 60% confidence level in television receivers. The data compiled for the Sprague Electric Life test program conducted at full rated capacitor voltage and rated ambient temperature has established a failure rate of 0.3%/1000 hours for

TABLE 2

Sprague Designation	Cover Style	Standard Can Diameters	Capacitor Section Design
Series DFP	Bakelite-rubber sandwich	¾", 1", and 1⅜"	Standard, 65C, 85C (instrument quality)
Series DEC	Laminated bakelite-rubber	1", 1⅜", 1½" 1¾", and 2"	Standard, 65C, 85C (instrument quality) Premium Quality, 85C
Series DFQ, Type 17D	Molded phenolic	1" and 1⅜"	Extended Life, 65C, 85C Premium Quality, 85C
Type 36D	Molded phenolic	1⅜", 2", 2½", 3"	Extended Life 65C
Type 32D	Molded phenolic	1⅜", 2", 2½", 3"	Premium Quality, 85C

TABLE 3

500 HOUR LIFE TEST — January, 1960 through August, 1961

Test	FAILURES		Total			Failure Rate (60% Confidence
Temperature	Unit Hours	Seal Leaks	Shorts	Opens	Failures	Level)
65 C	1,512,000	0	12	0	12	0.3 %/1000 hrs.
85 C	1,676,500	36	7	2	45	2.75%/1000 hrs.

65C rated capacitors and 2.75%/1000 hours for 85 C rated capacitors. Table 3 shows the test data which was used to arrive at these failure rates.

The DEC capacitor, shown in Figure 12, offers the same excellent reliability and performance characteristics that have been achieved with the DFP capacitor. The DEC seal is more reliable than a DFP, but it lacks the general versatility of the DFP seal construction. Its styling does permit larger capacitor sizes with an economical seal and cover enclosure consistent with the expected life and reliability of the capacitor.

Types DFQ and 17D capacitors are shown in Figure 13 and Type 36D and 32D capacitors are shown in Figure 14. The advantages of these capacitor styles have been discussed and some typical performance data has been shown in Figures 5, 6, and 7. Impedance, capacitance, and equivalent series resistance characteristics versus frequency and temperature are contained in Sprague Engineering Bulletins No. 3441B and 3431. Figures 15 and 16 show typical long term life test characteristics obtained on two 36D capacitors, and Figures 17 and 18 show life test characteristics of two 32D capacitors.

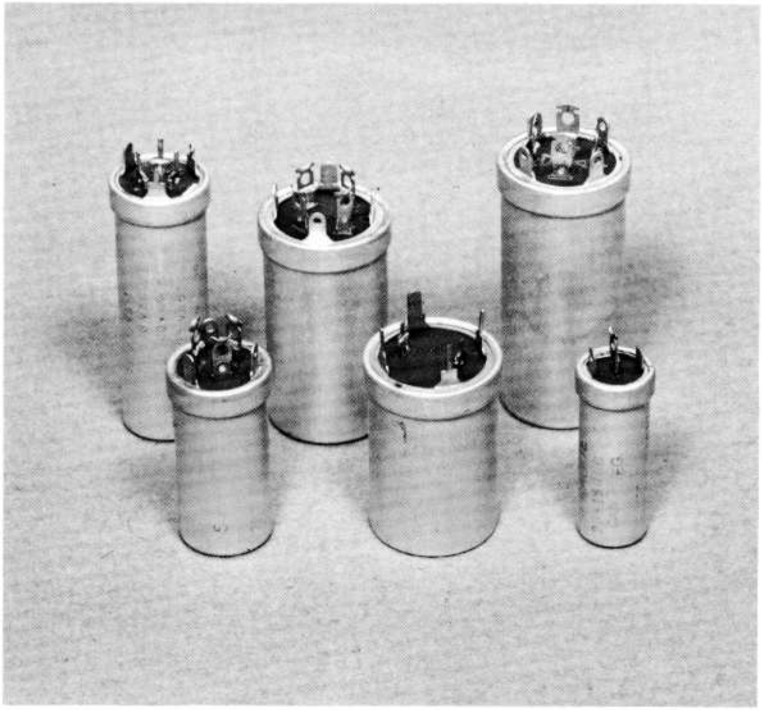


FIGURE 8
DFP CAPACITORS

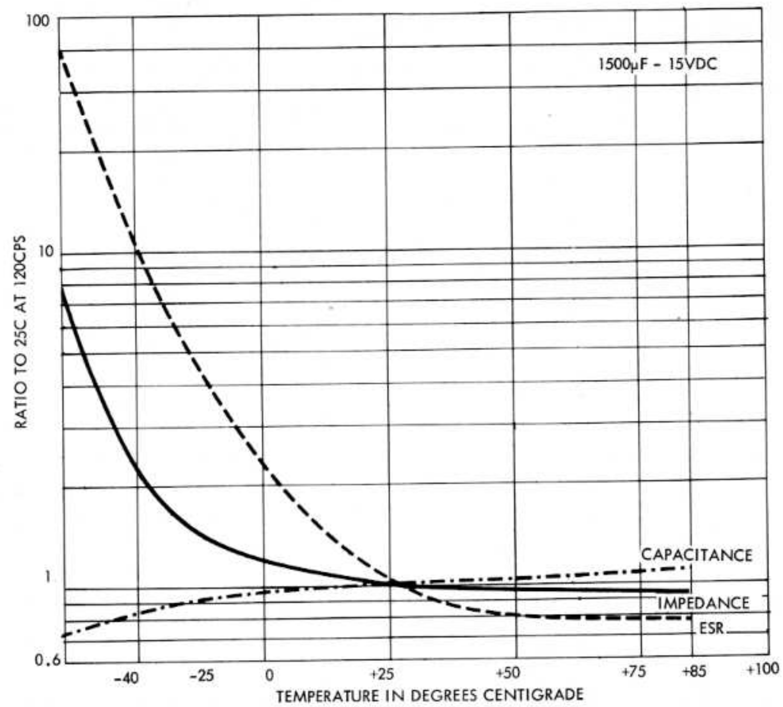


FIGURE 9
TYPICAL CURVES OF CAPACITANCE, IMPEDANCE, AND EQUIVALENT SERIES RESISTANCE WITH TEMPERATURE FOR 1500μF, 15 VOLT DFP CAPACITORS

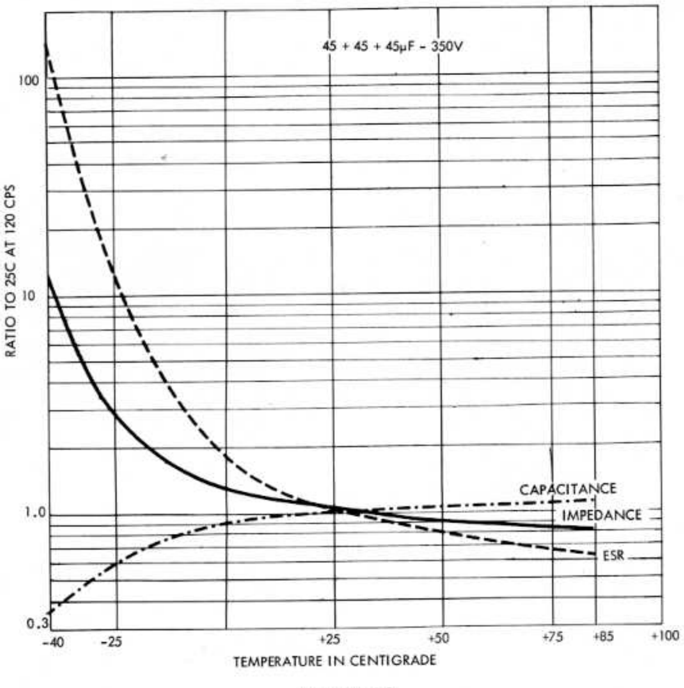


FIGURE 10
TYPICAL CURVES OF CAPACITANCE, IMPEDANCE, AND EQUIVALENT SERIES RESISTANCE FOR 45+45+45μF, 350 VOLT DFP CAPACITORS

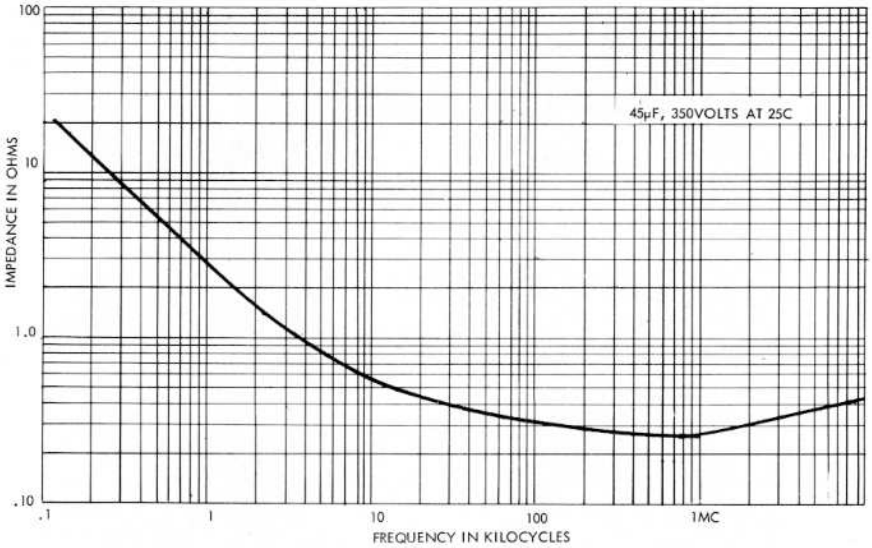


FIGURE 11
TYPICAL CURVE OF IMPEDANCE WITH FREQUENCY FOR 45μF, 350 VOLT DFP CAPACITORS

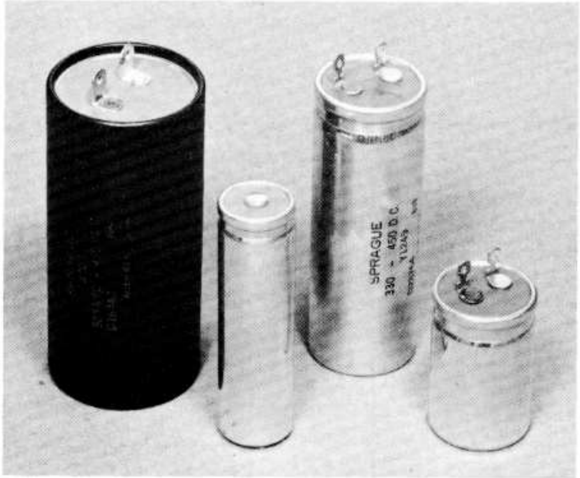


FIGURE 12
DEC CAPACITORS

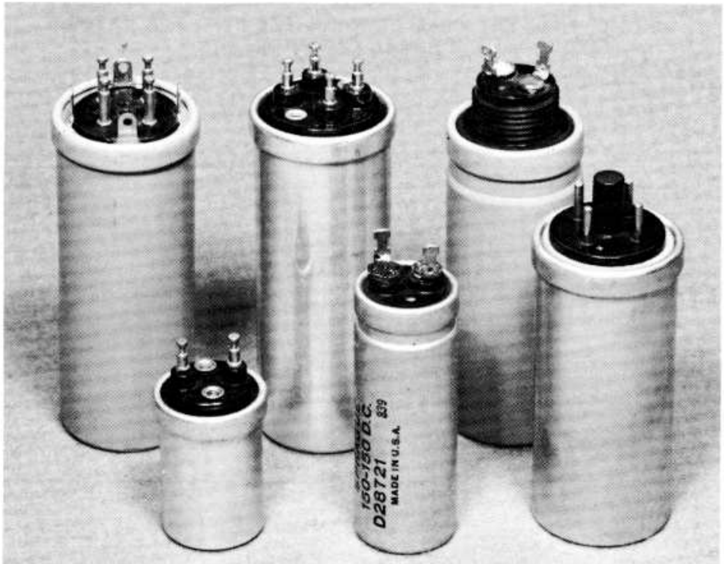


FIGURE 13
DFQ,17D AND MILITARY CAPACITORS

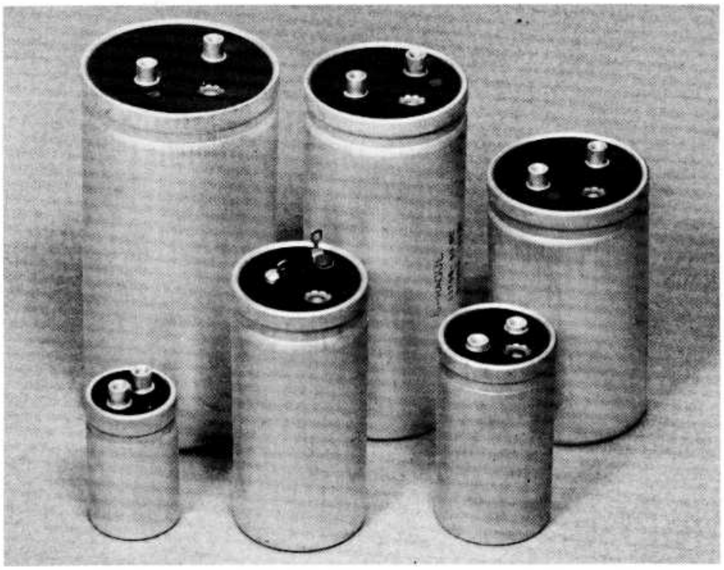


FIGURE 14
TYPE 32D AND 36D CAPACITORS

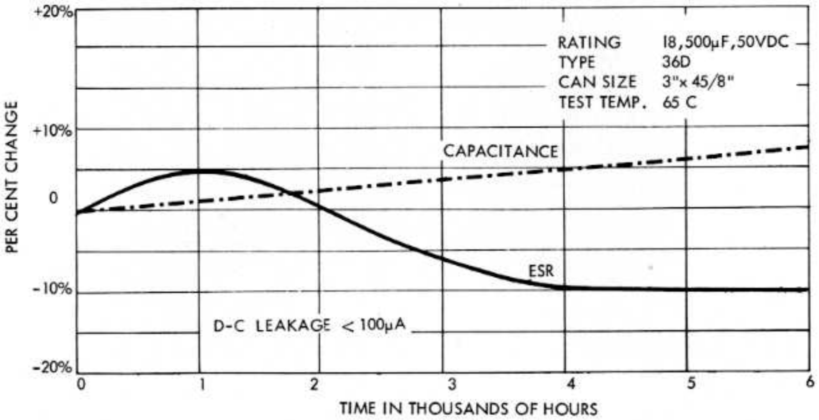


FIGURE 15
LONG TERM TEST CHARACTERISTICS FOR TYPE 36D, 18,500µF, 50 VOLT CAPACITORS

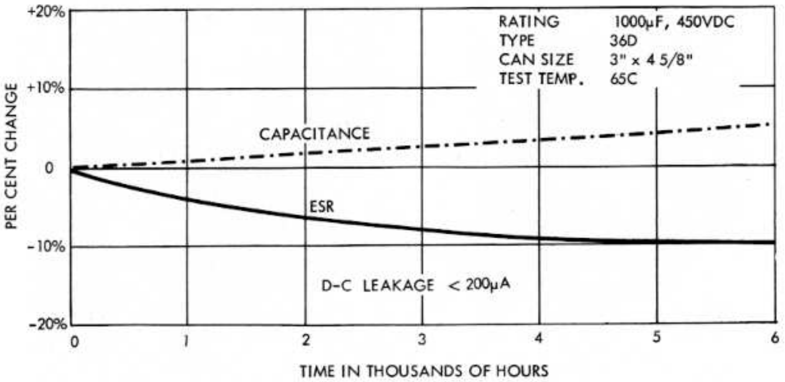


FIGURE 16
LONG TERM TEST CHARACTERISTICS FOR TYPE 36D, 1000µF, 450 VOLT CAPACITORS

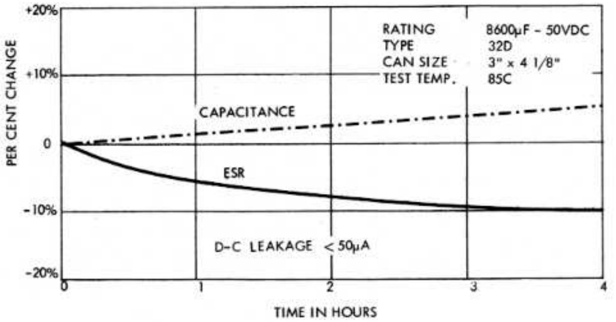


FIGURE 17
LONG TERM TEST CHARACTERISTICS FOR TYPE 32D, 8600μF, 50 VOLT CAPACITORS

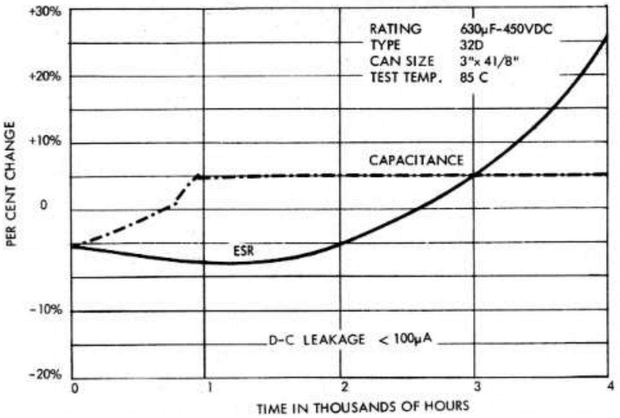


FIGURE 18
LONG TERM TEST CHARACTERISTICS FOR TYPE 32D, 630μF, 450 VOLT CAPACITORS

The excellence of these capacitor types is further proven by the enviable reliability record they have compiled. Table 4 presents the results of routine control life tests that have been run on samples taken from lots shipped to customers between mid-1958 and mid-1961. This time period was selected as being representative of modern production processes and designs. During this period both process and design improvements were made as analyses of life test failures indicated the modes and causes of failure, permitting corrective action.

Table 4 also shows the effect of the failure-analysis/corrective-action cycle on the decline in failure rates during the periods covered. Note the dramatic decline in failure rate during the second half of the three year time interval. It can be assumed that the figures shown for the 1960-1961 period in the table are typical of production at the present time.

Reliability Data

For over 20 years, the Sprague Electric Company has supplied aluminum electrolytic capacitors for use in telephone systems. Recent performance feedback data covers a period of approximately four years (35,000 hours). During this period, between 20 and 24 million aluminum electrolytic capacitors were being used in a variety of circuits. Only 22 failure reports have been received from the user, and even though the reporting system may not be infallible, and even if the reported failures had been 500 instead of 22, still it is obvious that the failure rate is incredibly low, and this stands as further evidence of the Sprague Electric Company's ability to manufacture long life, high reliability aluminum electrolytic capacitors.

TABLE 4

Time	Unit Hours	Total Failures	Failure Rate (60% Confidence Level)
	85 C RATED CAPACITORS		
July, 1958 - Dec., 1959	2,042,000	38	1.96%/1000 hrs.
Jan., 1960 - June, 1961	833,000	4	0.60%/1000 hrs.
	65 C RATED CAPACITORS		
July, 1958 - Dec., 1959	865,000	26	3.25%/1000 hrs.
Jan., 1960 - June, 1961	630,000	1	0.32%/1000 hrs.

CAPACITORS AS AN ENERGY STORAGE DEVICE

by

WILLIAM McQUEENEY

Introduction

The use of capacitors as energy storage devices is a well-known concept. As a matter of fact, it is quite a fundamental application. You will remember that the "original capacitor", the famous Leyden jar invented in 1745, provided the first means of storing electric charges. The design and construction of today's sophisticated capacitors certainly make the originals seem like primitive devices. But these first models *did* permit fairly large quantities of charges to be stored, a feat which was previously unaccomplished. Consequently, they aroused considerable interest throughout the scientific community of the day.

The zeal of these early scientists was quite extraordinary, to say the least. Dr. Einstein reports in his book "The Evolution of Physics" that an ambitious monk in a European monastery built a cylindrical Leyden jar six feet high and subsequently gathered all the monks in the courtyard in a circle around the jar. All hands were joined except the two on either side of the jar. At a given signal, these stout souls touched the jar, and the monastic chronicler reports "to a man they leaped several feet into the air".

Ever since those days, there has been a continued and progressive, albeit less lethal, investigation into the use of capacitors as energy storage devices.

$$(1a)\ C = \frac{Q}{V}$$

$$(1b)\ W = \frac{CV^2}{2} \qquad \begin{array}{l} W = \text{Joules} \\ V = \text{Volts} \\ C = \text{Farads} \end{array}$$

Equation 1a is the definition of capacitance.

Equation 1b defines the energy of a charged capacitor.

In an energy storage application, we are principally concerned with two things—the total energy available, and the operating voltage to be employed. These two considerations determine the type of capacitor required. A further consideration is that of energy versus size. From equation 1b we see that the higher the voltage, the greater the potential energy. It is therefore more efficient to use higher voltages where possible, because the joules per cubic inch is much greater than at low voltages.

Advantages and Disadvantages of Electrolytic Capacitors

For many years, the only capacitors considered for energy storage applications were paper-oil types. This was due primarily to the type of high resistance circuitry, requiring extremely high voltages, employed at that time. Moreover, early vintage electrolytic capacitors did not present an optimum case for energy storage because dielectric stability and overall reliability did not compare favorably enough with other types of capacitors. Also, the volumetric efficiency and higher capacitance and voltage values were not readily available. With the advent of the low resistance circuits, the requirements for smaller and lighter packages, the increased stability and reliability of electrolytic capacitors, and the excellent volumetric efficiency (CV Product) which aluminum electrolytics offer, the industry began a trend away from papers toward electrolytics. The primary advantages of an electrolytic capacitor over the paper type are:

1. Maximum energy density in the neighborhood of 4 watt-seconds per cubic inch
2. The relatively low cost per watt-second
3. The very light weight
4. Our ability through series arrangement to achieve a practical limit of 900 volts.

The shortcomings are:

1. At very low temperatures, because of the increase in ESR, too much energy is lost within the capacitor.
2. The effect that the higher d-c leakage current of the electrolytic capacitor exhibits. Because of this rather high leakage, one cannot charge them and then store them in the charged state for long periods of time without losing considerable amounts of the energy. Furthermore, on the initial charging cycle the power sources must be slightly heftier in order to account for the drain on them caused by the higher d-c leakage current.

When should you use a paper and when an electrolytic capacitor? A good rule of thumb is that up to 900 volts the electrolytic capacitor yields the highest volume efficiency. From 2000 volts up, the paper type capacitor yields the greatest efficiency. There is a grey area between 1000 and 2000 volts between which neither is particularly advantageous volumetrically.

D-C Leakage Current An Important Consideration

We have already mentioned that d-c leakage current plays a very important part in the ability of an aluminum electrolytic to perform correctly as an energy storage device. Since the d-c leakage current is a direct result of the quality of the dielectric, we are concerned with discovering how good a dielectric we have.

There are two significant ways to demonstrate the electrical stress characteristics and the stability of aluminum oxide as a dielectric. A high surge voltage test is used to prove the former; a high temperature shelf test demonstrates the latter.

Table 1 shows the measurements taken after the surge test. This test, conducted first at room temperature, calls for the rated surge voltage of the unit to be applied for 30 seconds, then removed for 9 1/2 minutes, alternately for 24 hours. The entire test is then repeated at a temperature of 85 C. As can be seen from the test results in Table 1, the change in capacitance and RxC is very slight. Also, the change in d-c leakage is downward in all but one case. Later on, data will be shown on more rapid charge and discharge rates at voltage levels less than surge voltage, but this stability under maximum design conditions is a necessary prerequisite to stability and reliability under lesser conditions.

TABLE 1

			Initial Measurement			Final Measurement		
Unit	μF	WVDC	Cap.	RxC	I_L (ma)	Cap.	RxC	I_L (ma)
			25°C, 525 VOLTS D-C SURGE					
1	860	450	1159	156	1.7	1156	169	.5
2	860	450	1217	162	2.1	1213	171	.52
3	630	450	638	114	6.9	637.4	119	3.1
4	630	450	716.5	167	.06	710.9	175	.06
			85 C, 525 VOLTS D-C SURGE					
1	860	450	1159	156	1.7	1167	153	.3
2	860	450	1217	162	2.1	1223	159	.28
3	630	450	638	114	6.9	645.5	106	.9
4	630	450	716.5	167	.06	703.3	158	.15

Table 2 presents the data on the change in characteristics after a standard shelf test of 100 hours at 85 C with no voltage applied. In any electrolytic capacitor there is a tendency for a reaction to take place between the aluminum oxide film dielectric and the electrolyte. This action, if widespread, impairs stability and results in high leakage currents. This action is more prone to take place under zero voltage conditions, and is greatly accelerated by higher temperatures. Consequently, the shelf test described is a significant one. We call your attention to the very slight changes in d-c leakage current shown here, and suggest this as effective demonstration of Sprague's excellent aluminum oxide dielectric stability.

TABLE 2

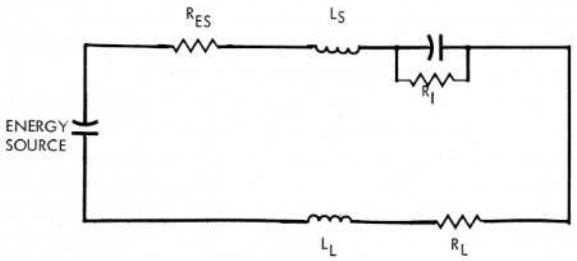
SHELF TEST

			Initial Measurement			Final Measurement		
Unit	μF	WVDC	Cap.	RxC	DCL (ma)	Cap.	RxC	DCL (ma)
1	1000	450	1189	158	.22	1226	196	.35
2	1000	450	1245	159	.21	1283	205	.38
3	1000	450	1220	161	.21	1267	209	.34
4	1000	450	1203	171	.22	1246	228	.35

Equivalent Series Resistance

The second major consideration in the use of an electrolytic is the ESR of the unit. Since we want to get as much energy out of a unit as we can, the ESR of the unit should be kept as low as possible. Capacitors to be utilized in photoflash and other energy storage applications are designed slightly differently from the standard high quality units. We make a positive effort to reduce the ESR and the X_L to a minimum. The ESR of the unit and the inductance of the unit also play a significant part in their association with resistances and inductances of the circuit.

Figure 1 shows the equivalent circuit of an energy storage capacitor with the terms as described.



R_{ES} = Energy loss in capacitor
L_S = Self inductance of capacitor
R_l = Shunt resistance
L_l = Inductance of load
R_L = Resistance

FIGURE 1
EQUIVALENT CIRCUIT OF AN ENERGY STORAGE CAPACITOR

Discharge Time

In all energy storage applications, the amount of time required to discharge the capacitor is extremely important because the loads require high currents. The flow of charge-per-unit-time is the definition of current, and both the resistance and the inductance of the circuit tend to increase the discharge time. The particular effect they have, however, is dependent not only upon the magnitude of both, but also on the ratio of their values to each other.

Effect of Resistance and Inductance

The effect of resistance and inductance is a most interesting phenomenon to observe and can be demonstrated by the formula:

$$B = \sqrt{\frac{R^2}{X4L^2} - \frac{1}{LC}}$$

for which there are three possible conditions: (1) B is real, (2) B is imaginary, (3) B is zero.

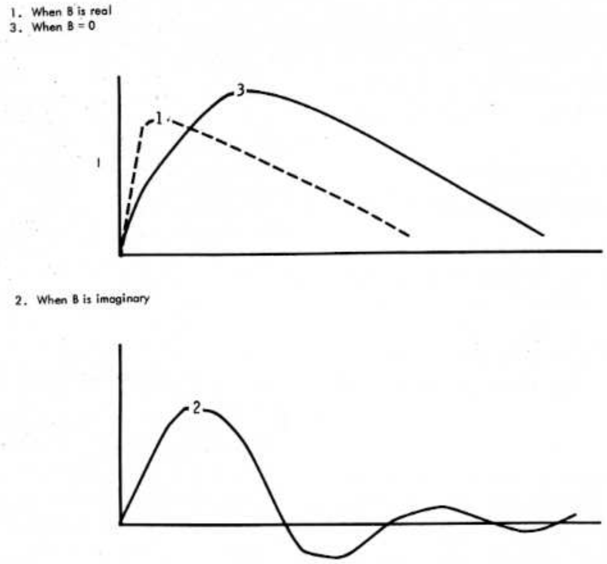


FIGURE 2
TYPICAL DISCHARGE PATTERNS

Curve 1 in Figure 2 shows a typical discharge pattern where B is real; that is, where the resistance of the load is sizeable compared to the inductance of the load. In this case, the current discharge reaches a peak quickly and then drops off rapidly.

Curve 2 shows a discharge of an oscillatory nature; that is, when B is imaginary. This phenomenon occurs when the resistance is very small with respect to the inductance. The current actually reverses direction for a short period. The voltage, while out of phase with the current, will also reverse. The magnitude of this reverse current and voltage varies with the particular conditions but may bring about certain problems, as far as electrolytic capacitors are concerned. The normal energy storage electrolytic capacitor is a polarized device, and if the magnitude of the reverse voltage is sufficient, the cathode plate may become formed, thus reducing the total capacity. This change can be avoided or minimized, however, by proper capacitor design. Therefore, the manufacturer should be informed if an electrolytic capacitor is to be used in such an application.

Curve 3 is for the case where $B=0$.

Three Standard Applications

Now, let's take a look at what we can define as three of the standard energy storage applications.

1. **Photoflash Applications.** The Sprague Electric Company manufactures a variety of styles and types of units for commercial photoflash applications, ranging up through the popular 525μF, 450 volts d-c in a can size of 2″ diameter by 4 1/8″ long. These units are manufactured using a capacitor section of the highest quality, placing emphasis on low leakage, low ESR, and overall stability. Because photoflash applications usually call for the capacitor to undergo a prolonged and closely repetitive duty cycle within a small physical area, and since there will be some energy loss within the capacitor (dissipated in the form of heat), Sprague Electric Company generally recommends that the diameter of these units not exceed 2″. In this way, the units will not operate at much higher than ambient temperatures, and you may be confident of a long, useful capacitor life. For less stringent flash requirements, units of larger sizes can be supplied. As described in Mr. Moresi's paper, there are several different enclosures available, ranging from the DEC type to the Type 36D. The choice is dependent upon the life desired and the duty cycle that the units will see.

Table 3 shows a chart of the life test results on one of the most popular Sprague photo-flash units rated at 380μF, 475 volts d-c. The chart shows the readings of capacitance and ESR during and subsequent to life testing at rated voltage, room temperature, and at a rate of 10 flashes per minute. The length of the test was 1,000,000 flashes, at a temperature of 25 C. Note the small change in characteristics, particularly the capacitance.

TABLE 3

Flashes	Cap. (μF)	ESR (Ω)
33,530	411.5	.54
78,100	421.1	.62
183,300	429.8	.66
288,475	438.6	.64
348,338	434.7	.66
496,556	428.6	.69
602,168	444.7	.68
702,803	440.0	.73
859,726	442.8	.71
1,011,687	446.3	.70

Final Per Cent Change: Capacitance, 7.5
ESR, 23

2. **Welding Applications.** Manufacturers of electric or resistance type welding apparatus have begun to use lower voltage and watt-second in-

struments. Thus, the use of electrolytic capacitors has drawn considerable attention. A typical application is one which requires 17,000μF, rated at 150 volts d-c. Several individual 1 3/4″ diameter units, rated at 720μF, 150 volts d-c, are paralleled and packaged in a container according to the customer's specifications. The highest quality section designs are used to insure optimum characteristics and long life. These capacitors also employ the most reliable hardware and end seals. In addition, the units are equipped with a safety vent. The completed assembly is tested at the factory prior to shipment. Information from customers indicates that life in excess of a million flashes can be expected.

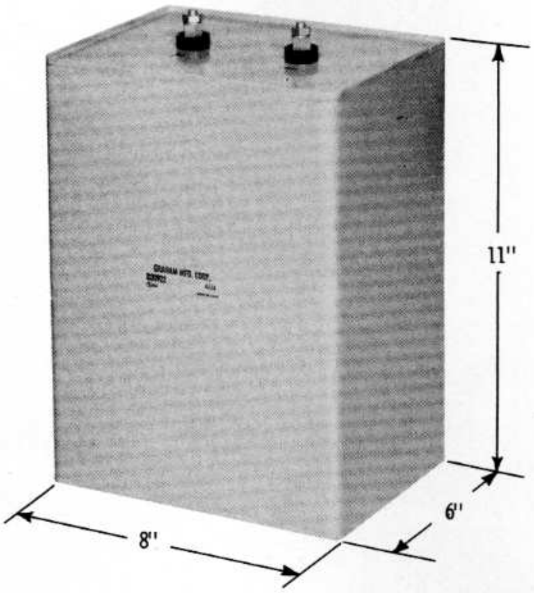


FIGURE 3
ELECTRO WELDING CAPACITOR BANK

Two infrequent situations arising in certain applications are: (1) Substantially increased capacitance and energy after being put into use, and (2) Customer concern about d-c leakage current after a period of non-use. It is possible that the capacitance will increase after several hours of use. This is usually due to an increased wetting of the sections. When we impregnate initially, we attempt to achieve a 100% impregnation, but we do not always succeed. In the finished unit, there is a small amount of excess electrolyte. With voltage stress and temperature changes, this excess electrolyte finally is absorbed and increases the capacitance somewhat. This increase in capacity is not due to dissolution of the oxide layer.

The second condition need not concern the user of Sprague capacitors. Previously supplied shelf test data justifies this statement.

3. **Signal and Flasher Applications.** In these applications, the capacitor usually discharges into a tube filled with gas at a very low pressure and the energy is dissipated in the form of light. The capacitor is subjected to a rugged duty cycle, and must be extremely reliable since most of these flashers are safety devices. Consequently, Sprague recommends and supplies its highest quality units for these applications.

Table 4 shows an extended life test that was performed on two 320μF, 250 volt capacitors used in series to yield a 160μF, 450 volt d-c unit. The capacitors were flashed at the rate of 80 flashes per minute. The majority of the test was conducted at 25 C, though there was in interim period of 150,000 flashes made at 72 C. The capacity and RxC of each of the two units was monitored during the test. The ambient temperature, the skin temperature, and the core temperature of these capacitors were also monitored. You can see that after 15,000,000 flashes, there was little or no change in the characteristics of the capacitors. We are still continuing these tests. Our limitation apparently is the life of the bulbs which we are utilizing. I think this should indicate that a properly designed aluminum electrolytic capacitor is capable of a very long life even with a rugged duty cycle. It is interesting to note that the customer for this capacitor group was looking for a life of 4,800,000 flashes, and had been unable to obtain satisfactory units prior to the manufacture and test of these.

TABLE 4

Hours	Number of Flashes	Ambient °C	Core °C	Core °C	μF	RxC
0	0	28			456.2	73
168	760,325	24	30	35		
410	1,913,600	26	40	44	474.8	56
700	3,235,319	40	43	46		
724	3,348,460	60	64	66		
748	3,461,380	80	84	86		
1080	5,057,062	29	40	44	474.8	56
2160	10,164,869	25	42	46	479.0	57
3500	15,367,998	27	43	44		

Testing and Measurement Problems

Finally, we would like to consider briefly some of the problems associated with the testing and measurement of electrolytic capacitors. Throughout the entire symposium we have been considering three basic parameters: d-c leakage current, ESR, and capacitance. We measure d-c leakage current in one of two ways—the method employed depending upon the value of the leakage current that will be encountered. With very high capacitance low voltage units, where the leakage currents are fairly high, a precision milliameter in series with the units can be used. But when one gets into very small capacitance high voltage units, the leakage currents are very low; and to be as accurate as possible, the method employed is a precision resistor of approximately 5000 ohms in series with the capacitor. The leakage current through the capacitor is then monitored as a voltage appearing across the precision resistor. The current can now be calculated from the known resistance and voltage. The last two parameters—capacitance and ESR (or, through a simple calculation, dissipation factor)—are measured on a bridge. All bridges at Sprague operate at 120 cycles. We balance both ESR and capacitance simultaneously. Over the years problems have arisen between the customers and ourselves in regard to correlation on capacitance and ESR readings. With the introduction of tantalums and high quality electrolytics, it became apparent that there was not available on the market a sufficiently accurate capacitance bridge covering the enormous range available in electrolytics. Consequently, we decided to offer to the market a replica of our own internal bridge. This bridge is unique, and is fully described in Sprague Engineering Bulletin No. 90010, but I would like to point out some of its salient features to you.

Most commercial bridges today apply a variable and often unknown a-c voltage to the unit. This can be as high as 100 volts on small fractional values, which is obviously beyond the capabilities of the capacitor to withstand. Furthermore, the accuracy of the dissipation factor, in particular, varies tremendously over the range because of introduction of lead resistances and bridge resistances in series with the capacitor. These problems have been eliminated with the Sprague bridge. Our bridge is a four-terminal device that submerges contact resistances and offers a true accuracy of 1.0% on capacitance and 2.0% on dissipation factor. The elimination of contact resistance as a source of error is accomplished by connecting these back into the balancing portion of the bridge. At no time is the capacitor subjected to more than 0.7 volts a-c, and no d-c bias is used or required. We have a bridge, thus, that is capable of being used either as a highly sensitive laboratory device or a rapid-readout production device.

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