Vacuum Variable Capacitors - An Introduction to their Design, Rating and Installation

The enclosed article has been published in the "Cathode Press" Magazine of The Machlett Laboratories, Inc. Machlett had been a very important partner for COMET, being licensor of COMET AG for the manufacture of X-ray tubes since the early fifties and being licensor of COMET TECHNIK for the manufacture of vacuum capacitors since 1965. This close cooperation between COMET and Machlett came to a halt in 1989 when Machlett was purchased by Eimac. Machlett stopped production of vacuum capacitors in 1969.

Although this article was published about 30 years ago, it is still correct in almost every aspect, except maybe for some brand names which have been changed in the meantime. It gives a concise summary of the subject and is interesting to read. The credit for this goes to Lars Giers who wrote the article back in 1966 as a development engineer responsible for variable vacuum capacitors at Machlett.

Lars has been our U.S. representative for vacuum capacitors and industrial X-ray tubes and is operating a successful reloading operation using COMET medical X-ray tubes.

Issue date 22-Feb-1994

Vacuum Variable Capacitors—An Introduction to their Design, Rating and Installation

by LARS GIERS,
Development Engineer

Introduction

The concept of using vacuum as a dielectric for capacitors is certainly not new. There are, however, relatively few manufacturers of vacuum capacitors in the world. It is just recently that their manufacture has been introduced in several Western European countries. It is now over twenty years ago that Machlett Laboratories was selected by the Western Electric Company to manufacture its then extensive line of broadcast and communications triodes. The selection of Machlett was recognition of the Company's competence in high vacuum, high voltage and expert tube manufacturing techniques developed through its long experience in the design and production of x-ray tubes. Since that time Machlett has gone on to establish an independent reputation in the exacting field of power tubes, now offering the most varied and comprehensive group to be found anywhere in the world from a single company.

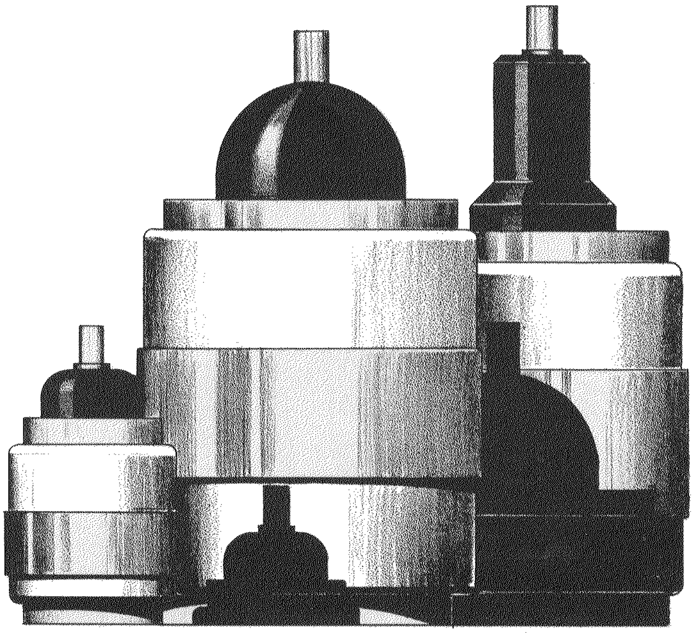
In relatively recent times Machlett extended its broad resources of experience and facilities in the area of high vacuum and high power, into the field of ceramic vacuum variable capacitors. Starting first with an extensive group of variable vacuum capacitors, the Company plans still broader offerings in the near future and on a continuing expansion basis. The basic Machlett identifying symbols chosen are **VCV**, denoting "VACUUM CAPACITOR VARIABLE" as are offered at present, and in the near future when fixed capacitors are offered the prefix will be **VCF**, denoting "VACUUM CAPACITOR FIXED."

Vacuum as a dielectric medium offers many advantages in a capacitor. Because of its high dielectric strength it is possible to maintain very close plate spacing (i.e., high capacitance) and still have a capacitor with good high voltage hold-off capabilities. Should the rated voltage inadvertently be exceeded to such an extent that a breakdown does occur between plates, this does not normally result in permanent damage which is often the case with capacitors using other dielectrics, such as paper, SF_6, mica, etc. Because of very low losses (high quality factor) and a heavy copper and ceramic construction the Machlett vacuum capacitors are capable of handling relatively high rf currents. Since the atmosphere is completely excluded from the plate area, vacuum capacitors are practically unaffected by moisture, temperature and atmospheric pressure. Variable vacuum capacitors can have a ratio as high as 300 to 1 between maximum and minimum capacitance. A ceramic vacuum capacitor is capable of handling large reactive power in a small package.

Construction

A typical Machlett vacuum variable capacitor is shown in Figure 1. As can clearly be seen in Figure 2 this capacitor utilizes two constant pitch spirals for electrodes rather than the more conventional—two sets of intermeshing cylinders or cups. The main reason for taking the spiral approach was to simplify manufacture, chemical processing and control required in the overall manufacture of the capacitor itself.

Issue date 22-Feb-1994



The individual handling, cleaning and storage of electrode cups was anticipated as being a potential problem and was therefore further avoided by our unique design approach. The use of spirals also gives a much greater design flexibility and permits an infinite variety of capacitance response characteristics. Oxygen free high conductivity copper is used extensively throughout the capacitor except in the bearing and bellows which are made from phosphor bronze. The insulator envelope consists of a high grade low loss ceramic. Ceramic to copper seals are of the butt type resulting in good rf current carrying capabilities.

Capacitance

The capacitance between two cylindrical concentric electrodes is given by the formula

$$C = \frac{Al}{\text{Log } r_2/r_1}$$

where C = capacitance in pF
A = $2 \times 8.85 \times 10^{-2}$ pF/cm
l = length of electrodes in cm
r_1 = radius of inner electrode in cm
r_2 = radius of outer electrode in cm

This formula does not take the edge effect into account. As stated earlier, the Machlett capacitors use a continuous spiral rather than concentric cups. However, for all practical purposes this formula holds true for any turn of the spiral away from the start and end of the spiral.

A capacitance vs turns curve for the ML-VCV 1 is shown in Figure 3. The curve consists of basically three different parts; a, b and c: two straight portions, "a" and "c", and one knee portion, "b". 750 pF on the x-axis of Figure 3 is the maximum capacitance value and is pre-set during manufacture by means of a nut, which determines the meshing depth of the spirals. As the drive screw is turned clockwise the two spirals begin to disengage at a rate depending on the pitch of the drive screw. As the plates are disengaging the plate area is decreasing and so is, of course, the capacitance. This decrease in capacitance is at a constant rate depending on the plate area and screw pitch (section "a" in Figure 3). Before the plates are completely disengaged the rate of capacity change becomes non-linear which is reflected by the "knee" (section "b" in Figure 3) section of the curve. At this point factors such as edge affects of the capacitor electrode and the relative location of the ceramic insulator and collars begin to affect the capacitance. The slope of the curve at the other side of the knee, "b", is primarily dependent on the diameter of the spirals, which when not in mesh have practically the same capacitance as two round discs of the same diameter as the spirals. The minimum capacity depends on how far the spirals can be moved apart and on the residual capacity of the two envelope halves which are separated by the ceramic. For example, in order to make the ML-VCV 1 adjustable to a minimum of 5 pF it was necessary to incorporate a 3″ long ceramic.

Issue date 22-Feb-1994

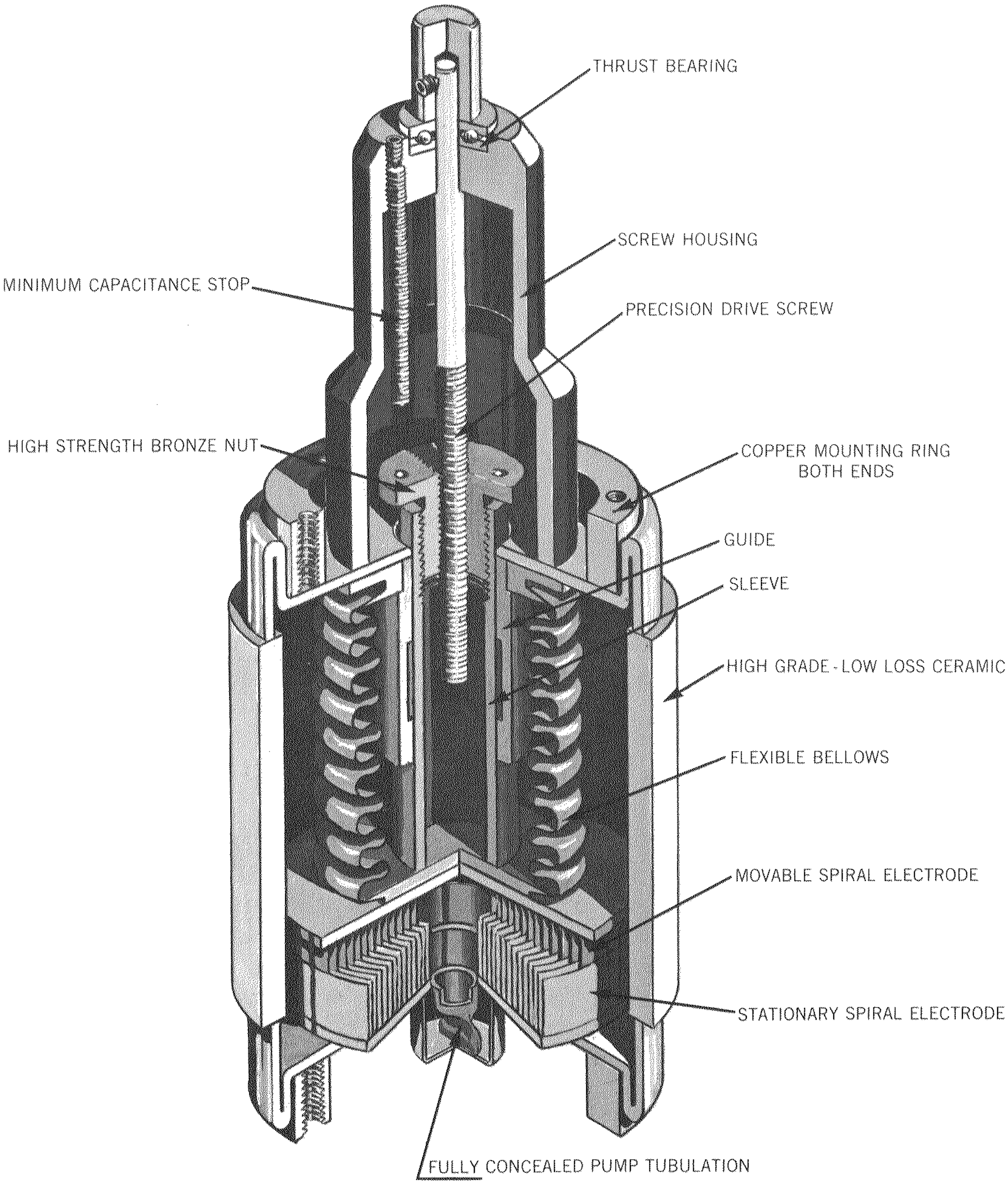


Figure 1 — A Machlett ML-VCV 1 Vacuum Variable Capacitor Shown in Cut-Away View.

Current

It is well known that at high frequencies the current density in a conductor is greater at the surface than in the center. Thus the rf current through a vacuum capacitor has to pass through the metal layer sealed to the ceramic and then through the bellows before reaching the capacitor electrodes. The layer forming the copper to ceramic seal is relatively "lossy" because of the presence of molybdenum, manganese, and nickel which are required to make the vacuum seals. The I^2R losses in the seal area are therefore higher than in other surfaces which have a higher conductivity. The heavy copper collars act as heat sinks and transfer the heat generated in the seals to the surrounding air and capacitor mounts. The second loss area of concern in a capacitor is the flexible bellows. Being made of phosphorous bronze it only has 20% of the conductivity of copper and since the bellows also has a very thin wall, the heat cannot be removed effectively and therefore the bellows are frequently the current limiting part in a capacitor.

The current through a capacitor is given by:

$$I = 2\pi f \times C \times E$$

where I = RMS current in amps
f = frequency in Hz
C = capacitance in Farads
E = RMS voltage in volts

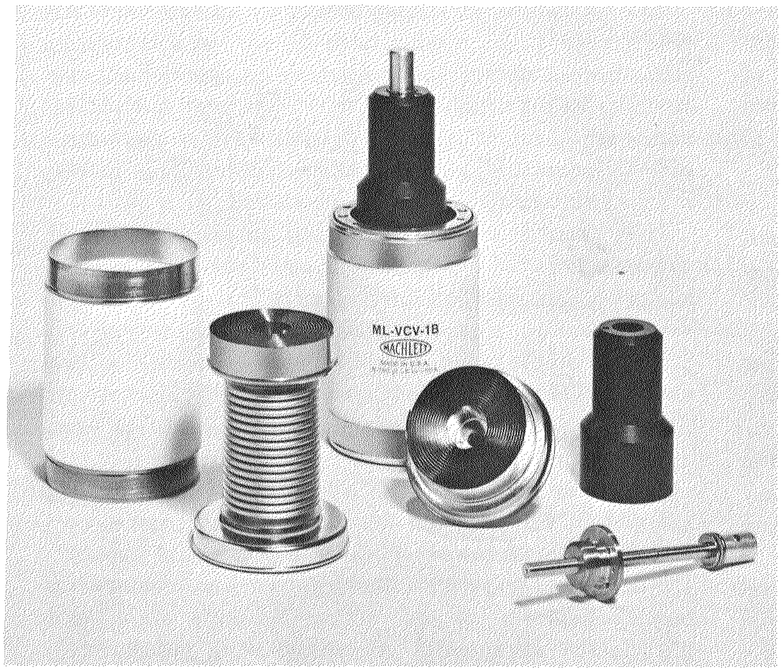


Figure 2 — Components of Machlett Vacuum Variable Capacitor, ML-VCV 1.

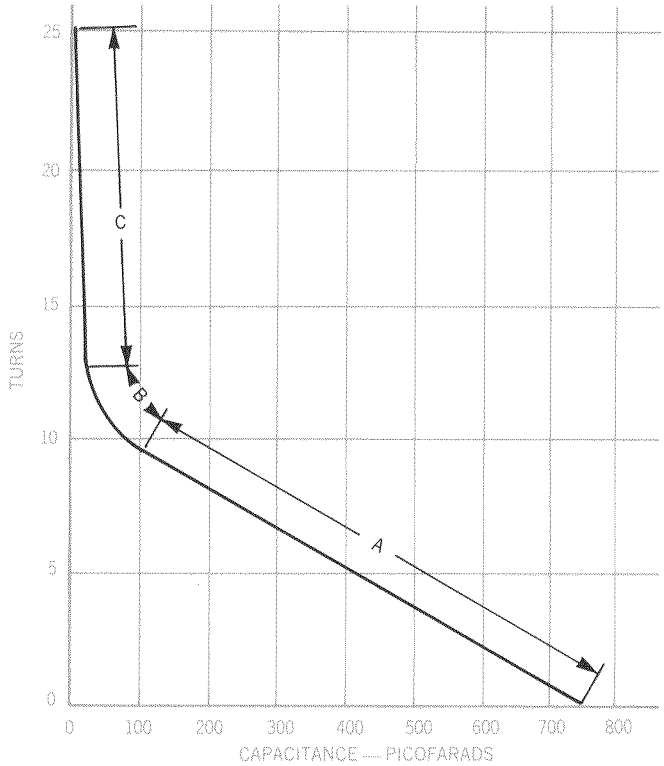


Figure 3 — Capacitance vs Turns for ML-VCV 1.

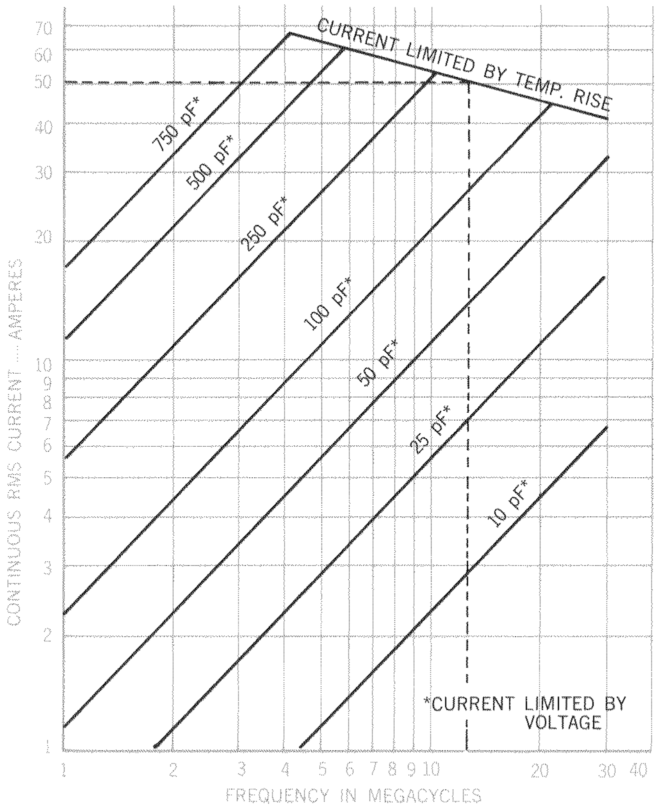


Figure 4 — Frequency vs Continuous RMS Current for Various Capacitances for ML-VCV 1.

The above equation is also illustrated in Figure 4. The published current rating applies at 13.6 MHz and is the current that will raise the capacitor temperature to 100°C. At frequencies below this value the capacitor will handle greater currents without temperature increase since the rf resistance is lower. At higher frequencies the maximum operating temperature is reached at a lower current than the published value. This again is due to a higher rf resistance.

A capacitor should never be allowed to operate above its rated temperature; i.e., above its rated current. If there is reason to believe that a capacitor is operating above its rated temperature this should be checked by applying a heat sensitive paint* to the seal area. With 100°C temperature at the seal area internal temperatures will be much higher. Operation with seal temperatures much above 100°C could eventually result in vacuum deterioration leading to internal breakdown or damage to the seals or bellows. The published current ratings are established without any heat sinking and can be increased by using heavy straps and/or chassis mounting. Forced air cooling

*Such as Tempilaq available from Tempil Corporation, 132 West 22nd Street, New York, New York 10011.

Issue date 22-Feb-1994

reasonably well distributed around the capacitor seal area will further raise the maximum allowable current. Before committing oneself to forced air cooling the possibility of obtaining a capacitor with a higher current rating should be considered.

Voltage

As previously mentioned the maximum voltage that can be applied across a capacitor without breakdown is dependent on the spacing between the capacitor plates and/or length of ceramic insulator.

The published voltage rating applies at 60 cycles ac test voltage and is the peak voltage at maximum capacitance. The voltage rating increases by a small amount as the plates are being disengaged (capacitance reduced) until the plates are completely disengaged. At this point a very sharp increase in voltage hold-off occurs simply because the internal spacing between plates is increased. This is illustrated in Figure 5. At a point near the minimum capacitance, voltage breakdown occurs across the outside of the ceramic insulator. An external arc is more easily triggered when the insulator is dusty and/or dirty. In applications where very high voltages are applied at a low capacitance value it is essential that the ceramic insulator is kept clean. Once an external arc occurs across the insulator additional arcs may take place at lower voltages because of the carbon trace left on the insulator from the initial arc.

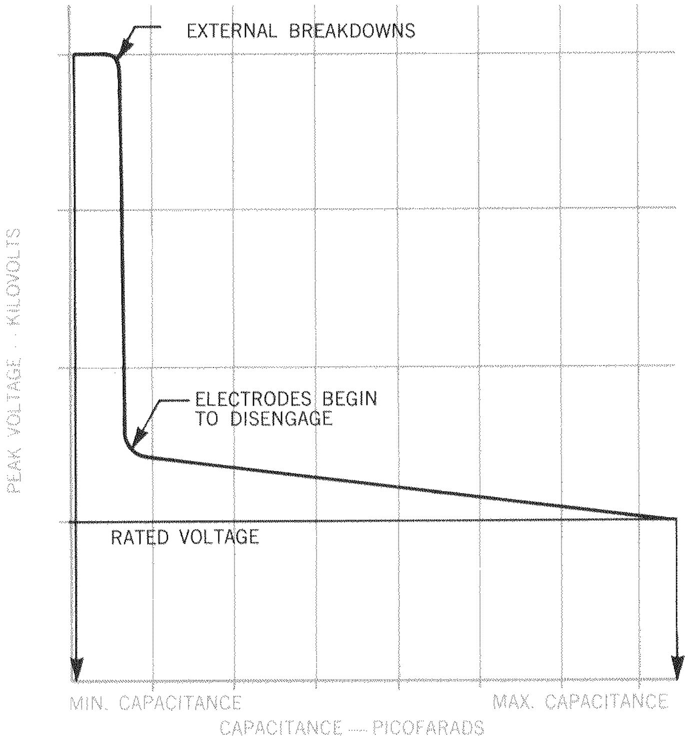


Figure 5 — 60 Cycle Peak Capacitor Voltage vs Capacitance.

The mechanism of voltage breakdown in vacuum is not clearly understood. Studies have shown that a breakdown starts from a microscopic projection on the cathode surface[1]. By letting a high voltage device arc, such microscopic points are burnt off and it is possible to raise the voltage further before additional breakdowns occur. This process is called voltage aging or "spot knocking".

It is possible and quite practical to control the high voltage stability of a capacitor to a certain point by cleaning and pre-outgassing of all internal parts. It is also considered very important that the vacuum capacitor is properly processed on the pump. The pump cycle consists of a bake-out at high temperature and "spot knocking". High bake-out temperatures insure stable operation at maximum operating temperatures.

If a capacitor is stored for a long period of time, some gas may be released into the vacuum. This may cause a few initial breakdowns at voltages where the capacitor should normally operate without breakdowns. The momentary "breakdown" of the vacuum dielectric which takes place when an internal arc occurs does not normally cause any permanent damage if the energy is limited. Arcs that are not current limited, however, can cause copper vaporization which can lead to deposits on the ceramic. (The resistance of any vacuum device during an arc can drop to below a fraction of an ohm.) This internal copper condensate will increase the leakage current and could also, at high frequencies, cause over-heating and cracking of the ceramic. Very high arc current can finally result in melting of the capacitor electrodes in small areas. For long trouble-free operation it is always wise to select a capacitor with a 40% safety margin in the voltage rating.

Self-Inductance

The major contributing factor to self-inductance in a variable vacuum capacitor is the flexible bellows. In the compressed condition, i.e., at minimum capacitance, the self-inductance is at its lowest value.

Internal resonance occurs when $\omega L = \frac{1}{\omega C}$. A typical self-inductance value at 750 pF for the ML-VCV 1 is 10.4 nano-henries. This gives a self-resonance frequency of 57 MHz which is well above the frequency where one would normally expect to operate with 750 pF. In high frequency applications where the self-resonance might be close to the operating frequency, low inductance connections must be used so that the self-resonance frequency always remains above the operating frequency.

Quality Factor

The quality factor (Q) describes the ratio between stored energy and energy dissipated per cycle[2,3].

CATHODE PRESS

$$Q = \frac{2\pi \text{ stored energy}}{\text{Energy dissipated per cycle}}$$

The stored energy for a capacitor $= 1/2\ CV_{pk}^2$

$$\text{Energy dissipated per cycle} = \frac{\text{watts lost}}{f} = \frac{I^2_{RMS} R}{f}$$

$$\text{Thus } Q = \frac{\pi C V_{pk}^2 f}{I^2_{RMS} R} \quad (1)$$

$$I_{RMS} = 2\pi f C \frac{V_{pk}}{\sqrt{2}} \quad (2)$$

Substituted in (1) and simplified

$$Q = \frac{1}{2\pi f C R} \quad (3)$$

R is dependent on frequency and follows: (4)

$$R = k \cdot f^{\frac{1}{2}}$$

Where k is a constant depending on the material.

Substituting $R = k \cdot f^{\frac{1}{2}}$ in (3) and disregarding the constant $2\pi k$ we find that Q varies with the frequency and capacitance as below

$$Q \propto \frac{1}{C f^{\frac{3}{2}}} \quad (5)$$

Because of this relation between Q, C and f a statement regarding Q should always be accompanied by a statement regarding capacitance and frequency. Without knowing C and f, Q is meaningless.

A good and accurate way to measure a high capacitor Q is to measure the sharpness (bandwidth) of the resonance curve in a cavity. Q can then be found from the equation:

$$Q = \frac{f_o}{f_2 - f_1} \quad (6)$$

Where f_o = resonance frequency in Hz
$f_2 - f_1$ = the two half power frequencies in Hz

A numerical example of how Q varies with capacitance and frequency is given below:

Consider a 50–1500 pF capacitor permitting operation at maximum peak voltage and RMS current at 50 pF and 30 MHz and also at 1500 pF and 2 MHz.

Q for this capacitor has been measured to be 430 at 1500 pF and 21.9 MHz. The capacitor Q at 2 MHz and 1500 pF is then obtained from (5):

$$\frac{Q_2}{Q_{21.9}} = \frac{1500\ (21.9)^{3/2}}{1500\ (2)^{3/2}}$$

$Q_2 = 36.2 \times Q_{21.9}$ $\qquad Q_{21.9} = 430$

Thus $Q_2 = 15500$

The capacitor Q at 30 MHz and 50 pF is:

$$\frac{Q_{30}}{Q_{21.9}} = \frac{1500}{50}\ \frac{(21.9)^{3/2}}{(30)^{3/2}}$$

$Q_{30} = 18.7 \times Q_{21.9}$ $\qquad Q_{21.9} = 430$

Thus $Q_{30} = 8050$

From equation (1) it can now be shown that the dissipated energy in the capacitor is constant along the line designated "current limited by temperature rise" in Figure 4.

Thermal Stability

As a vacuum capacitor heats up from the I^2R losses a line of complex expansions occur. Ideally the external expansion should be compensated by an equal amount of internal expansion resulting in no change in capacitance. This compensation is to a great extent carried out on the Machlett capacitors, leaving only a small net increase in capacitance as the temperature is raised. In general, capacitors having a long ceramic insulator (a low minimum capacitance value) tend to have a larger Δ C as compared to a capacitor with a short ceramic insulator. This is due to the fact that the ceramic has a very low coefficient of expansion.

The actual net change in capacitance is dependent on factors such as amount of heatsinking, ambient temperature and temperature rise. Since the heat in a capacitor is self-generated the internal capacitor temperature can be considerably higher than the external temperature. This is especially true when maximum or close to maximum currents are passed through the capacitor during a relatively short time.

The net change in capacitance is measured in a temperature test chamber. The temperature coefficient (TC) in parts per million per degree Centigrade (PPM/°C) is then derived from the following equation:

$$TC = \frac{(C_1 - C_2)\ 10^6}{C_1\ t}$$

where C_1 = capacitance at t_1
C_2 = capacitance at t_2
$t = t_1 - t_2$

C_1 is recorded at 85°C and C_2 is recorded at −25°C

Typical temperature coefficient values show a stability better than 40 PPM/°C.

For capacitors used under nonuniform heating conditions and/or in critical tuning applications a temperature compensating insert can be provided.

Bellows

The flexible bellows functionally seals off the vacuum. Since the bellows must also carry the rf current a low rf loss material must be used. In addition, the material must also be able to withstand great flexing without developing cracks that would mean loss of the vacuum. Phosphor bronze is a material that combines reasonably good conductivity and satisfactory cycling life. Other quite promising materials are under evaluation at Machlett Laboratories and suggest a foreseeable breakthrough in this area.

Issue date 22-Feb-1994

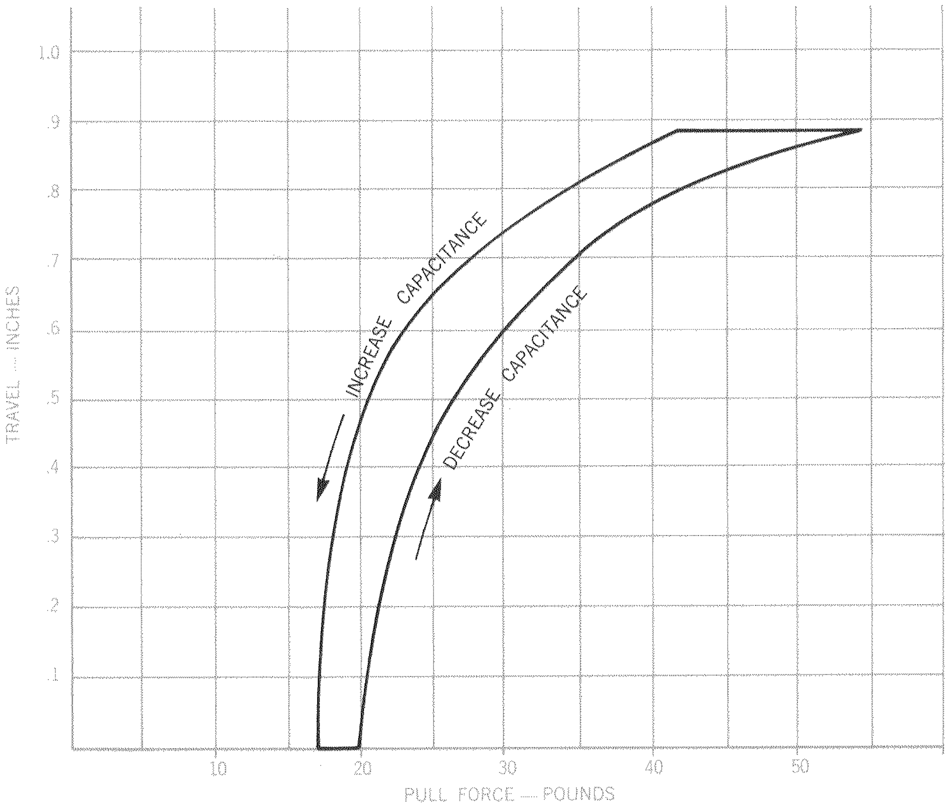


Figure 6 — Pull Force vs Travel, for ML-VCV 1.

The life of the bellows depends on the size of the bellows, the number and shape of the convolutions, depth and the extent of the stroke used. Metallurgical properties and variations in the wall thickness of the bellows will also affect the life. At Machlett bellows life tests are performed with a 100% stroke and a rate of 8 cycles per minute. Under these conditions the bellows can exhibit a life of up to 50,000 cycles before a crack in the bellows wall is developed.

Drive Mechanism and Bearing

Since the atmospheric pressure acts on the movable electrode, the force resulting from this pressure (the force depends on the effective area of the bellows) must be overcome when the electrodes are moved apart. The bellows which can be compared with a helical spring also requires a force to overcome the spring rate. This force increases as the bellows is compressed; i.e., capacitor adjusted towards a smaller capacity. The combined force acting on the movable electrode is plotted against travel in Figure 6. The torque required to operate the capacitor follows the same pattern. A typical torque curve for the ML-VCV 1 is shown in Figure 7. The dynamic and static torques are essentially the same. Generally the torque remains at a practically constant level throughout the life of the capacitor. Frequently re-lubrication is not required. However, if a capacitor is reset often and/or operated at maximum temperature, re-lubrication may become necessary. Capacitors working in a dusty, damp or corrosive atmosphere may, also, require lubrication.

The thrustbearing and drivescrew should be lubricated with "Molykote 505"*. For lubrication of the sleeve and guide a 25:1 mixture of Dow Corning No. 200† oil and Molykote‡ Type Z should be used. In order to insure a uniform suspension of the molybdenum in the oil this mixture must be well agitated before lubrication.

Mounting

All Machlett capacitors are shipped adjusted to minimum capacitance and well packaged in order to assure safe arrival. Upon arrival, it is, however, good practice to check the high voltage hold-off at maximum capacitance. This is best done with a 60 cycle high voltage power supply with the current limited in the secondary by a minimum resistance of 200 kohms. Raising the voltage in no less than 30 seconds to the maximum rated peak voltage, the capacitor should operate for 5 minutes without any signs of instability. After prolonged storage there may be a few

*Available from the Alpha-Molykote Corporation, 65 Harvard Avenue, Stamford, Connecticut.

†Dow Corning No. 200 oil is available from Dow Corning Corporation, Midland, Michigan.

‡Molykote Type Z is available from the Alpha-Molykote Corporation, 65 Harvard Avenue, Stamford, Connecticut.

Issue date 22-Feb-1994

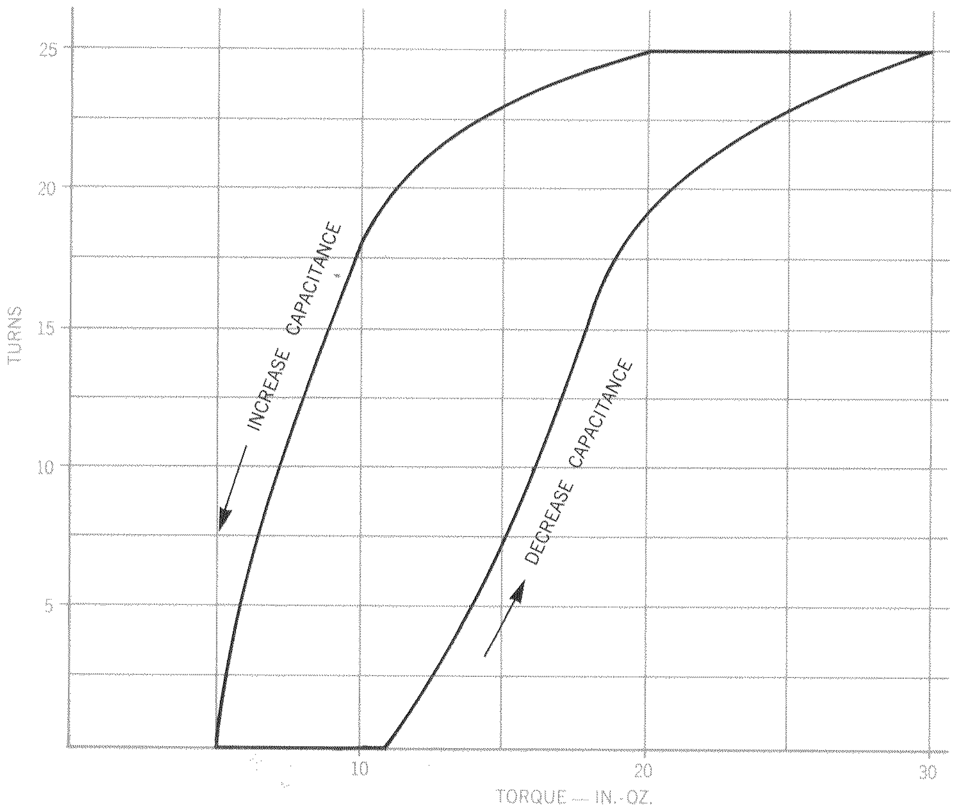


Figure 7 — Typical Torque Characteristics for ML-VCV 1.

internal breakdowns for the first minute or so at the rated peak voltage.

All Machlett ML-VCV capacitors are provided with mounting rings on both ends, the mounting surfaces are designated on the outline drawings.

By using heavy straps and mounting the capacitor directly on the chassis the capacitor can be held cooler. However, excessively rigid multiple connections to the capacitor should be avoided since this can result in excessive strain on the ceramic to metal seals. Allowance for expansion is also necessary. Vacuum capacitors can be mounted in any position with either end at ground or both ends off ground. In applications where the variable end is off ground the driving must be done over an insulated shaft. The capacitor should not be mounted too close to adjacent components or metal parts since this may crowd the electrical field lines in such a way that ceramic punctures may occur.

The driving mechanism for a capacitor should be designed in such a way that no sideloads are imposed on the bearing. For long trouble-free operation a flexible coupling should be used between tuning shaft and capacitor drive screw.

Shock and Vibration

The ceramic-metal construction of the Machlett capacitors results in a structure which is mechanically very strong.

As a design goal, a minimum shock requirement of 20 G's has been established. Capacitors have been tested to values in excess of 50 G's, without loss of vacuum, electrode alignment, or buckling of the copper near the seals which is often the cause of failure in glass capacitors.

Extensive tests have not yet been made on vibration at various frequencies. The capacitors will, however, withstand vibrations in excess of 10 G's at 60 Hz.

Conclusion

Manufacture of the vacuum capacitors by Machlett represents a natural extension of those techniques developed over the past thirty-five years in the design and production of, first, x-ray tubes and later, high power electron tubes. Now, after several years of engineering design studies and pilot production, Machlett makes available a group of newly conceived and thoroughly tested ceramic envelope, variable, vacuum capacitors. It is with confidence that these "ML-VCV's" are offered to the many manufacturers whose need for reliable, conservatively rated components is essential.

References

[1]Alpert, D., Lee, D. A., Lyman, E. M., and Tomaschke, H. E., *J. of Vac. Sci. and Technol. I*, pp. 35-50, 1964.

[2]Gray, Truman S., *Applied Electronics*, Second Edition, The MIT Press, pp. 638-641.

[3]Scott, Ronald E., *Linear Circuits*, Addison-Wesley Publishing Company, Inc., pp. 645-651.