A HIGHLY STABLE REFERENCE STANDARD CAPACITOR

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The transfer of the high accuracy of measurements at the National Bureau of Standards to other laboratories requires standards of correspondingly high stability. For example, NBS now calibrates capacitance standards of l000 pf at 1000 cps with an accuracy better than ±0.002% or ±20 ppm (parts per million). But, whenever a capacitor calibrated at NBS is moved to another laboratory, the uncertainty of the calibration is increased by the possible changes in capacitance when the capacitor is transferred to and measured at the new location. Capacitance changes of the order of 20 ppm can occur in most capacitors for several reasons.

SOURCES OF INSTABILITY

Mechanical Shock

Perhaps the most obvious source of change is mechanical displacement of the capacitor plates, resulting from vibration or shock in transport or in handling. Most capacitors must be handled with particular care to keep such changes below 20 ppm. Even with no handling at all, a capacitor sitting on a shelf ca change in capacitance with time, because any strains left in the capacitor materials at the time of construction can change with age and thus change plate area or separation.

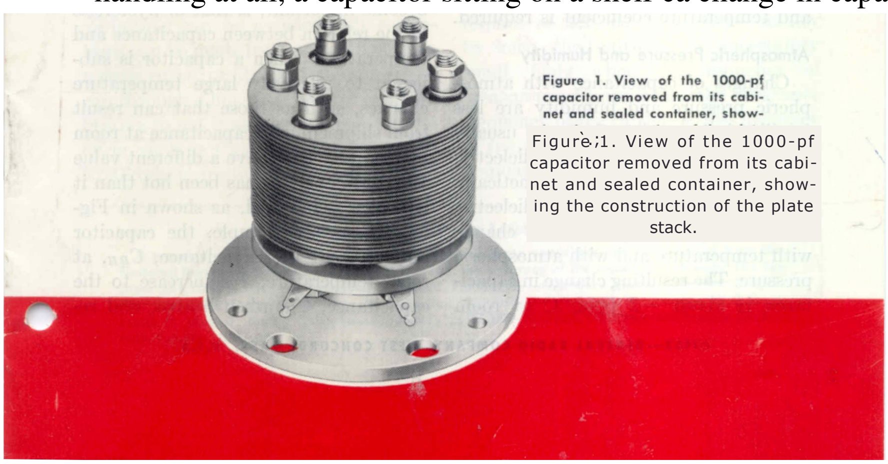


Figure 1. View of the 1000-pf capacitor removed from its cabinet and sealed container, showing the construction of the plate stack.

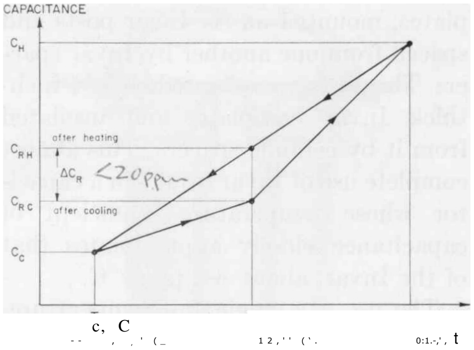


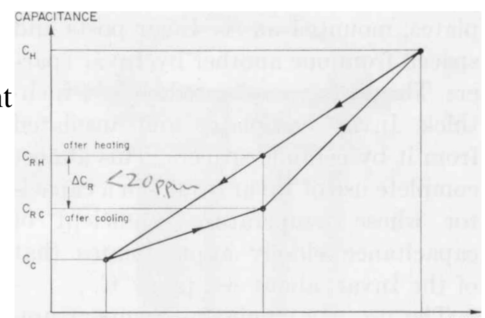
Figure 7. Capacitance vs temperature diagram showing hysteresis.

Temperature

Capacitance change also results from temperature change, not only because the dimensions are changed by mechanical expansion but also because the permittivity, particularly of solid dielectric materials, varies with temperature. Typical standard capacitors with air dielectric and plates of brass or aluminum have temperature coefficients of capacitance of the order of 16 to 22 ppm/°C, while the coefficient of a mica capacitor is of the order of 40 ppm/°C. Uncertainties of the order of go ppm can therefore result from temperature changes of only one degree. In order to apply corrections to reduce these uncertainties, accurate knowledge of both capacitor temperature and temperature coefficient is required.

Atmospheric Pressure and Humidity

Changes of capacitance with atmospheric pressure and humidity are less familiar because the effects are usually negligible. However, in an air-dielectric capacitor that is not hermetically sealed, the density of the air dielectric between capacitor plates will change with temperature and with atmospheric pressure. The resulting change in capacitance is about 2 ppm /°C at room temperature and +18 ppm per inch of mercury pressure change. Since the atmospheric pressure and density decrease with altitude, if such an unsealed capacitor is moved from Washington near sea level to the mile-high altitude of Boulder, Colorado, the capacitance will decrease by the no-longer-inconsiderable order of 100 ppm. If water vapor is present in the air, the dielectric constant is increased, and the capacitance increase with atmospheric humidity is approximately 2 ppm per percent relative humidity. Water that condenses on capacitor plates or soaks into solid dielectrics causes capacitance changes that are usually larger and less predictable.



Hysteresis

Another deficiency, which appears in most capacitors when parts per million become important, is that of hysteresis in the relation between capacitance and temperature. When a capacitor is subjected to relatively large temperature .changes, such as those that can result from shipment, the capacitance at room temperature may have a different value after the capacitor has been hot than it has after being cold, as shown in Figure 2. In this example, the capacitor may start at the capacitance, CRR, at room temperature, TR, increase to the capacitance, CH, when heated, and return turn to CRH when cooled to room temperature. This cycle can be retraced as long as the capacitor does not go much below room temperature. However, when the capacitor is cooled to the low temperature, Tc, and returned to room temperature, the capacitance at room temperature has a new value, CRC, lower than the initial CRH. Again, the cold cycle can be retraced from CRC to Cr if the capacitor does not go far above room temperature. When the capacitor at CRC is heated to T,1 and then cooled to room temperature, the capacitance may return to the initial value, Uncertanties of the order of 20 ppm can occur in capacitors that have such hysteresis unless: (1) large temperature variations can be avoided; (2) corrections can be made from a known characteristic curve; or (3) the capacitor can be run through a hot cycle before each calibration to put it at a known point in the cycle, such as C . The source of such hystersis is friction in the mechanical structure, which restricts the motion resulting from the thermal stresses. In most mechanical structures the hysteresis cycle is not so simple or so retraceable as assumed in this example.

Voltage and Frequency
Additional sources of capacitance change are variations in voltage and in frequency. Changes of capacitance no greater than a few ppm can be expected in standard air capacitors with voltages in the usual measurement range below, say, 100 volts. In silvered-mica capacitors, such as the TYPE 1409, changes from 10 to 200 ppm may occur for voltage changes from 1 to 100 volts. Such changes usually result from small isolated sections of the silver film that connect to the main body of film and add capacitance as the applied voltage increases. The magnitude of the change varies widely from capacitor to capacitor, depending upon the quality of the silver film. When foil electrodes are used instead of silvered mica, the changes with voltage decrease to the order of a few ppm.

In both air and mica capacitors the rate of change of capacitance with frequency is generally small enough to require no unusual frequency stability to keep the capacitance uncertainty small. Only when the frequency of measurement approaches the resonance frequency of the capacitor does accuracy of frequency become important, so that standard frequencies are required.

Connections
The changes in capacitances produced by the connections to the capacitor can also be a source of error. These connection errors were described in some detail in the Experimenter a few years ago.' In capacitors with unshielded plug-andjack connectors, a portion of the calibrated capacitance is associated with the terminals of both the capacitor and the bridge on which it is measured. Small changes in the geometry or in the environment of these terminals may produce capacitance changes as large as 0.1 pf. To eliminate uncertainties of this order, which are important in accurate calibrations of 1000 pf or less, the terminal geometry can, with care, be' defined and controlled to the required precision. Or more easily in most cases, the terminal capacitances and their uncertainties can be eliminated by the use of three- terminal capacitors and three-terminal measurements.

A NEW REFERENCE STANDARD
A new capacitor has been designed to obtain a standard in which capacitance changes remain small compared to 20 ppm without the use of unusual care in handling, in environmental control, or in measurement. This is the new TYPE 1404 Reference Standard Capacitor, a three-terminal, sealed, dry-nitrogen-dielectric capacitor with direct capacitance of 1000 pf or 100 pf. Stability in this capacitor has been obtained not by unusual design but by the use of a simple, solid, homogeneous structure of a single, low-temperature-coefficient material sealed in an invariant atmosphere.

Construction

The capacitor, as shown in Figure 1, is made up of a stack of round Invar plates, mounted on six Invar posts and spaced from one another by Invar spacers. The posts are mounted on a 14-inchthick Invar baseplate, and insulated from it by ceramic spacers. This almost complete use of Invar results in a capacitor whose temperature coefficient of capacitance closely approximates that of the Invar, about +2 ppm/°C.

The use of a single, low-temperature coefficient metal makes the coefficient of the capacitor more reproducible and eliminates the differential drift that can occur when the capacitor uses two metals of higher but mutually compensating coefficients.
The capacitor is mounted inside a hermetically sealed heavy brass enclosure. All electrical connections are made through glass-to-metal seals. Before the exhaust tube is sealed, the enclosure is evacuated to remove water vapor and is filled with dry nitrogen at atmospheric pressure. This permanent, positive sealing in an invariant atmosphere makes both capacitance and dissipation factor virtually independent of environmental changes in pressure, altitude, or humidity.

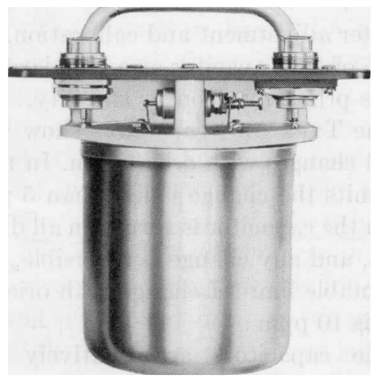


Figure 3. Panel view of the Reference Standard Capacitor

Figure 4. View of capacitor with cabinet removed, showing the sealed container and the three-terminal trimmer.

This sealed capacitor is mounted on a solid aluminum casting, which is fastened to the front panel of the cabinet, as shown in Figure 4. Webs in the casting provide shielding between the two leads from the capacitor, which are connected to two recessed locking TYPE 874 Coaxial Connectors on the panel. The left or tt connector is completely insulated from the panel to eliminate ground-loop troubles when long leads are used and to facilitate the use of the capacitor as a dissipation-factor standard. The panel connectors can be converted to most other common types of coaxial connectors by the use of the appropriate TYPE 874 Adaptor, and the locking version of the adaptor can be used to make the connection semi permanent.

Also mounted in the web is a three- terminal trimmer capacitor used to adjust capacitance over very small ranges. The capacitance of this trimmer is such a small part of the total, about 0.01%, that its effect on over-all stability is negligible

Stabilization and Test
After assembly and sealing, each capacitor is subjected to a number of hot and cold cycles of temperature to stabilize the structure and to determine the temperature coefficient and the magnitude of the hysteresis. The capacitor is heated to approximately 65 C or 150

(TH in Figure 2), then cooled to a room temperature. TR, of 23 C or 73 and measured to determine the capacitance CR11 after a hot cycle. Similarly, it is cooled to a temperature, T(', of —18 C or 0 F, then measured at room temperature to determine the capacitance, CRe. after a cold cycle. The hot cycle is then repeated to return the capacitor to the capacitance CRll and to determine the retraceability of the cycle. The limits for acceptability are that the cycle retraces within +5 ppm and that the capacitance at room temperature, , does not exceed 20 ppm for these hot and cold cycles. The capacitance change from hysteresis is typically less than 10 ppm. The change in capacitance at room temperature, ACR = Can — CRC, is the measure of hysteresis.

The temperature coefficient is determined from measurements of capacitance made during this cycling while the capacitor is at a known temperature above or below room temperature. The coefficient is, typically, constant ivithin + 1 ppm/°C over the temperature range of these cycles. The acceptable range of temperature .coefficient is from +0 to +4 ppm/°C. The typical coefficient is +2 ± 0.5 ppm/°C.

The temperature cycling is also a test for leaks in the hermetic seals. When leaks are present, the cycles do not retrace and the capacitance changes with time.

Adjustment and Calibration
After a capacitor has passed the tests for stability, temperature coefficient, and hysteresis, the capacitance is adjusted by means of the trimmer to make the measured capacitance very close to the nominal value of 1000 or 100 pf. The TYPE 1404 capacitor, unlike most previous standard capacitors, can be adjusted easily with an accuracy almost equal to the precision of measurement, which is better than +1 ppm. The measurement is made by comparison on a TYPE 1615-A Capacitance Bridge with one of a group of TYPE 1404 working standards that have been calibrated from a group of similar reference standards periodically measured by the National Bureau of Standards. The accuracy of the NBS calibration of these reference standards is + 20 ppm.

Each capacitor is adjusted at a room temperature of 23 + 1 C and a frequency of 1000 + 10 cps to a capacitance 5 ppm above the nominal value with respect to the General Radio reference standards. The adjustment to a value above nominal (e.g. 1000.005 pf) is made because the standard is a little more convenient for use in bridge calibration when it is slightly greater instead of less than nominal (e.g. 999.995 pf). Although the precision of adjustment exceeds 1 ppm, the uncertainties of room temperature and capacitor temperature coefficient add to the adjustment error, so that the adjustment accuracy at the stated temperature is approximately + 5 ppm.
The final adjustment of capacitance at room temperature is always made after the capacitor has last been through a hot cycle to 65_C, so that the capacitor is at the position

similar to CRII in the cycle of Figure 2.

Stability
After adjustment and calibration, the value of the capacitor as a standard depends primarily upon its stability.

The TYPE 1404 capacitors show very small changes with orientation. In typical units the change is less than 5 ppm when the capacitor is turned ingldiractions, and any change is reversible. The acceptable limit of change with orientation is 10 ppm.

The capacitors are relatively free from microphonics; therefore, the short- term stability is determined mainly by changes in temperature produced by environmental temperature changes. With the temperature coefficient of +2 ppm/°C, a high degree of stability can be obtained with only moderate temperature control. When higher stability is required, the capacitor can be operated in an air or oil bath with close temperature control, since the effects of connecting cables can be made negligible with three-terminal connections and measurements. When an oil bath is used, the panel with connectors and trimmer can be kept above the oil by the addition of longer spacers and shielded leads between panel and capacitor; only the. sealed container of the capacitor is immersed. The modification can be made without change in the calibrated capacitance.

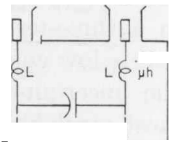
Any reference standard capacitor wears along with that title an implicit "Handle with Care" sign. Careful handling of the TYPE 1404 capacitors is always a wise precaution, but it is not always a necessity because the structure is not delicate. Sample capacitors have been put through impact shock tests of from 30 to 50 g with 11-millisecond durations, and the resulting capacitance .01" changes have not exceeded 50 ppm and have, in some cases, been only a few ppm. The capacitors have also withstood equally well those immeasurable, and apparently unavoidable, shock tests which occur in normal shipment.

Protection from both mechanical and thermal shock is provided by the ship, ping container of expandable polystyrene. The capacitor can be kept in this attractive plastic case, not only for storage and reshipment but also for reduction of thermal transients during laboratory measurements. The thermal time constant for changes in ambient temperature is increased from about 1 hour to 2.5 hours when the metal cabinet is covered by the plastic case and cables are connected trough holes in the case.

The long-term stability (the capacitance change with time) of a well-cod- dled capacitor is as important as it is particularly difficult to measure when the changes may he no more than a few ppm. Many months or years and many capacitors of the highest stability are required for stability measurement, and neither has been available in adequate quantity for this new capacitor. Present estimates of long-term drift must be based upon the intercomparison of a few capacitors for the period of a year or less and upon a few calibrations by NBS, but the available data indicate 'a drift rate well within 20 ppm per year. Data of more significance are now being accumulated by NBS and by the many standards laboratories which are already using the TYPE 1404 capacitors and sending them periodically to NBS for calibration. 05

High-Frequency Performance

Figure 5. Equivalent circuit of Type 1404 Capacitors.
CD" 1000 pf for Type 1404-A CD = 100 pf for Type 1404-B



I •
30 1 CH CL - 2- 8
pf 1 1 Pf

Although intended primarily for low- frequency applications, the TYPE 1404 r" capacitors can be used at higher frequencies if certain considerations are kept in mind. The direct or three-terminal capacitance at the terminals of the capacitor increases with frequency, primarily as the result of the resonance (in the equivalent circuit of Figure 5) between the series internal lead inductances, L, and the capacitance, CD, shunted by the ground capacitances, CH and CL, in series. The effective capacitance is C C0(1 f2/f,), where Co is the low-frequency capacitance and fo is the resonance frequency. The resonance frequencies are approximately 16 Ale for the 1000-pf TYPE 1404-A and 47 Mc for the 100-pf TYPE 1404-B, and the corresponding measuring frequencies, f, for a capacitance increase of 50 ppm are 113 ke and 332 kc.

When leads are connected to the capacitor, however, the series inductance and shunt capacitance of the leads will cause a capacitance increase similar to and probably larger than that produced by the internal residuals. Correction can be made for the effects of internal and external residual impedances, but high accuracy is difficult to Obtain with increasing frequency. Capacitors that can be connected to the bridge terminals without leads are recommended as standards for frequencies above, say, 10 kc

Dissipation Factor and D Standard

Tile losses in the TYPE 1404 capacitors are extremely low because the only effective dielectric in the calibrated direct capacitance is dry nitrogen. All the ceramic insulation affects only the capacitances to ground, which are excluded in a three-terminal measurement. The loss is low enough to be comparable to the uncertainties in the calibration of most available standards of dissipation factor. The best estimate at present is that the dissipation factor at 1000 cps can be maintained below 10 ppm and is typically less than that.

Because the dissipation factor is very low and constant in this sealed capacitor, the capacitor can also be used as a standard of dissipation factor, for example, in bridge calibration. The desired magnitude of D can be obtained by the addition of loss in the form of a calibrated fixed or decade resistor in series or in parallel with the capacitor.*

Uses

The primary use of TYPE 1404 capacitors is as reference or working capactance standards of the highest order for the calibration of other capacitors and bridges. The high stability should permit the accuracy of NBS calibrations to be transferred to other laboratories with uncertainties less than + 20 ppm.

For many calibrations, such as that of the TYPE 1615-A Capacitance Bridge, either the 1000-pf TYPE 1404-A or the 100-pf TYPE 1404-B capacitor can be used with equal accuracy. There is no significant difference in quality between the two models, but the difference in capacitance is useful for some special purposes, such as the extension of the precision of the TYPE 1615-A bridge.

CREDITS

The design and development of the TYPE 1404 Reference Standard Capacitor was carried out by Dr. Hersh, with mechanical design support from G. A. Clemow, Design Engineer. — EDITOR